TECHNICAL REPORT

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Post-glacial faulting in the Lansjärv area, Northern Sweden

Comments from the expert group on a field visit at the Molberget post-glacial fault area, 1991

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Information on SKB technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32), 1989 (TR 89-40), 1990 (TR 90-46) and 1991 (TR 91-64) is available through SKB.

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ABSTRACT

Post-glacial faults have been recognized in the northern Baltic shield for several decades.

It is important to evaluate whether such neotectonic movements can lead to new fracturing or decisively alter the geohydrological or geohydrochemical situation around a final repository for spent nuclear fuel.

The post-glacial Lansjärv fault was chosen for a interdisciplinary study because of its relative accessibility.

The goals of the study were to assess the mechanisms that caused present day scarps, to clarify the extent of any recent fracturing and to clarify the extent of any ongoing movements. All these objectives were reasonably met through a series of studies, which have been performed by SKB during 1986-1992 in two phases.

This report gives a summary of the first phase of the Lansjärv study (1986-1989) and describes achievements that have been gained during the second phase of the study.

As a final of the field-work in the Lansjärv area a meeting combined with a field excursion was arranged by SKB in June 1991 for a group of international experts. Comments from the expert group on the excursion and the overall Lansjärv Project are presented.

One of the major conclusions is that the Lansjärv post-glacial fault reactivated pre-existing old structures and that the causes of the post-glacial movement is a combination of plate tectonics and deglaciation.

ABSTRACT (in Swedish)

Förmodade postglaciala förkastningar har under de senaste årtiondena beskrivits och undersökts på ett flertal ställen i norra delen av Baltiska skölden.

Ur SKB:s synpunkt är det viktigt att försöka fastställa huruvida neotektoniska rörelser av detta slag kan åstadkomma sprickbildning i hela bergplintar och eventuellt ändra de geohydrologiska eller grundvattenkemiska förhållandena i anslutning till ett slutförvar för använt kärnbränsle.

Lansjärv valdes som undersökningsområde bl a med hänsyn till den relativa lättillgängligheten.

Målet för undersökningarna var i första hand att utvärdera de mekanismer som kan ha orsakat de postglaciala förkastningarna och att fastställa omfattningen av eventuell recent sprickbildning och pågående rörelser längs dessa.

Denna rapport innehåller sammanfattande resultat av fältundersökningarna samt kommentarer från den expertgrupp som deltog i en anslutande exkursion i Lansjärvsområdet sommaren 1991.

Bland konklusionerna må nämnas att den postglaciala förkastningen i Lansjärv reaktiverades i en redan existerande gammal svaghetsstruktur. Orsaken till den postglaciala rörelsen är en kombination av plattektonik och deglaciation.

CONTENTS

1. INTRODUCTION

The introduction provides an overview of the background to and objectives of the Lansjärv study which was performed by SKB during 1986-1992 /Bäckblom, Stanfors, 1989 and /Ericsson, Stanfors, 1993/. Earlier works on post-glacial faults in Sweden are presented and the scope of work in Lansjärv is outlined.

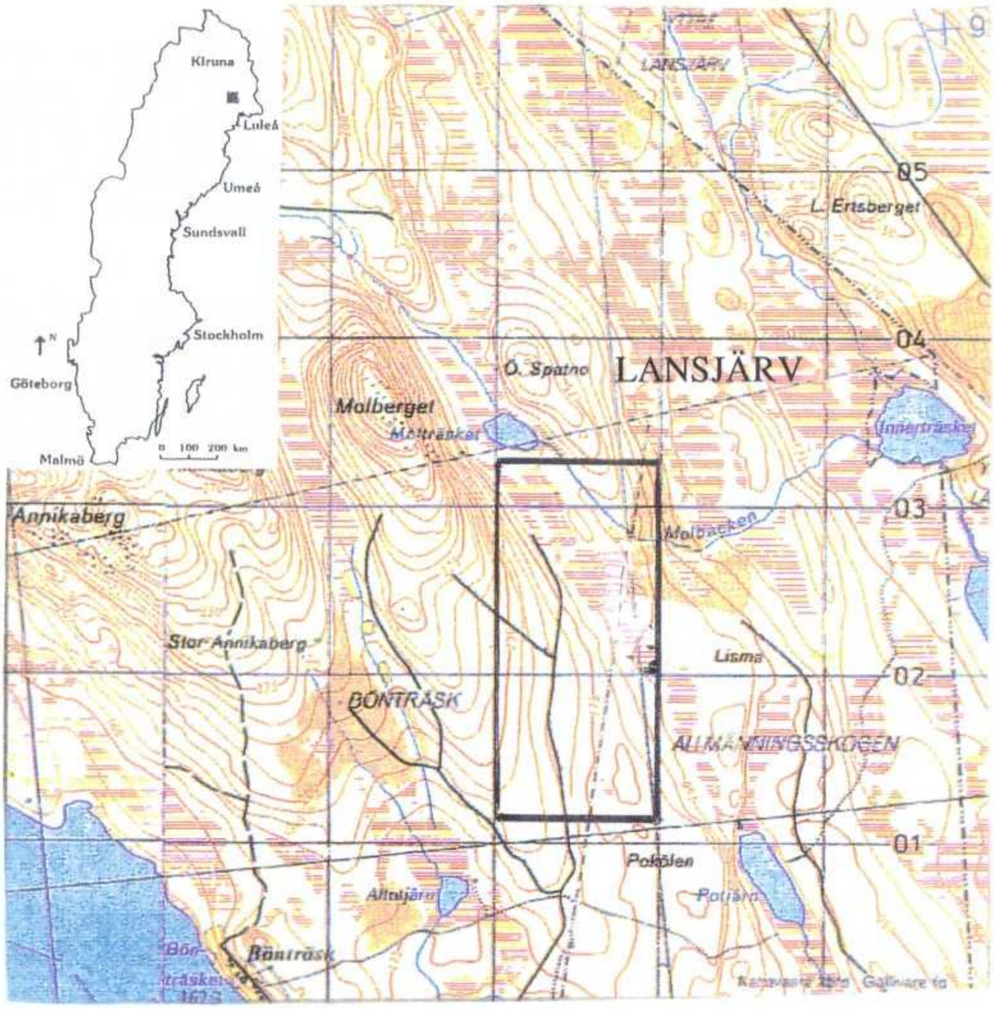

Figure 1.1 *The Lansjärv area. Framed area is enlarged in Figure 2.1*

1.1 BACKGROUND

The long-term safety of a repository can be demonstrated by using several redundant barriers. The performance of the waste and the engineered barriers - canister and buffer - is dependent on the chemical and geohydrological conditions in the rock mass. With respect to safety it is important that the rock provides mechanical protection, low groundwater flow and a favourable chemical environment over a long period of time. In order to carry through an in-depth analysis the possible effects of geological and climatic processes serveral studies have been launched in accordande with the research programme on handling the final disposal of nuclear waste.

One essential study within the programme on bedrock stability was the analysis of post-glacial fault movement in the Lansjärv area. The post-glacial fault movements that have been detected in Scandinavia probably ocurred along major fault zones that have already existed for hundreds of million years.

It is, however, of importance to evaluate whether these recent (neotectonic) movements can lead to new fracturing or decisively alter the geohydrological or geohydrochemical situation around a final repository for spent nuclear fuel.

1.2 OBJECTIVES

The objectives for the research programme on bedrock stability are

- to quantify or set limits on the consequences of earthquakes, glaciations and land uplifts to the safety of a final repository for spent nuclear fuel,
- to process, evaluate and increase knowledge concerning geodynamic processes in the Baltic Shield.

Within these overall objectives, specific objectives have been set for the Lansjärv study. They are

- to assess the mechanisms that caused present day scarps,
- to clarify the extent of any recent fracturing,
- to clarify the extent of any ongoing movements.

1.3 PREVIOUS STUDIES ON SWEDISH POST-GLACIAL FAULT MOVEMENTS

On of the first papers on Swedish post-glacial fault movements was published by Lundqvist & Lagerbäck (1976). The occurrence of similar fault scarps had previously been discovered in Finland, Kujansuu (1964). Robert Lagerbäck, Swedish Geological Survey, surveyed the Lappish "Pärvie" phenomenon during 1975 by request of Mr Aslak Partapouli. Lagerbäck concluded that the Pärvie-feature was largely composed by post-glacial fault scarps and a fault-line more than 150 km long was mapped. It became obvious that the Pärvie fault movement could be an example of a more common phenomenon and continued work revealed several expected post-glacial fault movements. Lagerbäck & Henkel (1977), Lagerbäck (1979).

Preliminary geological and geophysical characterization of the faults was carried through and published. Lagerbäck & Witschard (1983), Henkel et al. (1983).

These reports included interpretations of air-borne magnetical surveys, photogrametrical levelling, air-photo interpretation, investigations on outcrops and geophysical measurements on the ground, including seismic refraction profiling.

1.4 SCOPE OF THE SKB STUDIES

In a first phase during 1986-1988 a great number of investigations were performed in the Lansjärv area and presented in a SKB Technical Report, TR 89-31 /Bäckblom, Stanfors, 1989/. Henkel made a geophysical study in order to obtain basic data for an optional location of drill holes, excavations and deformation measurements.

2. SUMMARY OF THE RESULTS FROM THE FIRST PHASE OF THE LANSJÄRV STUDY

The specific goals for the first phase of the Lansjärv study were to assess mechanisms that caused present day scarps, to clarify the extent of any recent fracturing and to clarify the extent of any ongoing movements. All these objectives were reasonably met through a series of studies during 1986-1989.

Geological and geophysical interpretation

In the initial stage of the Lansjärv study existing geological and geoophysical data in an 150 x 200 km large area was complied. The tectonic interpretation map has utilized digital imageprocessing technique for the combined interpretation of magnetic, elevation relief, geology and gravity. This analysis and geophysical ground measurement identified three regional fault systems. Major single faults of the N and NW system are about 200 m wide and have generally steep dips. The third system strikes NNE and gently dips ESE.

Post-glacial faulting and paleo seismicity

By trenching across the fault scarps it has been possible to date fault movements relative to the Quaternary stratigraphy. It is concluded that the post-glacial faults in the Lansjärv area developed as single-event movements shortly after the deglaciation about 9000 years ago, possibly in connection to strong earthquakes. The scarps are developed in strongly fractured and chemically weathered zones of presumed pre-Quaternary age. The results from the trenches suggest, at least at the surface, that the faults are reverse and dipping between 40-50° and the vertical. It is concluded that most, if not all, the post-glacial fault movements took place along zones shattered and chemically altered long before pre-Quaternary times. Any new fractures that appear at surface are to be confined to within a few metres of the scarp.

Tectonic interpretation

The natures, geometries, histories, kinematics and recent dynamics of geological deformation structures and fabrics exposed in the bedrock in or near the post-glacial Lansjärv fault system and N- and NW-trending geophysical lineaments were treated in a tectonic interpretation in a regional scale of the Lansjärv area. The geological and tectonic studies concluded the post-glacial fault to strike NNE and dip gently to SES.

Seismic networks

Two seismic networks for earthquake monitoring have been established and operated in the Lansjärv area as part of the project. Up to February 1989 more than 90 events were detected by the six station permanent network with signals at 3 or more stations. The magnitudes were in the range M_L 0.1-3.6. The released stresses have the horizontal principal compression in the NW-SE quadrant. The dominating type of fault movements is strike-slip along sub-vertical planes. The mobile network for detecting seismic activity registered a few events during the 1987 period. For the 1988 campaign some of the stations were relocated and 28 events were detected. Plausible focal styles have been derived for four events, showing a variety of faulting styles. Many events are located at depths of 8-10 km.

Drilling

Based on the results and analysis of geophysical measurements and tectonic interpretation a site for core drilling was suggested. Three percussion bore-holes and a 500 m cored hole were drilled. As the cored hole collapsed at a depth of 148 m, casing was set down to this depth. The hole was logged with several geophysical methods. Core mapping shows predominantly red-gray granite as the general rock type. Pegmatites and aplites occur as dykes and veins. Tectonic breccia occurs in some sections of the borehole. The upper part of the hole, 32-300 m, is very fractured, while the lower section is less fractured.

Groundwater chemistry

Samples of groundwater chemistry at depths of 150 m and 237 m show that the Lansjärv water belongs to the group of intermediate non-saline granitic groundwaters. Eh (redoxpotential) monitoring as well as presence of detectable amounts of ferrous iron indicate the reducing character of the water.

Rock stress measurements

Rock stresses were measured by means of hydraulic fracturing. The minimum horizontal stress especially near the bottom of the hole (494 m) is exceptionally low, close to 6 MPa, compared to elsewhere in Sweden. Maximum horizontal stress values are more scattered, but is in general in the same order as the vertical stress. The direction of the maximum horizontal stress is depth dependent. At 300 m the direction is NW-SE. However, it rotates rapidly and steadily with depth and at the bottom of the hole it has turned to ENE-WSW. This re-direction of stresses with depth is unusual.

Hydrogeological testings

Hydrogeological testings in the hole included measurements of hydraulic conductivity and observations of groundwater pressures. The hydraulic conductivity decreases slightly with depth. The highest values (> 10^{-6} m/s) are obtained in the depth interval where the fracture frequency is highest and where the hole is interpreted to intersect the post-glacial fault. In the main part of the borehole there is no obvious correlation between hydraulic conductivity, fracture frequency, rock type, rock stress or infillings. Compared to other study-sites the conductivity show no clear anomaly, even though the rock may have experienced a M_L = 7 earthquake. Measurements of groundwater levels, however, show some peculiarities. The groundwater level is approximately 70 m below surface in the percussion hole HLJ 01 and there is a relatively large vertical gradient through the length of the borehole. Numerical modelling was done in order to study some aspects of the effects of fracture zone geometry on groundwater flow conditions. The modelling shows that the existence of a continuous fracture zone with an inclination of 15° does not explain observed hydraulic data. A steeper inclination of the fracture zone gives a better fit with data. Another possibility is several subhorizontal fracture zones.

Fracture-infillings

A mineralogical and geochemical study has been performed of fracture-infillings in the drillcore in order to identify evidence that may support recent reactivation and to determine whether low temperature rock/water reactions have contributed to changes in the fracture mineralogy and chemistry. Of particular interest to this study is the variation of U, Th, REE (Rare Earth Elements) from the fracture edges into the wall rock as well as their variation with depth. The study shows that the rock has been exposed to extensive hydrothermal activity especially pronounced in the upper 300 m of the drillcore. Subsequent to hydrothermal period(s) low temperature groundwaters have caused redistribution of elements as well as minerals e.g. the dissolution of calcite and the leaching of U and light REE along the flow paths in the upper part of the borehole.

Modelling of rock masses

Computer modelling of large-scaled bedrock has also been conducted to study effects of e.g. glaciation, ice sheet advance, deglaciation, ice sheet retreat, and melt down. The first part of the modelling project has been aimed at attempts to validate the numerical codes used. The Colorado School of Mines block tests have been used for checking the performance of the codes. Using the finite difference code MUDEC, the rock is essentially treated as a discontinuum. The modelled stresses indicate features similar to those measured in the CSM block i.e. rotations from blocks to block where crossing a joint. The ranges of values for deformations are in agreement with measurements. Using the finite element code HNFEMP the rock is essentially treated as a continuum. There is fair agreement in the orientations and magnitudes of displacement vectors and direction of principal horizontal stress. The effect of glaciation and deglaciation has been studied as well. Six loading cases were modelled for a 4.4 rock mass with three different fault set geometries. The results from one calculation using MUDEC show inter-block displacements in the order of 5 to 10 cm for the assumed material properties.

3. SECOND PHASE OF THE LANSJÄRV STUDY, 1989-1992

The second phase of the Lansjärv study, 1989-1992, comprised a more detailed study of one of the faults - the Molberget fault.

Based on the results from a seismic refraction survey three trenches were excavated across the Molberget fault. Three cored boreholes were also drilled across the faultline /Ericsson, Stanfors, 1993/.

A mineralogical study of samples from the bedrock in the trenches and from drillcores indicate among others that reactivation has occurred, perhaps repeatedly, along the mylonitic/cataclastic zone - along the fault scarp - which is characterized by chrushed granitic fragments and clays /Eliasson et al, 1991/.

In order to clarify the extent of ongoing movements in the Lansjärv, Sliding Micrometer measurements were performed in two boreholes at the Molberget fault during 1990-1991. Differences of 420 μm and 230 μm respectively were recorded in the near horizontal and the near vertical boreholes /Ericsson, Stanfors, 1993/.

The study of deformations according to different types of deposits in the Lansjärv was continued. Investigations in a number of trenches and pits gave further arguments to the theory that extensive occurence of soft sediment deformation in the Lansjärv area can be explained by early post-glacial co-seismic movements in the fault-set /Lagerbäck, 1991/.

As a final of the field-work in the Lansjärv area a meeting combined with a field excursion was arranged by SKB in June 1991 for a group of international experts.

4. MEETING AND FIELD EXCURSION IN THE LANSJÄRV AREA, JUNE 17-18, 1991

In June 1991, a group of international and Swedish geoscientific experts took part in a final meeting combined with a field excursion concerning post-glacial faults in the Lansjärv area.

The main aims of the meeting was to

- present the main results of the Lansjärv research project, 1986-1989, supported by SKB,
- demonstrate fault scarps, landslides and seismites in the field,
- discuss post-glacial faulting problems with special aspects to the disposal of radioactive waste.

As an introduction to the field trip, Robert Lagerbäck gave a historical background to the study of post-glacial structures in northern Fennoscandia and Ove Stephansson presented an overview of the Lansjärv project 1986-1989, supported by SKB.

The goals for the field trip during the first day were the Risträskkölen and the Molberget fault site under guidance of Robert Lagerbäck, Göran Nilsson, Eva-Lena Tullborg and Bengt Stillborg. During the second day of the excursion Robert Lagerbäck demonstrated seismically disturbed structures in the Elmaberget and the Furuträsket.

During the final part of the meeting John Adams gave a lecture on "Snap, crackle and pop: Crustal stresses, post-glacial faulting and earthquakes in Eastern Canada".

After discussion and sum up all the members were requested to give their comments on the excursion and the overall Lansjärv Project, especially concerning three principal questions. Some of the members participated in an excursion before and after the Lansjärv excursion and their comments are included in this summary.

1 Do the PGF's reactivate existing faults?

2 What are the causes of the PGF's movements?

3 Are the PGF's still active?

4 Is the Lansjärv area and its' PGFs and seismites unique?

5 Why are the PGFs orientated NNE?

6 What would be the impact of PGF movement on a repository site?

5. COMMENTS FROM THE PARTICIPANTS IN THE LANSJÄRV EXCURSION

JUNE 16-18 1991

SKB received comments from the following participants. All the contributions have been copied and are here presented according to the originals.

Prof. John Adams	Geophysics Division, Geological Survey of Canada Energy, Mines and Resources Canada 1 Observatory Crescent OTTAWA Canada K1A OY3
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Dr. D. R. Grant	Geological Survey of Canada Energy, Mines and Resources Canada 601 Booth Street OTTAWA Canada K1A OE8
Dr. Søren Gregersen	Boligministeriet Kort- og Matrikelstyrelsen Geodætisk-Seismisk Afdeling Seismologikontoret Rentmestervej 8 DK-2400 Copenhagen NV Denmark

Prof. Sven Hansbo	Chalmers University of Technology, Dep of Geotechnical Engineering 412 96 GÖTEBORG Sweden
Prof. Arch C. Johnston	CER, Memphis State University 3890 Central Avenue MEMPHIS, Tennessee 38152 USA
Prof. Jan Lundqvist	Department of Quaternary Research University of Stockholm Odengatan 63 113 22 STOCKHOLM Sweden
Dr. Robert Maddock	GeoScience Ltd Silwood Park ASCOT SL5 7QW United Kingdom
Dr. Robert Muir-Wood	BEQE 278 Cambridge Science Park Milton Road CAMBRIDGE CB4 4WE, United Kingdom
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COMMENTS FROM THE PARTICIPANTS IN THE LANSJÄRV EXCURSION

FIELD VISIT TO SITES OF POST-GLACIAL FAULTING IN SWEDEN, JUNE 1991

John Adams

INTRODUCTION

This reports on a visit to four areas of post-glacial faulting in Sweden, at the invitation and expense of SKB (Svensk Kärnbränslehantering AB), the Swedish Nuclear Fuel and Waste Management Company.

The four areas visited were:

1 Post-glacial faults and moraines in the Stockholm area.

2 Post-glacial faults in the Kiruna area.

3 The Lansjärv Fault.

4 Äspölaboratoriet, site of the Swedish Hard Rock Laboratory.

Douglas Grant accompanied me on all the visits, which were lead by Robert Lagerbäck (visits 2 and 3) and Nils-Axel Mörner (visits 1 and 4).

1 Stockholm

Sites in the suburbs of Stockholm at Erstavik, Skogsö, and Ragnorök, claimed by Mörner to represent post-glacial fracturing of the bedrock and/or post-glacial faults (Tectonophysics v. 163, p. 289-303), were visited. These are mostly short bedrock outcrops, 0.5 - 1.5 m high and with a sharp edge, that disappear beneath soil along strike. An exception is the Erstaviken fault which is 3.6 km long, crosses a valley, and is an aquifer. I saw these first in 1988, during a visit with Mörner, and wished to revisit them in conjunction with the other post-glacial fault visited on this trip. In 1988 I was uncertain of their significance; on the present visit (partly by comparison with similar features at Äspö) I believe that most (but not necessarily all) are unlikely to represent faulting. In 1988 and again this year I told Mörner that selected excavation was necessary to test his hypotheses; the issue of these scarps will not be resolved until he secures the funds to do so.

We also saw the bouldery moraine field at Bromma. Mörner (following De Geer) attributes the necessary fracturing of the bedrock (allowing plucking of the blocks by the ice) as due to an earthquake that occurred shortly before the area was deglaciated. This is a very plausible scenario, but other hypotheses should be tested. Confirmatory evidence for earthquake shaking from the varve stratigraphy should be collected rigorously.

2 <u>Post-glacial Faults in the Kiruna area</u>

I went on a 2-day field trip led by Robert Lagerbäck, from Luleå to Kiruna and thence back to Överkalix. Other attendees were Douglas Grant, Robert Muir-Wood, Phil Ringrose, Clark Fenton, and for the second half, Arch Johnston. Brief comments on each stop follow.

Stop near Tärendö.

An esker, of very fresh and post-glacial appearance, had apparently been covered by the ice at least twice, as shown by till stratigraphy in the hollows. This could have occurred if the ice accumulated and melted without appreciable lateral movement. If old, pre last-glacial features like this one are widely preserved, one might expect to see faults dating from those deglacials also.

Lannio-Suijarvaara Fault at Viikusjärvi.

The very high scarp (≈ 30 m) at this site was visited. Remarkable was the lack of glacial rounding and removal of blocks. The upper part of the scarp is probably a smoothed and sloping glaciated surface that has sagged down into the valley. Adjustment for the likely original shape of the surface reduces the apparent displacement above the level of the swamp by one-third. The lack of relative displacement between the boulders is startling. Apparently no freeze-thaw action can work because the rockpile is too free-draining. Very few rocks had fallen into the swamp (though more could be buried). If the fault scarp had formed today, it seems likely that many more large rocks would have been shaken off the scarp to roll away from it. One plausible explanation is that the faulting occurred while the scarp was covered by stagnant ice, and the ice held the broken rock mass together during the moment of faulting. After the melting of the ice the scarp - in more or less original place - would have been exposed. I have argued something similar (but involving winter snow cover) for the lack of loose rock shaken off a cliff very close to the 1989 Ungava fault scarp.

Near the road end of the rock scarp, there is a place where the rock pile is replaced by finer deposits. Here the apparent height of the scarp is lower, though whether because the true height is recorded (rather than the exagerated height suggested by the collapsed bedrock scarp) or because of the deposition of post-faulting sediments, as thought by Lagerbäck, is uncertain. This site would be worth trenching to resolve the stratigraphy, the throw on the fault, and the timing of faulting. Investigations in the swamp with the same goals would be worthwhile.

Water was freely flowing from springs at the base of the scarp, and may have been warm enough to have advanced the blooming of **Ranunculus**. It is likely that the water is surficial, very young and not very warm. Nevertheless, chemical and isotopic measurements are worthwhile in case deep water circulation is involved (with consequences to dispersal of waste buried in deep repositories). A seasonal set of photographs taken by a local resident monthly or weekly could establish the effect on vegetation.

Antithetic strand of the Pärvie Fault at Aitejakke River, SW of Kiruna.

We walked along this strand, which may have controlled the course of a stream near the face of the scarp. The scarp has collapsed into a gentle slope, covered with small trees. None of the trees show trunk bending indicative of active down-slope motion. No observations could be confirmed at this place to decide if the fault was normal or reverse sense. The over-all impression was more that of a collapsed terrace edge than a fault scarp, thus showing the need to use air photograph analysis to set the scene for field investigations.

Pärvie Fault near Pärvie Lake, NW of Kiruna.

SKB and the Geological Survey of Sweden jointly funded a helicopter trip into the Pärvie fault, very close to the Norwegian border. This segment of the fault is anomalous in orientation and also in that bedrock is exposed for a considerable distance along the scarp, resulting in a spectacular cliff in otherwise undulating terrain. The fault was accentuated by snow drifts in the lee of the scarp, with the snow as a guide, the scarp could be seen crossing a hill 4-5 km away. There is no doubt that this site is one of the most spectacular neotectonic sites I have visited. The party walked along the fault and also to an antithetic scarp in surficial deposits about 1 km to the southeast.

On the outward flight, the helicopter followed the fault south to Torneträsk. Although the fault trace is not continuous, and the individual segments are sinuous, it was easily followed during the 20 km flight.

Discussion

While the fault scarp of the Pärvie Fault was more spectacular than I expected, the two antithetic scarps we saw are not very spectacular from the ground. As similar scarps are said to be typical of much of the Pärvie fault (along its length bedrock outcrop and scarps are rare), it is perhaps not surprising that geologists working from the ground had missed their significance until 1975. With hind sight, and especially with aerial coverage, the faults are extremely obvious. The lesson for large areas of the glaciated Canadian shield, where much of the Quaternary geology has been mapped from air photographs is that discontinuous, sinuous linears that cut across topography need to be reviewed in a new light.

3 Lansjärv

Meetings at Överkalix

The meetings consisted of good briefings by Robert Lagerbäck on the fieldtrip sites and rather hurried discussions of the project results and their interpretation. Some focus was given by the attempt to discuss the "General Conclusions" section of SKB TR 89-31, but the time available was insufficient. I would recommend that any similar trip be structured as an intensive field visit followed by no less than two days of discussion (perhaps at SKB offices in Stockholm to reduce costs). I am most grateful to SKB for its support of the June 15-16 Lagerbäck trip, as considerable discussion occurred during the long trips in the van. It is a pity that Lagerbäck was the only Swede present.

Ristäskkölen

Time did not permit an extensive walk around this spectacular upthrust wedge, though the characteristics could be seen from the bus. The tectonic implications are remarkable.

Lansjärv Fault at Molberget

The trenches gave an unparalleled view of the bedrock scarp. I was struck by how unfractured the bedrock was (this is a relative consideration, as others were struck by the high degree of fracturing), in my terms, I mean that the bedrock had not been clearly broken into large, separated blocks. Fracturing to that degree has been proposed by Mörner to explain the exceptional bouldery moraines at Bromma and the boulder train at Äspö, so its absence here, right on a known active fault, suggests that the true explanation is different.

Indicators of strong shaking, Furuträsket and Elmaberget

The work on strong ground shaking indicators is very important because it provides confirmatory evidence for the faulting and may help to date it. Study of features such as the landslides in till, the seismicially-graded tills, and water-escape features in sediments could be transferred from their known association with the post-glacial faults of northern Sweden and applied in southern Sweden, where there are as yet no mapped faults of similar post-glacial movement. The study of disturbances in adjacent varve-sequences that might correspond to the faulting on the Lansjärv and the other faults is lacking.

Discussion

The work done on the Lansjärv fault has been multidisciplinary and well summarized in the SKB report 89-31. Specific comments on the work are collected in Section 5 (see below).

4 Äspölaboratoriet

Äspö Island lies on the east coast of Sweden about 300 km south of Stockholm. It is close to three nuclear reactors and currently the site of an extensive pilot project to test the feasibility of constructing deep underground storage vaults for high-level radioactive waste. Experience gained at Äspö and other sites in Sweden will lead to the choice of three other potential sites in the next few years, and one of those three will be the final repository, perhaps starting around 2020. The present stage of development is the construction of an inclined access tunnel from near the reactor buildings to beneath Äspö, where it will meet up with a shaft and spiral down to the final depth.

The Äspö site has therefore been heavily studied over the last few years. The wooded island is about 1 km across, is reached from the mainland by a causeway, and has a network of recreational trails. About a quarter of the island is smooth, glaciated bedrock and the remainder is covered in soil and vegetation.

I am unsure of the extent of the initial Quaternary geology investigations at Äspö, but in 1989, Mörner was funded by SKB to produce a report on 'possible post-glacial faults on Äspö', in light of the work he had done around Stockholm (Tectonophysics, v. 163, p. 289-303). He had time and funds only for 50 hours field work, but produced a well-organized and well-illustrated report (Post-glacial faults and fractures on Äspö, Swedish Hard Rock Laboratory Progress Report 25-89-24, 80 pp.) that documented observations at some 100 sites, and concluded that not only was post-glacial faulting and fracturing pervasive, but that one, if not more, large earthquakes had occurred in the immediate vicinity of Äspö at the time of the ice retreat. He attributed the surface fracturing as a secondary consequence of a major earthquake on an east-west fault just north of Äspö. Many of Mörner's "sites" are sharp bedrock outcrops in the forest of very limited extent (say 1 m high and 20 m long). Subsequent to the report, SKB excavated two of Mörner's sites and showed that they represent glacial plucking, not fracturing and faulting. Mörner's work was reviewed during a field visit in May 1990, and I have heard that most of his claims were discounted, probably based mostly on the excavation results.

For a further opinion, Mörner drove Adams and Grant from Stockholm to Äspö and back (SKB paying expenses), and we spent 6 hours touring the island accompanied by Olle Zellman, the site manager.

Discussion

- Mörner's report makes a great deal of a boulder train that extends across the island. It is clear that the boulder train is well defined and has originated from a source just off Äspö. Mörner's interpretation that the boulders were released only slightly before the ice front retreated back across Äspö seems plausible. His inference that the apex of the train represents the epicentre of a large earthquake is, however, implausible because an earthquake of the inferred size would occur along a fault and not be confined to a single point. It seems clear that some late-glacial event caused the bedrock to be shattered (here as at one other site Mörner showed us), and then transported by the ice, but it is not at all clear what type of event was involved.

- I was not at all impressed by many of Mörner's bedrock scarps in the forest. These scarps have a very short length in relation to their height, and they disappear beneath the thin cover. The example (Site 39) chosen by Mörner for excavation is typical, but even without excavation did not look like a likely candidate for faulting.

- In walking over the bedrock exposures Mörner pointed out some places (and we found others) where the level of the smooth bedrock surface changed across a joint. A typical feature would be 50-70 mm high and 5-7 m long (until the end of the outcrop) and with a slightly rounded edge. There seemed to be no reason why such steps in the rock should not have been planed-off by the ice to the general level of the outcrop, so the best inference is that they represent faulting under the ice, slightly before the time of ice retreat (so that the edge was rounded but not completely planed off). These features could have formed about the same time as the rock in the boulder train was released. Although more widely spaced and larger in offset (perhaps because of the widely spaced joints in the granite), they resemble the post-glacial faults described by Adams and Grant from Canada.

- The most significant outcrops seen were sites 86 and 30 from Mörner's report.

- Site 86 is a glaciated step in the bedrock at a shoreline exposure. The step is nearly parallel to the ice flow direction and the initial impression is that one side has dropped down about 0.5 m. The face of the scarp is striated and smoothed. During our brief visit we concluded from matching up the fractures on both sides of the scarp that the motion was most likely lateral (strike-slip in a dextral sense) thus accounting for the apparent vertical offset. If confirmed (by excavation of the outcrop along strike and by detailed fracture matching), I consider this highly significant because strike-slip faulting of bedrock during the late glaciation has been demonstrated almost nowhere.

- Site 30 clearly represents extensional and lateral faulting of the bedrock ridge (5 m high and 15 m wide). The edges are less glaciated, so it may have happened right at the end, or after, the ice retreated. I have lingering doubts as to whether this represents faulting or large-scale ice-push of the ridge. Excavation may be warranted.

Conclusions

Although Mörner's report contains many sites that I believe are unlikely to represent post-glacial faulting (or even fracturing consequent on a near-by earthquake), I consider there to be very good evidence for **some** movements in late-glacial or immediate post-glacial time. This had apparently been missed by the previous geological mapping. At this stage, a phased program of rigorous mapping, surface excavation, and if possible examination of the fractures at depth (when the underground excavation reaches the site) is recommended. A tectonic synthesis to see if the verified displacements are consistent with the stress field of a single tectonic driving force (rather than random failure during uni-directional ice push) should be performed. The faults with possible strike-slip motion are very interesting because they have the potential for extending deeper than the dip-slip faults (which could die out on the multitude of subhorizontal fractures).

5 Questions and further work needed

The following items are critical to the interpretation of the post-glacial faults and their future importance:

Have the mapped post-glacial faults moved more than once? I agree that the evidence I have seen and heard from most of the mapped faults suggests a single neotectonic episode, but the significance of repeated Quaternary movement should not be underestimated. Robert Lagerbäck's explanation for the trench at Molberget (where the bedrock scarp is twice as high as the surface scarp; Fig. 3-4 of SKB TR 89-31) is plausible, but should be tested at other places along the fault where wave action cannot be a factor. It would be very important if the fault at Molberget had moved twice, because it might suggest that the present group of mapped post-glacial faults represent the set of weaknesses liable to move again in the future; the alternative, that any old fault will move only once, makes the identification of future faulting much more difficult.

Where are the faults that moved at the end of previous glaciations? Since the most recent deglaciation caused extensive faulting, one might hypothesize that so should each of the previous deglaciations. Robert Lagerbäck says that a large area of Norbotten was covered by a static ice-sheet during the last two or three glaciations, and that during these local erosion was insignificant. Hence one might expect to see two earlier generations of deglacial faults. Robert says they are not present, so clearly more thought is needed to develop testable hypotheses as to why they did not form.

What was the nature of faulting on the post-glacial faults? How deep do the faults extend? It would be interesting to attempt to discern the regional deformation caused by the post-glacial faults. In an ideal case (our study of the 1989 Ungava deformation comes close), the throw, dip and depth of the fault can be obtained by fault-dislocation modelling, given a deformed reference surface. For northern Sweden, the question is: does a reference surface exist, and can its deformation be measured accurately enough?

What is the lake bottom record? Seismic profiling of post-glacial lake-bottom sediments from small, transportable boats (e.g., the work done by Shilts in Canada) seems to have been neglected in Sweden. Classic sites such as where the Pärvie Fault crosses Torneträsk would provide complementary information on fault offset to that obtained on land. In lakes near the Lansjärv fault it may be possible to study the fault offset uncomplicated by the erosion caused by the dropping sea level. In addition, the Canadian work has shown extensive sub-lacustrine landsliding, which in Sweden might provide complementary evidence to the subaerial landsliding. As well as the seismic profiling, coring might provide evidence of earthquakes, as the Canadian work of Doig has shown.

Is there sedimentary evidence to confirm the shaking? A full restudy of post-glacial sedimentation in Sweden, with the aim of finding the sedimentary record caused by the post-glacial faults (if it exists), is warranted. If Robert Lagerbäck is correct, the possibility of tsunamis from the Lansjärv fault displacement increase the likelihood that distant sedimentation effects (turbidites) distinct from, and in addition to, shaking effects could be found. Mörner has claimed for some time that the drainage varves in the Swedish varve chronology represent earthquakes, but only he appears to have restudied the varve chronology with this in mind, and his publications reflect his lack of time he is able to devote to this subject. A person dedicated to the task for about 3 years would probably be adequate. There seems to be no reason why this could not be pursued as a PhD thesis, as long as the supervision is adequate. This approach has worked well in Scotland (e.g., Ringrose and Fenton's PhDs). The intended products would be:

- Confirmation of the time of faulting for some of the post-glacial faults
- Lack of similar evidence for earthquakes in more recent times (confirming the hypothesis that the mapped post-glacial faults all moved in a short time during and after deglaciation) or evidence for young large earthquakes in Sweden (as have been found in Scotland).
- Possible proof of end-glacial earthquakes in southern Sweden (as claimed by Mörner), even though no young fault scarp like those in northern Sweden has yet been identified.
- Increased confidence that no significant recent faulting episode has gone unnoticed in the vicinity of any proposed waste storage vault.

6 Implications for Waste Disposal Vaults in Sweden and Canada

The work begun by SKB is important because of the severe consequences of failure should a fault rupture an underground repository and cause a dramatic change in groundwater flow (viz. the springs at the foot of some post-glacial faults and the groundwater changes that followed the 1989 Ungava earthquake). SKB is to be commended for its open approach to the problem and for the funds and people it has committed.

The suggestions made at the meeting in Överkalix, and the questions I raise in section 5, make it clear that there is still much more information needed before the paleoseismicity of any site in Sweden can be said to be known with enough confidence for long-term vault location (Canada lacks any information at all). In addition, with little understanding of why particular old faults were reactivated during the deglacial period, there is not yet a resolution of the problem of how to site an underground repository in a region that may have ancient weak zones that could potentially fail during one or more glaciation/deglaciation cycles.

The situation is far from hopeless, and the advances of the last 15 years (and particularily the last 5) make me hopeful that our understanding will advance sufficiently during the decade of the 90's that safe vault siting can proceed in the next millenium. A continued commitment to fund selected excavation of the post-glacial fault scarps and other paleoseismology investigations, together with open and frank meetings of the scientists involved (at greater length than possible at Överkalix) are necessary to produce the rapid growth of knowledge needed.

Canada is 10-15 years behind Sweden in studying brittle deformations associated with the the deglaciation and the history of late-glacial earthquakes in the shield. Now is not too soon to begin the process of catching up.

REPORT ON SKB LANSJÄRV EXCURSIONS JUNE 17--18, 1991

Clark Fenton

Introduction

My comments regarding post-glacial fault (PGF) activity are based on visits to the Lainio and Pärvie faults with Robert Lagerbäck (SGU) and the Stouragurra fault with Oddleiv Olesen (NGU) as well as on the information gathered during the Lansjärv excursion. In addition to the information gained from these field sites, observations from my own studies of PGFs in Scotland will be used in order to address the questions posed both at the end of the SKB Report 89-31 and by Lars Ericsson during the Lansjärv excursion.

1 Are PGFs new or reactivated features?

The evidence from slickensides observed at the Molberget site on the Lansjärv fault suggest that there have been at least four episodes of fault movement (strike-slip or oblique-slip) prior to the most recent (vertical) post-glacial movement. Likewise all other PGFs investigated in northern Scandinavia show evidence of movement prior to the most recent movement episodes. This is also the case with PGFs in Scotland, where movement has occurred along basement faults that have had a long history of movement. However, it should be noted that the sharp changes in the trajectories of some of the faults suggests that the most recent fault ruptures, although utilising lines of pre-existing weakness, are ultimately capable of creating their own courses and will only use such pre-existing crustal weaknesses when they are compatible with the desired propagation direction.

2 What are the causes of movement?

From the evidence presented during the Lansjärv excursion this is a question that cannot be answered with any degree of confidence. From my own work on Scottish PGFs it seems to be that fault activity is the result of a number of factors acting in conjunction to give rise to anomalously high stress levels with the crust. During the period of ice residence in an area of compressive stress to the imposition of an external load acts to remove the crust from failure. This also allows the build up of tectonic stress without passing the failure threshold for brittle crustal material. Sub-glacial fluid recharge from basal ice melt can further act to remove the crust from the region of failure. Upon deglaciation the crust is left in a critically over stressed state. This results in faulting and attendant seismic activity.

3 Why are PGFs orientated NNE?

The current regional stress field in Scandinavia, like the majority of NW Europe, is NW-SE orientated horizontal compression. The likely fault movement in such a stress field would be reverse faulting orientated perpendicular to this direction ie. NNE to NE. In addition it would be expected that there would be strike-slip fault movement orientated approximately parallel to the direction of S_{Hmax}. As yet there seem to be no lateral fault movements of this orientation detected in Scandinavia. In Scotland about 50 % of the PGFs are orientated NW and display cumulative strike-slip movement of up to c. 160 m. As Scotland is subject to a broadly similar stress regime to that of Scandinavia it would not be unexpected to discover faults of such offset and orientation in Sweden.

4 Is there any present movement along PGFs?

The evidence we were presented with at Lansjärv was not conclusive. The down-hole micrometer measurements are suggestive that movement is presently not occurring. At least what is detected is not due to tectonism and is more likely to be the result of fluid flow within the rock, or due to the expansion and contraction of microcracks within the rock in response to thermal effects. There are no features along other Scandinavian PGFs to suggest that there is any present movement of any consequence. This is also the case with PGFs in Scotland.

5 Is the Lansjärv area and its PGFs and seismites unique?

With respect to the rest of Sweden, ie. the area to the south of Norrbotten, I am not qualified to determine whether the features that I have observed in northern Scandinavia are unique to that area. If all that has been discovered in the southern part of Sweden are the small "faults" that have been reported in the scientific literature then it must be concluded that the large scale PGFs in Northern Scandinavia must be unique to the northern part of the country. With respect to Scotland, PGF activity has only been reported from the Highlands in the north and west of the country. This however may be merely a reflection on the intensity of fieldwork that has been undertaken in this area. I feel this may also be the case with Sweden where a number of smaller faults (<10 m high?) may have been overlooked? An interestering relationship between PGFs in Sweden and Scotland is the scale difference: in Sweden the large PGFs are of the order of 100 km long and occur at c. 100 km intervals whereas in Scotland the faults are generally 10 km long and spaced at c. 10 km intervals. This may be some reflection on the build up stress during the glacial period.

The seismites we were shown during the Lansjärv excursion, namely the graded tills are unique. To my knowledge this phenomena has not been reported from elsewhere; this may be due to the fact that they have not been recognised as seismites elsewhere. The other seismite features reported in Robert's SKB Report 91-17 are the same as those that have been described from more active tectonic regimes. Similar structures attributed to the effects of palaeoseismic activity have been described from a number of localities in Scotland.

The slope failures associated with the Lansjärv fault are not unequivocally of seismic origin; the problems of attributing slope failures to palaeoseismic events are universal. However, the fact that the slope failures seem to be one off events are now relict, displaying no present movement, suggests that they were triggered by a single event or series of events that occurred in a short time period. The fact that the slope failures occur on very low slope angles shows that there must have been a large degree of liquefaction-induced lateral spreading involved in the failure mechanism - this is strongly suggestive of a seismic trigger.

6 What would be the impact of PGF movement on a repository site?

The consequences of fault rupture of a repository site, be it a surface or underground installation, are threefold:

- physical rupture of the repository and the barriers designed to prevent the transport of radionuclides outwith the repository site
- alteration of the hydrological regime in the vicinity of the repository site
- alteration of the stress regime in the vicinity of the repository.

Related effects would be the opening of fractures providing new fluid flow conduits and the mechanical weakening of the surrounding rock mass with possible disaggregation of fractured rock masses due to near-field strong motion activity. The release of the large volumes of gas created as a consequence of radioactive decay could further act to destroy the integrity of the fractured rock mass. The possibility of fault rupture must be addressed seriously, especially in light of the ground rupture in the region of Ungava, Quebec, Canada as reported by John Adams at the Lansjärv Meeting. This incidence shows that even moderate sized earthquakes in regions of continental shield are capable of producing ground rupture.

Miscellaneous comments

The amount of research that SKB has put into the Lansjärv site is truly impressive. However, much of the work that has been carried out does not seem to have a direct relevance to the understanding of PGF activity. From reading the SKB Report 89-31, although the research is of high quality, it does not directly address the central questions raised at the end of the report, but merely provides interesting background to the problem in hand. It is now up to SKB to "streamline" research into the phenomena of PGFs and address the questions of the cause and future risk from PGF activity. From my impressions of what I have seen in Sweden and from my own work in Scotland the following are possible avenues of future research in order to tackle the outstanding problems:

- a further, more extensive, programme of mapping seismites would give a much better idea of the seismic activity at the time of deglaciation and also help identify smaller faults that may have been overlooked in previous investigations. This, in my opinion, must be given priority as it is the most conclusive (and cost-effective) manner in which to address the problem of palaeoseismicity and post-glacial tectonism

- stress measurements adjacent to PGFs would confirm/deny low stress zones around these faults

- a comparison of the results from the Lansjärv area must be made with other PGFs to confirm that the inferences made from the present study can be applied as universally as possible. Lansjärv maybe (and probably is) unique in some aspects

- the search for other large PGFs in Scandinavia could be eased by looking for other features at a spacing of c. 100 km. More careful search should be made for smaller PGFs that may have remained undetected due to the thick cover of glacial sediments

- in addition to the above recommendation, the controversy concerning certain "PGFs" in southern Sweden should be cleared up. Whether such faulting exists, and if so its nature must be fully documented and compared with that described from Northern Scandinavia.

POST-GLACIAL FAULTING IN SWEDEN

(a report to SKB, the Swedish Nuclear Fuel
Waste and Management Board)

D.R. Grant

This report is a brief assessment of evidence of **post-glacial faults (PGFs)** that was demonstrated by experts in five areas, 13-20 June 1991:

* Stockholm area **(N-A Mörner)**
* Viikusjärvi-Tärendö area **(R Lagerbäck and colleagues)**
* Kiruna area (Pärvie fault) **(R Lagerbäck and colleagues)**
* Lansjärv area **(R Lagerbäck and colleagues)**
* Äspö island **(N-A Mörner)**

Based on the above observations, it addresses seven questions posed by SKB concerning problems which PGFs present for the choice of a site for the safe storage of radioactive waste:

* Are PGFs new faults or reactivated old ones?
* What causes PGFs?
* Why do PGFs trend mainly north-northeast?
* Are PGFs shallow or deep?
* Are PGFs moving at present?
* Are the PGFs at Lansjärv anomalous in Fennoscandia?
* Are PGFs relevant to nuclear repository design?

SUMMARY OF FIELD OBSERVATIONS

Stockholm area

Vertical bedrock scarps, described as PGFs by Mörner (Tectonophysics 163/289-303), were briefly examined at several places (e.g. **Erstavik, Skogsö, Ragnarök**). The scarps are up to 2 m high, yet only a few metres long, where visible, but most are largely obscured by vegetation and drift cover. They are vertical and commonly intersect at large angles. Most have sharp edges with no glacial abrasion. Most are straight and **parallel to existing joint planes in the country rock**, but a few are curved. The question therefore is whether the scarps are simply joint planes exposed by glacial plucking (as would normally be assumed uncritically by most glacial geologists), or whether they are the result of deglacial and/or post-glacial upheaval along pre-existing fracture planes.

I was convinced by the structural geometry at some localities that the once-continuous glaciated surface had indeed become vertically offset after deglaciation, if not also shortly before. At most sites, however, poor exposure made it impossible to establish the former continuity of the glaciated surface across the scarp. Excavation could resolve this uncertainty in a few places. The point, therefore, is not whether **all** scarps which interrupt the glacial surface in the Stockholm area are post-glacial faults, but that **a few of them certainly are.**

Minor moraines and block fields in the **Bromma** area, which were highlighted by De Geer (1940, and earlier), bear on the question of deglacial/post-glacial faulting. The moraines are mainly composed of very coarse rock rubble which appears traceable back to slightly disaggregated bedrock outcrops where the original fit of huge tilted and slightly rotated blocks is obvious. These aspects gave rise to the original explanation which attributed the shattered bedrock to seismic shaking that occurred just behind the glacier margin shortly before deglaciation. The rubble thus produced was therefore moved only a short distance. **I am prepared to accept unreservedly de Geer's explanation of these so-called "seismic moraines"** because no other mechanism seems to explain all of the features satisfactorily. However, whether the supposed deglacial seismic event(s), said to have caused the Bromma features, also produced surface faulting is a separate question which cannot be answered because there is no evidence to establish an age correlation.

<u>Viikusjärvi-Tärendö area</u>

Near **Viikusjärvi** a scarp said to be due to post-glacial upthrusting on the Lainio Fault was examined. The north and south ends of the feature are obscured by thick glacial and colluvial deposits, but the central portion rises to a ≈30 m rock cliff overlooking a peat bog. On the ground, there is nothing to indicate the scarp is a post-glacial fault; it resembles any one of a multitude of rock structural lineaments typical of glaciated Shield terrain where fault and joint planes are exposed by plucking. Noteworthy was a spring issuing from the foot of the rubble. It was depositing iron hydroxides and was sufficiently warmer than the surrounding surface water to advance the blooming of a pond weed (Ranunculus?). Along the drift-covered segment of the scarp, there are inactive gullies with alluvial fans, and slump-like features, whereas the rock cliff portion has a rounded (glaciated?) edge that is "ravelling" by slow outward creep and tilt of blocks. **I am <u>not</u> convinced that the disaggregation and the blocky talus represent seismic shattering.** If the scarp is truly a post-glacial fault, excavation in the sediment-covered part would be instructive.

Near **Tärendö** an esker with a fresh, sharp-crested form, typical of a feature produced during the last deglaciation, had kettles containing ancient organic sediment which proves that it dates from a much earlier deglaciation. Such perfectly preserved pre-last glaciation deposits and landforms cover a large area occupied by the last ice sheet in northern Sweden. The current explanation for their preservation is that the last ice sheet was cold-based (frozen to its bed) and therefore incapable of either removing these pre-existing features or burying them with till. This findings bears on the problem of PGFs in two ways. It means that some fresh-appearing PGFs may date from earlier deglaciations, in which case such **relict PGFs give an exaggerated view of the number of recent faults.** Conversely, if all PGFs date from the last deglaciation, it raises the question of **why are no PGFs from previous deglacation yet recognized.**

<u>Kiruna area</u>

Near the mouth of **Aitejakke River** southwest of Kiruna a scarp considered to be a segment of the **Pärvie Fault** was walked for a few hundred metres. Its origin had been established on the basis of airphoto mapping (which would have been instructive to examine). The scarp, about 5-10 m high in apparently thick drift, is fairly straight and parallels the river for several kilometres. (It looks simply like a river terrace or cutbank, but presumably it is obvious on airphotos that the scarp determined the river's course, rather than being the product of it). In any case, there is nothing visible from the ground perspective to lead one to guess that the scarp was a fault. This experience underlines the fact that large and lengthy post-glacial faults can be established conclusively from airphoto mapping, whether or not ground appearances are corroborative. **From this, the question can be asked whether all parts of Sweden, particularly the drift-covered areas, have been examined sufficiently carefully by experts in post-glacial fault recognition to be sure that all such faults have been found.**

The great **Pärvie Fault** was visited northeast of **Torneträsk** near the Norwegian border to gain a first-hand impression of the appearance of a classic post-glacial fault that is extremely large and well-exposed. The way it cuts drumlins, meltwater channels, and lake shorelines demonstrates that it is a recent offset of the post-glacial terrain. Its sharpness and abruptness in areas of thin drift permit its approximate course to be delineated through intervening areas of thicker drift. **Being able to view the feature from the air was crucial** to appreciating its significance because the several subordinate antithetic scarps, which are not at all conspicuous on the ground, are clearly visible and easily photographed. This relationship further underlines the fact that

post-glacial faults must be mapped from the vertical perspective, that is to say using airphotos; ground observations are better suited to discovered smaller faults on rock outcrops and in pits.

Considering the clear expression and great length of this great feature, it is surprising that it was discovered and described relatively recently. I also got the impression that its regional significance is not yet fully appreciated, especially outside Sweden. The Pärvie Fault and the work that has been done on it serves as a model case for the recognition and study of post-glacial faults in high-latitude glaciated areas.

Lansjärv area

The Lansjärv fault complex and associated features were examined at several large carefully prepared excavations over a wide area. At **Risträskkölen** the fault has a rectilinear, orthogonal trace that strongly suggests the margin of a shallow thrust plate. Its bold surface expression cuts across glacial and post-glacial terrains, thus demonstrating the relative youthfulness of the feature.

At **Molberget**, the main study area, three pits exposed the fault plane and its extension through overlying glacial tills, post-glacial marine sediment, and colluvium. The fault plane is strikingly sharp - being confined to a narrow, pre-existing, near-vertical mylonite zone in granite. The main fault plane has a throw of 2-3 m and, within a few metres either side of it, are numerous smaller displacements of the glaciated surface. They are normal and reverse faults ranging up to a few decimeters and are localized mostly along pre-existing fracture planes of various orientations. It is noteworthy that the top 0.5-1.0 m of the granite just below the till was completely shattered along intergranular contacts. The grains had been moved apart so that in places void spaces exceeded 50%. There was no fine material from the till matrix or other overlying sediment in the voids, thus showing that the expansionary disruption postdates the glacial and marine depositional episodes.

The fine marine sediment layers had fluidization features (involutions, flame structures etc). These indicate sudden porewater pressures exceeding the liquid limit. However, because such structures can also form slowly and as a result of non-tectonic mechanisms, they can only serve as corroborative, not definitive, sedimentary evidence of associated seismic shaking. Nonetheless, their close association with the fault is a very significant demonstration of their potential usefulness because **involutions are widespread in other deglacial areas and have perhaps have been discounted too readily.**

Similarly the landslides at **Elmaberget** and the pitted terrain of graded tills at **Furuträsket** are important findings in that they further demonstrate the variety of geomorphic and sedimentary features indicating seismic shaking. However, like involutions, both are the result of transient excess pore-water pressure and this may have resulted from a number of non-seismic causes. Nonetheless, the close association of these sedimentary structures with the Lansjärv Fault provides further support for the hypothesis that they can also be diagnostic of strong ground motion. The excellent Swedish work on these features has **wide implications for their interpretation elsewhere in the world.**

Äspö

It was particularly instructive to have an opportunity to review Mörner's findings of post-glacial faults on one of the possible nuclear waste-disposal sites. As in the Stockholm area mentioned above, most of the fault-like features on Äspö do indeed give the **appearance** that they offset the glacial surface. However, many could not be **demonstrated** to be post-glacial faults at the time of the visit because, owing to the lack of excavations and other definitive tests, it was not possible to establish that the glacial pavement on either side of the supposed fault plane was once a continuous surface and thus prove that it had been subsequently dislocated. Notwithstanding the number of inconclusive and ambiguous cases, the writer is satisfied that several of Mörner's purported faults are indeed bona fide post-glacial faults. **Thus, I most concur with Mörner that there are post-glacial faults on Äspö**. However, the issue of post-glacial faults on Äspö will remain clouded until a few more of the questionable features are cleaned off to permit the necessary observation. I suggest that use of **a portable high-pressure fire pump (e.g. Wajax type) could expose the crucial occurrences quickly, easily, and at minimal expense.**

Finally, I found Mörner's suggestion very interesting that a large train of angular blocks with distinctive conchoidal fracture represents a train of rubble liberated from outcrops by seismic shattering just behind the ice margin, then glacially transported a short-distance before deglaciation. In other words, I saw no evidence to counter the seismic hypothesis. Given that there are a few post-glacial faults on Äspö, I accept the suggestion that there was probably also accompanying **strong seismic shaking if not also surface shattering which could easily liberate blocks to the moving ice.**

POST-GLACIAL FAULTS IN THE CONTEXT OF NUCLEAR WASTE DISPOSAL

1 Are the PGFs new faults or reactivated old ones?

In all cases it is evident that the faulting has taken place along pre-existing faults or other fracture planes (e.g.

joints). Only a few minor subordinate fractures, some with offsets, are new and related to the faulting. However, I do consider the distinction of whether the faulting caused new fractures or simply used existing ones to be significant to the assessment of future fault risk. Fractures with almost every conceivable direction are so abundant in the Swedish geological terrains that stress from almost any direction could be readily relieved by movement along these old surfaces.

2 What causes PGFs?

The stratigraphic context shows clearly that the main cause is release of stress during deglaciation (or shortly after). No present-day faulting has been demonstrated and measurements purporting a very minor creep along the Lansjärv Fault are inconclusive. All the evidence thus shows that the stress release occurred only in the distant past and that it was related to a special set of conditions associated with glaciation. This is important for the nuclear waste-disposal issue because it means that repositories will likely not be threatened with damage of this sort **until the next glaciation.**

3 Why do PGFs trend mainly north-northeast?

The trend of PGFs is related more to the direction of the causative stress than to the orientation of pre-existing fractures along which the movement has been accommodated. PGFs in Sweden, most of are also in northern areas, are restricted to a narrow range of azimuth despite the wide range of orientations of pre-existing fractures. Providing that the distribution is real and not an artifact of local conditions which promote discovery, the apparently preferred orientation and the lack of lateral movement indicates that **the principal stress was from the east-southeast.** This direction is essentially the same as the trend of present horizontal compressive stress which is considered to represent the long term tectonic stress field resulting from plate drift. It may therefore be suggested that the faults represent release of normal crustal stress that had been stored during the period of glacial loading. This would explain why **the faults occurred only during a short period of deglacial time and apparently not later.**

4 Are PGFs shallow or deep?

The consensus of expert opinion is that, despite their generally steep surface inclination, the **PGFs flatten to relatively gentle attitudes at shallow depth** (several hundred metres to a few kilometres). I am not qualified to dispute this interpretation and I see no inherent reason why this should not be true. Indeed, to argue that they are more deepseated would be to attach a far greater significance to the faults than is warranted by the evidence.

5 Are PGFs moving at present?

There is no evidence whatsoever that any of the post-glacial faults are still active. Virtually all of the faults had their inception during deglaciation or only slightly later; none continued to move in later post-glacial time; none can be ascribed to the recent past. At present, it therefore appears reasonable to ascribe all PGFs to the short period when the glacier margin was retreating across any given area, where maximal differential crustal stress prevailed between the zone of extraglacial rebound and the still-depressed subglacial zone. If true, this determination is significant for the nuclear waste-disposal issue because it means that there **is little reason to worry that any of the PGFs will become reactivated, at least in the near future.**

6 Are the Lansjärv PGFs anomalous in Fennoscandia?

The Lansjärv PGFs are not materially different in any way from other post-glacial faults in Fennoscandia, based on what was seen in four areas of Sweden and what is reported in the literature for other parts of the Fennoscandian region. This is significant because it means that the results gained from an intensive site-specific study are probably generally applicable to post-glacial faults as a whole in Fennoscandia. Still, there is the nagging suspicion that, if even a small proportion of the research effort had been expended on a few of the other major faults, perhaps additional findings might have been made which could have further clarified the causes and timing of post-glacial faults in Fennoscandia.

7 Are PGFs relevant to nuclear repository design?

From the above findings, it is clear that **post-glacial faults are indeed relevant to the choice and design of repositories for nuclear waste because they provide information on past, present, and probable future crustal dislocations of a magnitude which could endanger the integrity of a subterranean vault.**

Evidence as to the age of PGF:s indicates that all are comparatively ancient and have not moved during the last several millennia. This means that there is **no reason to believe that new faults will occur or old ones reactivate in the near future**. However, the same evidence links them closely to the process of glaciation, specifically to the phase of crustal unloading during ice retreat. Therefore, **it may be safely assumed that the next glaciation will be similarly capable of rupturing the earth's crust.**

Important questions about the peculiar age distribution remain. It may be significant that all are presently attributed to the **last** deglacation, but this may be simply a false premise based on the findings at Lansjärv. If it can be demonstrated that no faults are relict from previous glaciations, this then poses the further question on **why the last glaciation was uniquely capable of producing throughgoing crustal rupture.** Perhaps it was a purely local anomaly, having to do with the style and rate of ice retreat. On the basis of the evidence as to the cause and age of post-glacial faults, it must be concluded that **the integrity of nuclear vaults will likely be compromised within the time span stipulated for safe disposal.**

As to the distribution of PGFs, it seems that the major occurrences are restricted to northern areas. This may be more apparent than real. Perhaps it is a function of better exposure due to thin drift cover and sparse vegetation. Still, it seems that smaller examples can be found wherever a careful search is made. Perhaps, then, PGFs are ubiquitous, but larger in the north because of greater ice load, faster retreat, and/or greater stored tectonic stress. Until it can be established that PGFs are indeed absent from certain geological terrains, namely those in the south, **it cannot be assumed that at prudent choice of repositories can be made** on the basis of existing information.

In sum, I feel that it has been amply demonstrated that post-glacial faulting is sufficiently widespread to be considered a general phenomenon, that it will recur within the stipulated time frame, and that it attains sufficient magnitude to constitute a threat to the integrity of a conventional rigid underground vault. Until and unless a means can be found to neutralize the waste before the next glaciation, the geological evidence provides a perspective on the dislocations which may occur if the waste is stored underground as part of the rock mass. Whatever the outcome, the knowledge about post-glacial faulting, particularly that gained from studies in Sweden and the programs which made it possible, will continue to have a decisive and positive impact on future systems on nuclear waste storage and the disposal of hazardous waste in general.

COMMENTS ON SKB FIELD TRIP TO THE LANSJÄRV AREA, NORTHERN SWEDEN JUNE 17-18, 1991

Søren Gregersen

It was a real pleasure to see the faults in nature, which I have read about in the scientific literature. Talking to Robert Lagerbäck as well as to other excursion participants I got convinced, that one is finding large escarpments and landslides in the same general areas. One also finds tremendous disturbances of the unconsolidated sediments, but according to another excursion participant, Jan Lundquist, these kinds of disturbances are found in many parts of Sweden. So the significance of these is doubtful. Either there is some other mechanism than shaking to generate these so called "load casts", or shaking has also occurred in other parts of Sweden.

On the particular questions raised by SKB my comments are:

New or reactivated:

From the 1 1/2 day excursion one is not able to answer this question fully. As a participant in the excursion I can go along with Robert Lagerbäck's judgment. His arguments, that the faults shown to us were reactivated, were convincing.

Causes:

With a background in seismological research with a recent involvement in the World Stress Map Project I am convinced that the major causes of stress nowadays are the plate boundary forces, notably the "ridge push" from the North Atlantic. And it is impossible to imagine, that this ridge push force did not exist, also during the Ice Age. While the ice covered Scandinavia we would have no earthquakes, just like it is in Greenland or Antarctica today. The energy would be stored for release as soon as the ice cap was gone. So large earthquakes would be possible at the time of the deglaciation. How much the off-loading of the ice cap itself means is up for discussion. It must have some effect. Altogether it means, that the stress regime right after the Ice Age was really different from that of the present day, in magnitude and possibly in orientation.

Present movements?

In the seismicity picture it looks like the faults are not active. Whether the extension/compressions measurements will show some motion over a 5 year period does not matter much. One will afterwards have a hard time sorting out, what is actual movement on the fault and what are environmental effects like temperature and water load. Geodetic measurements, like levelling and horizontal distance monitoring, will be necessary to establish, whether the fault zone is actually moving.

Anomalous?

Again a question one will have to answer on second hand. The literature on neotectonics and seismicity convinced me, that the Lansjärv area is part of an anomalous region in northern Scandinavia together with the other post-glacial fault zones.

Thank you for the chance to see the special post-glacial phenomena of northern Sweden. Between the participants we had some very productive discussions.

COMMENTS ON THE LANSJÄRV EXCURSION JUNE 17--18, 1991

Sven Hansbo

I myself is not an expert on post-glacial faults or on the geological background to faulting and shall, therefore, only present my views on the phenomena behind the distorted soil strata and the separation into different grain-sizes with increasing depth in the superficial parts of the till.

In my opinion, many features indicate that vibrations caused by earthquakes are the true cause of the distortion and the grain-size separation observed, as claimed by Robert Lagerbäck. The foremost features in support of this theory are: obvious signs of piping and a grain-size sequence with finer grains at the top and increasingly larger grains towards the bottom of the superficial till layers. However, this idea ought to be checked and proved experimentally in a geotechnical laboratory provided with suitable equipment, e.g. a shaking table, to simulate the effect of an earthquake.

The testing procedure could be the following. Soil from Lansjärv with proper characteristics should be placed in a container of, for example, plexiglass in such a way that it can be assumed to represent the original site condition (layered sediments and till of original composition). The amplitude and frequency and the time of vibration needed to cause similar effects as those observed at Lansjärv should be investigated. In particular, a grain-size separation in till similar to that observed at Lansjärv does not seem to have been the subject of study before and is thus of special interest.

The landslides observed in till also indicate that, for some reason, liquefaction has taken place. Earthquakes seem to me the most plausible explanation. Thus, a build-up due to heavy rainfall of high enough excess pore water pressure to cause a landslide (which is another possible explanation) seems less plausible, especially since the landslides observed in till are concentrated to the fault zones.

POST-GLACIAL FAULTS IN NORTHERN SWEDEN
A post-meeting assessment to SKB

Arch C. Johnston

The large-displacement post-glacial faults (PGFs) in northern Fennoscandia are unique in the world and therefore deserve intense study in their own right, apart from siting questions for a radioactive waste repository. A systematic search of arctic Canada (or - less likely - Siberia) may uncover additional PGFs, but it is unlikely that anything on the scale of the Pärvie or Lansjärv PGFs remains undiscovered. The support of SKB for a broad PGF research program is to be commended and should not be abandoned entirely. In particular, plans should be made to preserve and permanently maintain the trenches, which contain perhaps the finest examples of large-scale, primary bedrock faulting in the world.

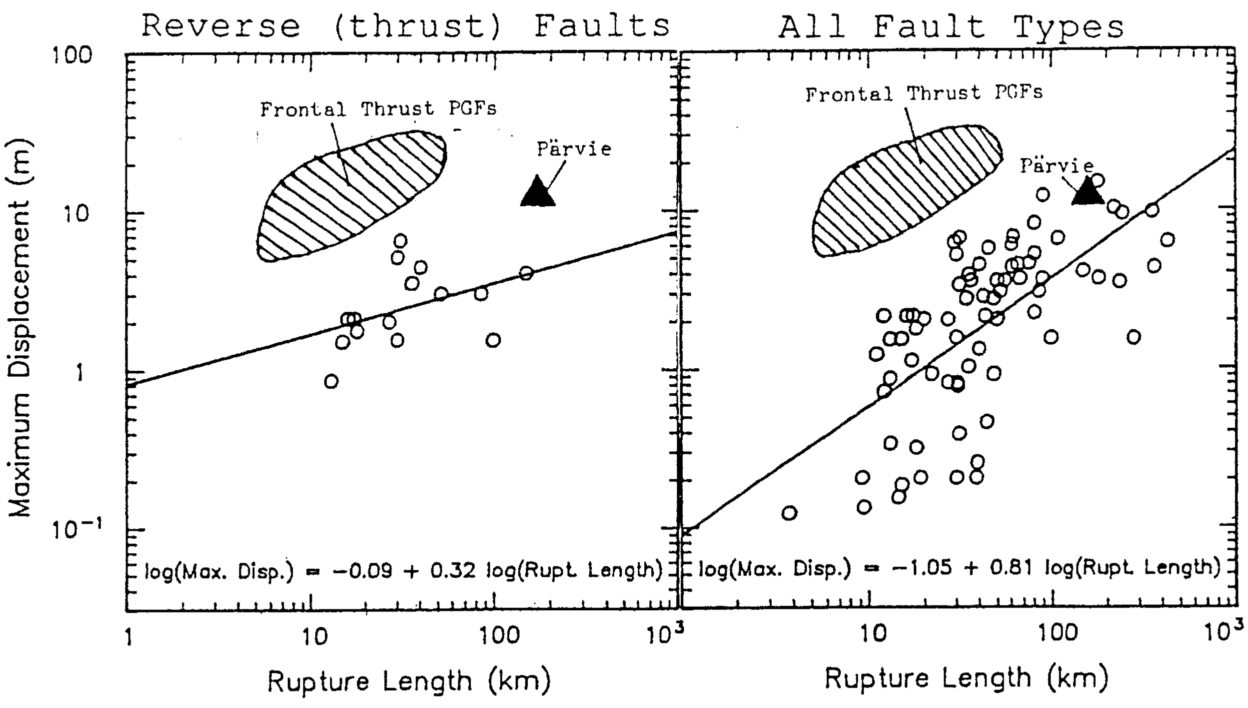
I will make a series of observations on the PGFs - especially the Pärvie - which should encompass most of the specific questions put to the meeting's attendees by SKB.

A It appears that the Pärvie and other major fault segments formed during **single dislocation events**. This is by no means proven, but their linearity, consistent sense of slip, and the trench stratigraphy all are consistent with this interpretation. This then means that the Pärvie and some of the shorter segments in Lansjärv and elsewhere have the largest known measureable single-event thrust (reverse) fault displacements in the world.

Some repeated-offset strike-slip faults in south-central Asia and California rival the PGFs in this regard. For example, 1857 Ft. Tejon, Calif., max. displ. D_{max} = 9.4 m; 1920 Kansu, China, D_{max} = 10.0 m; 1931 Kehetuohai, China, D_{max}= 14.6 m; 1931 Beng Co, China, D_{max} = 12.0 m; and 1957 Gobi-Altai, Mongolia, D_{max} = 9.2 m. However, the largest known maximum displacements for primarily thrust faulting events average about 5 meters: 1896 Rikuu, Japan, D_{max} = 4.4 m; 1930, Salmas, Iran, D_{max} = 5.1 m; 1964 Niigata, Japan, D_{max} = 3.3 m; 1968 Meckering, Australia, D_{max} = 3.5 m; 1980 El Asnam, Algeria, D_{max} =

6.5 m; and D_{max} is ~10 m for the famous Kutch, India earthquake of 1819. Thus the Pärvie fault may be rivaled by the "wall of God" scarp of the Kutch earthquake, but many of the shorter segments - such as the Lainio and Risträskkölen with D_{max} on the order of 20-30 m - have no known parallels in the world.

B The Pärvie and other PGFs are also seen to be anomalous with regard to their D_{max} versus fault length, L, ratio. Shown below are compilations of reverse faulting and all faulting types (Wells, D., K.J. Coppersmith, D.B. Slemmons, and X. Zhang, **"Earthquake source parameters: updated empirical relationships among magnitude, rupture length, rupture area and surface displacement", preprint, 1991**) on which some of the PGF data have been added. The long Pärvie fault trace is discrepant, but the shorter frontal thrust segments such as Risträskkölen (D_{max} ~20 m) or Lainio-Suijavaara (D_{max} ~30 m) are so far from the D_{max}/L ratio usually observed in earthquakes that they seem to belong to a different class of fault altogether.



Another parameter which sets the PGFs apart from the more "usual" earthquake scarps is fault dip. In the trenches at Molberget, the scarp was essentially within a few degrees of vertical and may even be a normal fault (see below). The Pärvie and other faults where bedrock is exposed are very steep, within 10-15° of vertical. Such steep dips for thrust fault scarps are not known elsewhere in the world. In Australia, for example, the Meckering scarp and the Lake Surprise segment of the Tennant Creek scarp exhibit shallow dips of 20-30°. The impression is that for the PGFs the upthrown blocks were driven upwards under conditions of unusually high deviatoric stresses or that an unusually large amount of elastic strain energy was available for release.

C **What size were the earthquakes that produced the PGFs?** I'll use seismic moment (M_0 dyne-cm) or moment magnitude (**M**) as the best measure of size and restrict most of my comments to the Pärvie fault. There are two approaches to make this estimate; both require the assumption that the Pärvie formed during a single event (see (A) above).

The first way is to use regression analysis, such as that by Wells et al. (1991), cited above. The two best determined fault parameters for the Pärvie are maximum displacement (D_{max} ~12 m) and surface rupture length (L ~150 km). For thrust (reverse) faults Wells et al. give

$$\mathbf{M} = 6.16 + 1\text{-}59 \log(D_{max})$$

$$\mathbf{M} = 4.29 + 1.69 \log(L)$$

These regressions yield $\mathbf{M}(D_{max}) = 7.9$ and $\mathbf{M}(L) = 8.0$, respectively.

Another approach is to make maximum and minimum M_0 estimates,

employing

$$M_0 = \mu \bar{D} A$$

and $\mathbf{M} = 2/3 \log (M_0) - 10.7$

where $\mu = 3.5 \times 10^{11}$ dyne/cm^2 is the crust's rigidity modulus, $\bar{D}$ is the average fault displacement, and A is the rupture area in cm^2. For a minimum size estimate I take $\bar{D} = 5$ m, L = 140 km and fault width W = 15 km, which yields $\mathbf{M}_{min} = 7.7$. For a maximum size, I assume that the rupture extended through the entire crust, not just the brittle upper crust, so that W = 45 km, L = 150 km, and $\bar{D}$ = 10 m. This yields $\mathbf{M}_{max}$ = 8.2.

The two approaches are in good agreement. An average of the four determinations above yields **M** = 8.0 (±0.25) for the Pärvie earthquake. For the smaller PGFs in Lansjärv, Norway and Finland, ~6.0 ≤ **M** ≤ ~7.5 appears appropriate.

D Antithetic faulting appears to have been an important process in PGF generation. The trenches at Molberget are apparently on a scarp antithetic to the main Lansjärv system, and long reaches of the northern portion of the Pärvie have subparallel antithetic faults, located on the upthrown block 1-2 km from the main fault trace.

These antithetic faults are, I feel, important because they are telling us something about the PGF faulting process. I call them antithetic because at least along the Pärvie and at Molberget they appear to dip in an opposite sense to the main faults. The Molberget trenches reveal a near-vertical, "step function" upthrown block, but in all trenches the dip is consistently a few degrees into the hanging wall, i.e., normal faulting. It is likely that the paralleling subsidiary faults along the Pärvie are also normal.

If the antithetic faults are indeed normal, it removes the requirement that the main faults be listic at depth, such as in the Muir Wood model (figure 3 of Muir Wood, 1989, Extraordinary deglaciation reverse faulting in northern Fennoscandia, in, **Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postgacial Rebound**, S. Gregersen and P.W. Basham, editors, Kluwer, Dordrecht, The Netherlands, p. 141-173) because there is then no need for the main and antithetic faults to intersect at depth.

The presence of normal antithetic faults supports the argument that the PGFs formed in large, single-event, abrupt shear dislocations. Consider that the Pärvie earthquake occurred in a thrust faulting regional stress regime in which σ_1 is horizontal and oriented WNW, that is, perpendicular to the Pärvie. The large dip-slip displacement - mainly vertical but also with a WNW horizontal component - will introduce a tensional stress component in the upthrown (hanging wall) block that is essentially subparallel to σ_1. If the main displacement event is sufficiently large, σ_1 will be locally replaced by σ_3 at some distance from the main scarp on the upthrown block, and normal faulting will occur as a brittle crustal failure response to this new, transient stress state.

If this model is correct, the subparallel, normal antithetic faults should be found on the PGF upthrown blocks opposite main scarp maximum displacement segments. It would also be quite useful to model the stress and strain fields by finite element methods to test whether this model is viable.

Response to specific SKB questions

1 **Are the post-glacial faults new or reactivated faults?**

I feel that the model of the PGFs occurring on ancient (probably Proterozoic) shear zones is the best model available for explaning these exceptional faults. The geological and mineralogical assessment of shear zones is not in my field of competence, but I found the SKB analyses and presentations on this subject at Molberget thorough and reasonably convincing. Furthermore, it is reasonable that in a crustal state of enhanced stress and strain accumulation, properly oriented, preexisting zones of weakened crustal rock (i.e., shear zones) will localize failure. One important question that was not answered at the workshop, is whether all PGFs occur in ancient shear zones. Has this been systematically investigated?

2 **What are the causes of post-glacial movements?**

I agree with, indeed advocate, the model, in which elastic strain energy release is suppressed during periods of continental-scale glaciation. Therefore, the strain energy is stored in the elastic or brittle portion of the crust and is available to power large PGF earthquakes when the ice overburden is removed and preexisting faults are "suddenly" in a deviatoric stress state that is much closer to failure. The large-scale PGFs, therefore, require a special set of circumstances - as supplied by the last ice sheet - in both time and space in order to occur.

3 **Why do the PGF scarps trend NNE?**

Present-day fault plane solutions or **in situ** stress indicators have little or no relevance to this question. What is critical is, what was the crustal deviatoric stress state 8,000-9,000 ybp? I believe it is a very good assumption that the plate tectonic stresses were similar to those of today so that northern Fennoscandia would be under ~NW-SE compression. The presence of a large continental ice sheet affects primarily the vertical stress; the effect on the horizontal stress state was probably not sufficient to alter this regional NW-SE orientation (again, an assumption but I feel it's a good one). Hence, when the ice is removed the optimum orientation for maximum shear stress planes in a thrust faulting stress regime will be in the NE quadrant.

In Precambrian cratons the accumulation of shear zones and other types of crustal heterogeneities occurs over many and differing tectonic episodes. This leads to the availibility of a population of structurally weak zones of practically any orientation. When the ice melted, those zones oriented NNE had the most optimum orientation for reactivation, given the NW-SE regional stress field and hence were selected for failure.

4 **Are the PGFs surficial phenomena?**

I don't believe the low-dip, shallow thrust "flakes" model of the PGFs is an open question. One look at the Pärvie exposed scarp or the ~vertical fault faces in the Molberget trenches can dismiss the shallow thrust model. Also, the length and fairly regular sinuousity of the PGFs, especially the Pärvie, argue against shallow dip. Also, I've seen no evidence on why the PGFs should be listric. I believe they extend deep in the crust, perhaps through the entire brittle upper crust. (The Pärvie may involve the lower crust as well.) A program of shallow seismic reflection on the PGFs would be an excellent way to perhaps resolve this question. Given the extensive other geophysical investigations, I'm surprised this was not attempted.

5 **Are there present movements?**

The present-day seismicity occurring in northern Fennoscandia is unremarkable. It is the same scattered low-level activity observed in cratons and other stable continental interiors worldwide. Rarely, these events - such as the 1819 Ranafjord, Norway earthquake - can reach the mid-magnitude 6 range. This activity has nothing to do with the PGFs; from the reports provided us there is no evidence that any of the PGFs are currently seismogenic.

The displacement measurements at the Molberget site yield a strain rate of $\dot{\epsilon}$ = ~7x10^{-6} yr^{-1}. A strain rate of nearly 10^{-5} yr^{-1} is much too fast for continental interiors and probably represents shallow adjustments to the trench excavation. Of greater interest and significance is the regional tectonic strain rate as separate from the glacial rebound strain (which is of minor-to-negligible import to seismic activity). The regional tectonic strain rate is probably on the order of 10^{-9} to 10^{-10} yr^{-1} and is essentially unknown since a long-term geodetic monitoring program was considered too expensive. Again, the PGFs were a product of a special crustal stress and strain state brought on by the appearance and disappearance of the continental ice sheet. I believe that they have little or no connection with current stresses and strains in northern Sweden.

6 **Is the Lansjärv area, with its PGFs, anomalous compared to the rest of Fennoscandia?**

Unless the Lansjärv area differs in the relative abundance and/or orientation of Proterozoic shear zones (about which I have no knowledge) it has no obvious significant differences with the rest of the Baltic shield or for that matter, with other continental cratons/shields worldwide. The special conditions that caused the PGFs seem to have been isolated to a very narrow time window - just when the ice sheet disappeared from the region.

7 **What is the potential impact of PGFs on repository design and performance assessment ?**

Unless sometime in the future the repository site is subjected to another ice age cycle, the PGFs have little significance to repository siting. I believe that large PGF-scale faulting events (**M** = ~7.5-8.0^{+} earthquakes) cannot occur in stable continental regions (craton, shields and Paleozoic foldbelts) without exceptional conditions such as those imposed by the last ice age or without the presence of rifted post-Mesozoic crust. This would hold true as long as PGFs are indeed restricted to preexisting shear zones, which can then be avoided for siting of critical facililities. I don't believe that such a categorical PGF precondition has been absolutely proven, but a strong and defendable case for it has been made.

The real seismic risk to a Fennoscandian radioactive waste repository is the rare 6.0 ≤ **M** ≤ ~6.8 craton earthquakes that have been observed in Australia, Africa, South America, and North America. Whether or not these occur only on preexisting faults or shear zones is an important and controversial question. Adams (SKB workshop) feels that the Ungava, northern Quebec, earthquake occurred on a preexisting fault, basing this opinion apparently on topography. Crone and Manchette (pers. comm.) have found trenching evidence for an ancient shear zone for at least a portion of the Tennant Creek, Australia fault scarp. None has been found for Meckering, Australia, but hasn't really been actively looked for either. The hazard to a particular nonshear-zone craton site from the essentially random **M** > 6 craton earthquake is probably down around 10^{-5} to 10^{-6} per year and therefore acceptable.

COMMENTS AFTER THE LANSJÄRV MEETING JUNE 17--18, 1991

Jan Lundqvist

1 I consider the dating of the Lansjärv (and Pärvie) faults reliable: The movements took place in close connection with the local deglaciation after the Late Weichselian glaciation, roughly 9000 years ago.

2 Disturbances and partial resedimentation of till and waterlain sediments in connection with the fault movements are also proved, according to my opinion. This applies to landslides in till as well as liquefaction of tills and waterlain sediments.

3 I cannot estimate, however, if similar liquefaction (load-cast) structures in sediments in other parts of glacial sediments in, e.g., eastern Svealand and central Norrland, have the same origin. If the origin is the same as in the Lansjärv area they are evidence for a considerable seismic activity in close connection with the local deglaciation.

4 It is also clear that faulting has mainly occurred along older tectonic lines in the bedrock. Occasionally a fault may jump from one such line to another.

5 The faults in northern Norrland and adjacent areas are unique, in terms of both space and time. No comparable features are observed in other parts of Sweden and do not seem to have been formed in connection with older periods of deglaciation (that is, after the Saalian glacial and earlier Weichselian stadials). I am convinced that, if they exist, they would have been observed.

COMMENTS ON POST-GLACIAL FAULTS IN THE LANSJARV AREA NOTHERN SWEDEN

Robert Maddock

Introduction

This brief note reports some of the author's observations made during an internationally-attended field meeting on post-glacial faults (PGF) in the Lansjärv area, northern Sweden. The meeting was organized by SKB and held in Överkalix on 17-18 June 1991. During the meeting, PGF scarps, landslides and seismites were examined in the field and a summary of the results of recent SKB-supported studies of the area were presented, with the aim of addressing three principal questions:

1) Do the PGF's reactivate existing faults?

2) What are the causes of the PGF's movements?

3) Are the PGF's still active?

General Comments

The PGF scarp morphology (especially in trenches at Molberget) and the spatial relationship between the scarps and nearby landslides and seismites provide convincing evidence of the seismic nature of the fault movements. The proposed late-glacial to post-glacial age of the youngest movement on those faults which have been examined in detail is well-constrained by the faulted offset of late-glacial drift deposits as at Molberget, and by a ^{14}C-date of about 8000yrs for the earthquake-triggered(?) landslide at Elmaberget.

The evidence for earthquake-triggering of the landslides and the deformation in the seismites (eg. Lagerbäck in Bäckblom and Stanfors, 1989) is also convincing. However, at the meeting considerable discussion centred on the practical difficulties of distinguishing between earthquake-induced soft sediment deformation and that resulting from mechanical processes unrelated to radiation of seismic wave energy.

Although the NNE to NE-trending strike of the PGF's in the Lansjärv area is well-constrained, disagreement exists concerning the variation in dip of these faults with increasing depth. Neither the geophysical investigations or the borehole investigations reported in Bäckblom and Stanfors (1989) appears to have had sufficient "resolution" to satisfactorily resolve this question. The considerable along-strike extent of many PGF scarps together with the presence of a (Precambrian?) metabasite dyke seen in the fault plane trenched at Molberget may indicate a steep dip. However, the remarkable curvature of the fault scarp seen at Risträskkölen is inconsistent with a simple, steep dip in the near-surface region.

Do the PGF's reactivate existing faults?

Major crustal fault zones exhumed by uplift and erosion often show a prolonged history of movement (including recent seismic activity) reflected in a changing style of faulting and of faultrock deformation (eg. Bak et al, 1975; Sibson, 1977).

In Northern Sweden, the pre-PGF existence of NNE-trending lineaments or shear zones is discussed by Henkel and by Talbot et al in Bäckblom and Stanfors (1989). It is clear from these sources that the NNE to NE-trending structures are less clearly defined than the N- and NW-trending structures. However, excellent evidence of a pre-PGF NNE-trending discontinuity at the Molberget site is provided by the metabasite dyke referred to above.

The PGF exposed by trenching at Molberget undoubtedly occurs within a zone containing fractures and exhibiting localized, shear-related grain-size reduction. However, when examined in June 1991 little evidence was seen of pervasive, long-lived or repeated shear displacement in the form of plastically-deformed mylonites or brittle-deformed cataclasites which clearly pre-dated formation of the PGF. The fractures are healed by mineral assemblages of greenschist and lower metamorphic grade (Eliasson et al, 1991). The youngest, open fractures of weathered appearance and partly coated by iron oxy-hydroxide phases, seen within a few metres of the main fault plane may be directly related to the PGF movements.

(Eliasson et al (1991) note that poorly-cemented clay gouge material may have been lost from the core during water flush drilling. Attention is drawn here to the advantages of using a triple tube core barrel with a rigid plastic liner in maximizing both core recovery and the preservation of delicate structure in fault zones, albeit at increased cost).

Small-scale structures seen in the trenches at Molberget provide evidence for the sense and direction of slip and for more than one episode of movement. Slickenline lineations of both dip slip and horizontal orientation, which comprised wear grooves and ridges on veneers of red (hematite-rich) clay gouge were seen. (These slickenline orientations are consistent with those reported by Lagerbäck in Bäckblom and Stanfors, 1989; and Eliasson et al, 1991). A shear band fabric was also seen in a 3cm thick poorly-cemented gouge/cataclasite layer on the main fault plane in one of the trenches. The orientation of this fabric suggested sinistral strike-slip displacement. The vertical and horizontal slickenline lineations and the shear band fabric are all developed in poorly-cemented gouge and could therefore reflect young (PGF?) movements. If this is indeed the case, and the small-scale structures were all formed during co-seismic slip, then formation of the PGF scarp at Molberget may have been associated with more than one earthquake.

<u>What are the causes of the PGF movements?</u>

In spite of fairly extensive field and modelling studies (partly reported in Bäckblom and Stanfors, 1989), only a very generalized consensus emerged at the meeting in answer to this question. It was agreed that the post-glacial earthquake faulting in northern Sweden appears to have occurred through the interaction of (plate) tectonic and glacio-isostatic stresses and their release.

<u>Are the PGF's still active?</u>

Discussion of the rapid post-glacial uplift in the Lansjärv region and its possible partitioning between seismic and a seismic movement is given in Bäckblom and Stanfors, 1991.

Attempts to measure directly the current rate of straining by means of borehole sliding micrometre measurements at the Molberget site were presented at the meeting. Discussion of the significance of these movements was vigorous and there was general agreement that continued measurement and further examination of the existing data should be undertaken.

COMMENTARY ON THE LANSJÄRV FIELD EXCURSION JUNE 17--18, 1991

Robert Muir-Wood

1 Introduction

First it is necessary to applaud SKB's decision to subject the Lansjärv study to a form of international peer review. Issues relating to crustal stability are profoundly difficult, and are not conducive to "absolute" statements. The most important understanding can only be obtained by collecting primary information. The methods of research, results, models to explain the results, and plans for the next stage of the investigation should continue to be subjected to scientific, preferably international, scrutiny.

It is important that SKB takes the lead in the investigation of new data concerning crustal stability in Sweden. The studies so far undertaken of the Lansjärv Fault are not just of local interest but are of global significance, in the investigation of a tectonic phenomenon that appears to have no exact analogue today.

2 Comments on the overall Lansjärv Project

There was some disappointment at the Lansjärv meeting that not all those involved in working on the project were available to "defend" their research. The balance of the meeting was concerned with the trench exposures, which formed only a small part of the overall programme. However it appears that these trenches have contributed a very significant proportion of the results. Before considering the observations accumulated from the trenches it is perhaps worth making some remarks concerning the other investigations, as reported in the Lansjärv Volume: SKB Technical Report 90-31.

With respect to the geophysical section of the report much of the discussion presented as geological and tectonic "fact" reflects models employed to explain the distribution of magnetic anomalies. These models (such as those discussing "shear-lenses") are simply possible interpretations, that await confirmation from new sources of data.

Likewise the idea that the reverse faults seen in Lapland are only the most visible component of end-glacial reactivation of major strike-slip shear-zones is highly improbable. It is of course a difficult hypothesis to refute absolutely.

3 The location of boreholes

The "identification" that the late glacial faults are fundamentally shallow dipping structures was never a likely model, either from their surface morphology, fault kinematics, from a consideration of the deglaciation stress-field or from analogues in other regions. There may of course be isolated sections in which a "flake" of rock has become involved in the near-surface displacement. The results of the hydrogeological observations in borehole KLJ1, appear to indicate that the actual fault itself is located beneath the bottom of the borehole, as would be expected with a more steeply dipping fault.

If an international discussion had been arranged prior to siting the borehole one would have gained a range of opinions, including supporters for a steep dip to balance those who preferred a shallow model. These alternatives could have first been tested through cheaper and quicker trenches, to try to identify the near-surface dip. The more that steep dips were encountered in trenches the more the argument should have become weighted in favour of a steep dip model. The borehole should then have been located so as to discriminate between alternative hypotheses, not simply to attempt to prove one "low probability" hypothesis. The fact that the borehole appears to have been drilled in the wrong place, and failed to intersect the fault, and hence that no sub-surface view of the fault has been obtained, is a significant disappointment.

4 Project Co-ordination

As a general comment the success of the results of the Lansjärv project appears to have depended more on the calibre of the individual researchers, than on a coherent interactive programme of research. Sweden is a relatively small Earth sciences, and even smaller seismotectonic, research community. Among these researchers there are a remarkable number with very strong opinions or specialized interests. This makes the community unbalanced, in that there is not always a researcher or group of researchers to counterbalance more extreme opinions. SKB might be recommended to ensure a stronger element of international peer review in project planning in this area.

The Lansjärv Project was initiated with a series of objectives: problems requiring to be solved. It would be useful to have a formal statement of the objectives behind each project, the interaction between the results of the different projects and the overall success rate at achieving the original objectives. As a general comment concerning the written reports there does not appear to have been much interaction between projects.

5 Comments on the interpretation of the trenches

It is perhaps unnecessary to review the findings from the trenches except where the interpretation differs from that discussed by Robert Lagerbäck. The only point of disagreement concerns the causes of the graded till deposit, as observed in the trenches at Furuträsket. Such deposits appear to have resulted from a combination of three phenomena: liquefaction to allow the particles to become density stratified; agitation to encourage continued movement of the blocks to encourage closer packing, and consolidation thereby squeezing out water, to reduce the porosity to some 25% of its original value. Perhaps the most important of these is consolidation, without which some density stratification might have occurred but yet with only a small reduction in porosity. A large reduction in porosity requires a load on top of the material.

These three phenomena could not have all occurred in the short (1 minute?) duration of strong ground motion that would have come from the original Lansjärv Fault rupture. All of the graded tills have been located in the hangingwall of the fault, and (it is understood) are distributed over subcircular areas, typically tens of metres across.

Any explanation has to find a cause for the additional load required to achieve consolidation, as well as the prolonged agitation and liquefaction. The liquefaction is perhaps the easiest to explain. Much of the saturated sandy till in the region is likely to have liquefied following the vibration that accompanied the Lansjärv Fault rupture, remaining in that state for several hours. However, if the grading was a phenomena resulting solely from liquefaction and earthquake vibration, why is it only found in the hangingwall of the fault? As this region was under the sea at the time of the earthquake, the only conceivable extra load is something formerly floating in the water that becomes beached as a result of the hangingwall uplift of the seafloor - such as an iceberg.

Continued wave action, during the period when the underlying till remained liquefied, in particular any disturbance associated with tsunami waves, would continue to bounce an iceberg and agitate the underlying till, encouraging further density stratification and closer packing. The several hours, or even several days over which this process could continue would provide sufficient time for the extraordinary degree of size sorting seen in the trench section, to have developed.

It would be interesting to test this proposal in an exploration for similar phenomena in another formerly glaciated region subject to large earthquakes, in which tills are now located above sea-level: such as Alaska, British Columbia or southern Chile.

6 Are the post-glacial faults new or reactivated?

At the Molberget fault trenches it was clear that the recent displacement had occurred primarily along a pre-existing fault. Some relatively minor displacement of the glaciated rock-surface could be seen in the hangingwall (or more correctly raised block of the near-vertical fault-trace). These displacements of a few centimetres appeared to decrease in magnitude and frequency away from the fault. However, from the length of the trench it was impossible to say to what distance such minor fracturing continued. It is possible that such fracturing could continue to some distance, in particular where there is a change in the dip of the underlying fault, but it would be most probable that such displacement would become more concentrated along pre-existing fractures.

It would be useful to plot the displacements of the glaciated surface on fractures, in combination with the fracture-frequency in the exposed rock-outcrop, both in the hangingwall and footwall, for all the trench sections. Plotting these figures vs. distance from the fault would show the amount of angular strain that was not concentrated on the fault itself and could also allow some extrapolations to be made of the likely displacement and fracture separation at greater distances. Such an analysis does not appear to have been performed.

The complex course of the Lansjärv Fault trace suggests that this fault rupture has dodged from one fault plane to another. A fault plane of this dimension with a long history of movement and with a large overall displacement would be expected to be more regular in its course. Hence it is likely that the Lansjärv Fault is a compilation of other fault traces, some of which have had longer histories of movement than others. The fault observed at Molberget does not appear to have been suffered a very significant displacement history, at least since it has existed in the brittle upper crustal temperature regime.

It is also important to understand why a fault that appears to be typically a reverse fault dipping at 45 degrees, should be manifest as a vertical fault plane. Some component of horizontal shortening, observed at most of the trench sections, is missing from the Molberget outcrop. Where has it gone? Is there some other fault nearby with a high horizontal to vertical displacement (either a backthrust or a frontal thrust) or is it distributed across many fractures? Most likely this has become concentrated on the opposite dipping backthrusts found in the hangingwall at this locality. The existence of these backthrusts suggest that the intervening hangingwall of the fault may be fairly highly strained (and shattered?).

Although it is to be expected that the fault follows pre-existing fracture planes, this may not be the case everywhere. While geophysical traverses across the surface scarp offer evidence in support of a pre-existing structure (or more correctly anomaly), the nature of the geophysical signal is too imprecise to substantiate a rigorous argument concerning reactivation. Trenching the fault is the only effective way of solving the question.

Having ascertained that the fault intersected in all trenches so far appears to follow a pre-existing structure, the hypothesis can only be tested by attempting to refute it: ie. by planning to dig a trench at some bend or dog-leg in the line of the fault, at which point the fault appears most likely to take a path that could jump from one fault to another. Hence the answer to the question must be based on the degree to which an attempt has been made to trench the fault at such a location. From the presently available data the fault must be considered to follow pre-existing fractures for perhaps at least 90% of its length. Additional trenches at the most critical locations could hope to raise this figure towards 99 %.

The very high vertical displacement to length ratio of the Lansjärv Fault, relative to the ratios of other recent reverse faults implies that the angular strain that was relieved by the fault movement was higher than is typical for reverse fault earthquakes, and hence that the crust was resistant to breaking in this manner. The Lansjärv Fault was in effect a "reluctant" fault. This lends support to the supposition that the conjoined faults that comprise the Lansjärv Structure, may have never previously moved in combination. Repeated movement would tend to reduce the resistance to dislocation and hence encourage fault rupture at lower levels of angular strain, more typical of present-day reverse faults. If such a model is correct, it becomes more likely that the surface fault may for short sections cut through fresh rock, as it shortcuts from one pre-existing fault to another.

7 What are the causes of post-glacial movement?

The formation of the Lansjärv Fault scarp reveals that the angular strain became higher than rock strength for some period towards the end of deglaciation. The strain associated with the faults reflects both a component of horizontal crustal shortening and differential uplift. Glaciation and deglaciation are associated with rapid changes in vertical load, and hence are likely to be responsible for any changes in vertical elevation through this period. The horizontal crustal shortening could have two origins, either from strain related to intraplate tectonic crustal shortening that was suppressed beneath the ice-cap, or else a liberation of the horizontal strain that occurs towards the centre of the downwarped "bowl" beneath the ice-cap, simply as a result of differential loading.

If the rate of ice-cap unloading is far faster than the rate at which the lithosphere can rebound, then this crustal shortening may become manifest as reverse faulting. Such an explanation would not require any external plate tectonic control, the orientation of the faults simply reflects the orientation of the strain gradient that is determined by the thickness variations across the ice-cap, controlled by the NNE-SSW trending topography of northern Fennoscandia. It is also of course not improbable that the crustal shortening reflected in the faults reflects both downwarping strain and plate-boundary strain.

8 Are the late-glacial faults still active today?

The current strain regime of northern Sweden is one of extension, associated with rebound doming. This extensional strain is far more rapid than any likely strain associated with plate tectonic processes. Hence the crust surrounding these late-glacial faults has not only failed to begin to regain the high horizontal stresses that were associated with the fault rupture, but has, as a result of continued extensional strain continued to be destressed. Hence these faults could not possibly undergo a renewed episode of reverse faulting as long as the rebound continues. It is however not impossible that these faults could be reactivated in extension, but such movements would be most likely to be very small and on very short sections of the fault, as the present angular strain across northern Sweden associated with rebound is very low, and the act of reducing the NW-SE horizontal stress is likely to distribute brittle failure across a large number of small faults.

9 Conclusions

Perhaps the most important outcome of the Lansjärv Excursion was the demonstration of the power of trenching to help solve difficult problems related to past fault movements and earthquakes. It should be recognised that there is a fundamental problem that affects surface derived geophysical observations, that they can never achieve the unique and high-definition interpretation, which is required to demonstrate seismotectonic relationships. Boreholes also suffer from the near impossibility of being able to demonstrate complex tectonic inter-relations, as well as from the difficulty of coring faults. In Robert Lagerbäck Sweden has one of the most experienced excavators and interpreters of late Quaternary deposits in the world. Trenching should be given the highest priority in any future investigations of fault movement or palaeoseismic phenomena elsewhere in Sweden.

THE LANSJÄRV FAULT ZONE: SOME IMPRESSIONS

Nils-Axel Mörner

In 1990, SKB arranged a short excursion to the Molberget segment of the Lansjärv Fault Zone. During this visit the exposures did not show any clear characteristics of post-glacial vertical dislocation; on the contrary this segment seemed rather to have remained more or less free of motions with a possible local - and possible even new - lateral divergence to the Stupforsen Fault which runs in about 45/135° angle to the main Lansjärv Fault Zone (Mörner, 1990). During the 1991 SKB excursion, we were led by the primary investigator of the Lansjärv Fault Zone, Dr. R. Lagerbäck (e.g. 1988, 1990, 1991), and he had prepared new trenches for our inspection. It was now quite clear that even the Molberget segment had moved in post-glacial time. On the whole, I am happy to acknowledge an excellent show by Lagerbäck. Besides this, I report the following observations and impressions.

1 The Molberget fault segment

In the new trench (trench 2), it was clearly seen that the till had been cut by vertical faulting. The liquefaction structures and disturbancies in the glacial lacustrine sediments (in trench 1) date the seismotectonic event to the glacial lacustrine phase just post-dating the free-melting. Because the covering littoral sediments are not affected, and there is only about 10 m - representing less than 100 years in this rapidly uplifting region - between the Marine Limit (about +185 m) and the trench surface (about +175 m), there can only have been a short time between the free-melting and the seismic event.

In trench 1, the bedrock surface immediately east of the fault scarp is heavily fractured with vertical dislocation of some parts. In trench 3, there is a major fragment that has been slightly dislocated with sediment infilling below. All this indicate syn-seismic lateral fracturing and dislocation (just as reported on by Mörner from southern Sweden: e.g. Mörner 1978, 1989; Mörner et al., 1989).

In trench 1, I took a sequence of oriented samples for magnetic fabric analysis. The analyses are still in progress (to be reported on at the SGU symposium in December 1991).

As previously proposed (Mörner 1990), the nearby Stupforsen fault segment is likely to represent a new side branch of the Lansjärv Fault Zone. This should be further investigated.

2 The Risträskkölen fault segment

This segment is impressive in its vertical off-set. The change in direction in relation to the shear-zone indicates that there were simultaneous active forces along the shear zone, and that the interaction between these forces and those associated with the Lansjärv Fault Zone caused the local directional curvature at Risträkkölen.

3 The seismic till stratigraphy at Pokölen

The seismic till stratification claimed by Lagerbäck (1991) is very interesting. I have seen no comparative notes in the litterature. The trenches that were demonstrated gave interesting insights to this problem.

4 The seismic till slide at Elmaberget

Earth slides are common features. An earth slide in till - above the marine limit - is quite rare, however. A seismic origin seems reasonable.

5 Syn-seismotectonic bedrock fracturing

In the Molberget trenches one can observe that the bedrock surface is fractured, including slightly dislocated local blocks, in the vicinity of the fault scarp.

Along the roads following the Lansjärv Fault Zone, one could observe that the bedrock surface often is heavily fractured; sometimes into heaps of loose angular blocks.

This is important as it lends support to the findings of Mörner that heavy bedrock fracturing and breaking loose of blocks in latest glacial to early post-glacial time can be associated with high amplitude seismotectonic events (e.g. Mörner 1978, 1985, 1990, 1991; Mörner et al., 1989).

The situation along the Lansjärv Fault Zone should, therefore, be specially analyzed in view of this question.

6 New faults and fracure

The Lansjärv Fault Zone runs more or less perpendicular to the main NE-SW shear zone (Henkel 1988, Pl. 1). The original formation of the Lansjärv Fault Zone probably represent new geodynamic forces. The age of this initial event is not known today.

Beyond doubt, the Lansjärv Fault Zone was reactivated in earliest post-glacial time. This does not mean that it totally followed old faults and fractures; on the contrary it seems highly likely - not to say quite clear - that it also includes new segments, courses and local disturbancies. This is also what Lagerbäck claimed during the excursion (in contrast to the general conclusion in the collective research report by Bäckblom & Stanfors, 1989).

7 Conclusion

The Lansjärv Fault Zone provides exceptionally good and clear morphological details of a major post-glacial paleoseismic event. The investigation has been skillfully performed by Lagerbäck.

The last movement along the zone seems to include new segments, new courses and extensive new lateral fracturing and disturbances. This should be studied in further details.

Acknowledgements

I thank SKB for a most interesting and perfectly arranged excursion in a good and constructive atmosphere.

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COMMENTS ON THE INTERDISCIPLINARY STUDY OF POST-GLACIAL FAULTING IN THE LANSJÄRV AREA, NORTHERN SWEDEN, 1986-1988

conducted by the Swedish Nuclear Fuel and Waste Management Co

Oddleiv Olesen

The results from the Lansjärv Project were presented at a meeting in Överkalix in June 17-18, 1991. An excursion to the Lansjärv post-glacial fault was arranged at the same time.

As a geophysicist working with post-glacial faults in northern Norway, I am impressed by the results obtained in the Lansjärv Project during the period 1986-1988. I especially find the 3D regional interpretation of the geophysical data by the geophysicist Herbert Henkel and his co-workers to be outstanding, with regard to both methods and results. I also think that the research work by the quaternary geologist Robert Lagerbäck is a major contribution to the understanding of the youngest period of the Fennoscandian geological history. In particular, I find the results from the dating of the main movements along the fault and the associated generation of "seismites" to be the most interesting.

I also found the discussion following the meeting to be useful. The time was, however, short for discussion of the many aspects of neotectonics, and I think that another joint workshop and excursion for scientists working with neotectonics in northern Fennoscandia would be rewarding. There exist similar post-glacial faults in the northern regions of both Finland, Sweden and Norway. Although investigations have been carried out in all three countries, coverage in neither Finland nor Norway has not been as great as in Sweden. A compilation of the results from the different investigations could nevertheless help delineate both the kinematics and the hazards related to the neotectonics in Fennoscandia. So knowledge of faulting in Finland and Norway could directly contribute to the Swedish nuclear waste programme. Review papers of the different aspects of the neotectonics in northern Fennoscandia could be compiled for publication in an international journal. An internordic collaboration project could also help finding the most appropriate path, along which the future research should be directed.

COMMENTS ON THE LANSJÄRV PROJECT - FIELD EXCURSION AND MEETING JUNE 17--18, 1991

Dr Philip S Ringrose

General comments:

It should be made clear that this presentation of results and inspection of sites was focused on the **geological** investigation of the Lansjärv fault (mainly field study, trenching work and mineralogical study of fault infill and adjacent rock). The remaining topics addressed by the Lansjärv Project were only briefly summarized at the meeting. I have therefore separated my comments into two sections:

1 Items presented and discussed in detail at the meeting, and

2 other items discussed in the report (SKB TR 89-31) but only briefly summarized at the meeting.

1 Field studies presented and discussed at the meeting

Fault movement

Commendable efforts were made to investigate the Lansjärv fault by excavating trenches across and adjacent to the fault line. Field evidence for the relationship between post-glacial stratigraphy and the fault scarp demonstrating the timing of the fault rupture was very convincing. The interpretation that almost all of the fault displacement occurred at circa 9000 BP therefore appears sound. In the exposures seen, the movement appears to have been vertical on a near-vertical fault plane. Other evidence (slickensides, mylonitized zones) indicated that various pre-Quaternary movements had also occurred. In summary it appears that the post-glacial bedrock rupture, evident as a prominent scarp in the glaciated terrain, occurred during a short period of time around 9000 BP along the locus of a pre-existing basement fault.

Evidence for paleoseismicity

Two phenomena were presented as evidence for contemporaneous seismicity - graded till and liquefied silt/sand deposits. The interpretation that the localised occurrence of highly graded till (viewed in two trenches at

Furuträsket) were produced by ground shaking appeared plausible, but has not been reported from anywhere else. Alternative explanations should be carefully evaluated before this paleoseismic interpretation is given full weight (for example, fluidization due to emanating groundwater or excess pore pressures developed beneath surface ice might explain the grain-sorting observed). The interpretation of liquefied silt/sand deposits as being paleoseismic in origin is more readily acceptable. Examples seen in the exposures near the Lansjärv fault at Molberget and the photographs documented in the SKB Reports (TR 89-31 and TR 91-17) are remarkably similar to exposures in Scotland (in a similar glacio-stratigraphic setting) which I have also interpreted as being paleoseismic (Davenport & Ringrose 1987, Ringrose 1989). Nevertheless, more systematic studies on these deposits and the causes of their deformation should be done so as to tighten up the arguments for paleoseismicity.

Other studies

Two other studies were presented in some detail:

a The mineralogical study of fault-infill material was quite good, but it was restricted to hard and lithified minerals. The study provided further evidence for a complex history of pre-Quaternary movement along the fault. Further work on more recent fault-infill material (clays and unlithified minerals) should be done to compliment this work, thus shedding more light on the movement during the Quaternary. Attempts to date fault-material should also be made.

b The reason for conducting the study of Sliding Micrometer displacements in boreholes across the fault was not clear. If the intention is to evaluate current strain rates along the locus of the fault then a more detailed study over a period of several years will be required. It will be necessary to monitor temperature, water and ice distributions in the vicinity of the fault and also to establish control measurements away from the fault, in order to resolve the effects of earth tides, temperature, hydrodynamic pressures and freeze-thaw action on the rock mass. Efforts would, however, be better directed towards obtaining good geodetic measurements.

2 Other topics presented in the report

The topics presented in the report (SKB TR 89-31), but not discussed in any detail at the meeting were: Regional tectonic studies (Chapters 2 and 4), Analysis of microearthquakes (Chapters 5 and 6), Borehole drilling and geophysics (Chapter 7), Hydrological studies (Chapter 8) and Modelling of rock masses (Chapter 10). My main comment is that, although these studies represent detailed work on a number of important and related topics, very little attempt has been made to synthesize the studies with regard to understanding the PGFs.

In particular, I have the following comments:

a The presentation of regional tectonics and Proterozoic shear zones is a little confusing - Do ancient shear zones have any relevance to the problem of understanding PGFs other than providing a convenient locus of movement?

b More effort is required in understanding the stress and hydrological conditions around PGFs and around similar ancient faults which have not been reactivated post-glacially.

c The relationship between present-day seismicity and the PGF phenomenon is not clear. From the studies presented, it would seem that microearthquake studies have very little to say about past or future locations of PGFs.

3 Conclusions drawn from the report

I feel that it is not possible to give satisfactory answers to the eight questions posed, and to some extent answered, in the report (SKB TR 89-31, Chapter 11). It would be more helpful at this stage to ask the interdisciplinary group to compile an answer to the single question:

> What is our **current** understanding of how major PGFs occurred in northern Scandinavia at c. 9000 years BP?

With some kind of detailed hypothesis established (or a few alternative hypotheses), SKB and its advisers can then proceed, with a little more clarity, to answer the questions of more direct concern (e.g. the likelihood of faulting near repositories). They would also be able to direct further research in areas most critical to the problem.

Conclusion

The Lansjärv Project comprises a very useful multidisciplinary study of post-glacial faulting in northern Sweden. In order to use this study to assess the risks associated with disposal of radioactive waste in Sweden, a synthesis of work is needed. An argument for the stability of a repository site can only be made on the basis for a plausible model of past and future strains in the crust around proposed sites. Attention should be focused on establishing an understanding of how past crustal strains in Scandinavia were achieved. At present there is still something of a mystery surrounding these faults and our understanding of how such extraordinary displacements occurred along them only 9000 years ago.

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COMMENTS TO POSTGLACIAL FAULTS IN THE LANSJÄRV AREA FOLLOWING THE MEETING AT ÖVERKALIX 17-18 JUNE 1991

Ove Stephansson

I have revisited Chapter 11, General Conclusions SKB 89-31 and have the following comments to make:

Are the post-glacial faults new or reactivated?

The additional trenchings since 1988 have confirmed our previous postulates that PGF at Lansjärv follows old fracture zones.

Our latest modelling of faulted rock mass response to glaciation seems to indicate that we can have had an additional vertical displacement from the ice load. This assumption is based on the most recent paper by Baotang Shen and myself *) where we applied two different stress state to a generic model of Lansjärv with a steep (60^0) and shallow (30^0) fracture zone reaching the surface.

If we apply a stress state in accordance with the Fennoscandian Rock Stress Data Base (FRSDB) to the model, minor displacement will appear on the surface due to a glaciation cycle. If we apply a stress state according to the recorded stresses in KLJ01 we obtain severe vertical displacement along the steeply (60^0) inclined fault.

This result is based on the assumption that the Lansjärv fault was stress relieved prior to the Late Weichselian glaciation. A possible scenario is shown in Figure 1.

*) Stephansson, O and B. Shen, 1991. Modelling of faulted rock mass response to glaciation, thermal loading and seismicity. Quarterly Journal of Engineering Geology, V 24 (in press)

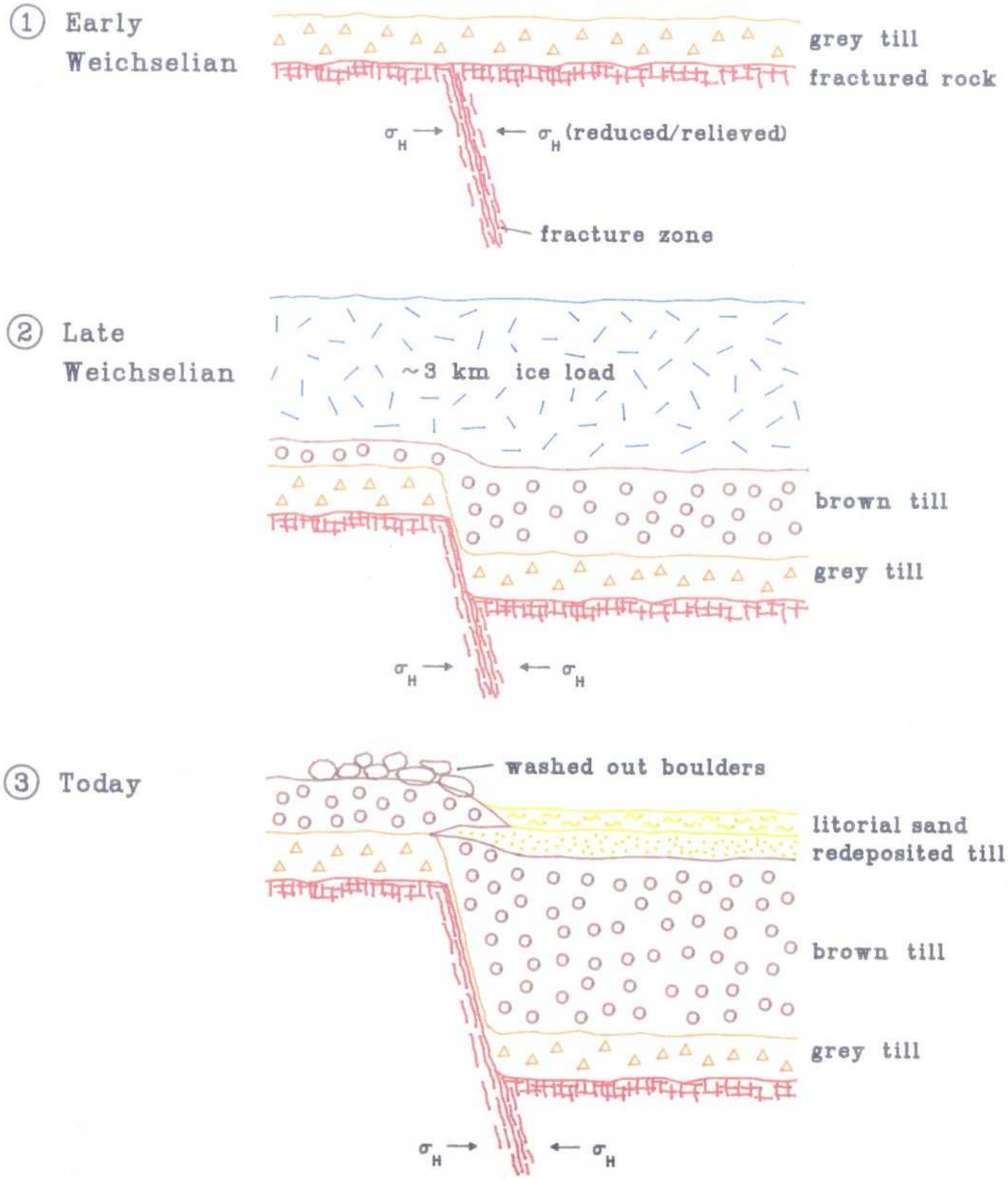

Figure 1. Possible scenario of post-glacial faulting (PGF) at Lansjärv with the assumption that maximum horizontal stress across the fault is relieved. The vertical ice loading causes vertical displacement of the rock mass.

The sequences depicted in Figure 1 are:

1 Early Weichselian till(s) was deposited.

2 Late Weichselian ice loaded the area and caused vertical displacements and deposition of "Brown till". The area of the downfaulted block was filled with more till then the opposite side of the fault.

At this stage of development the fault movement may well be accompanied with earthquake, but this means that we do not need to look for a M=6-7-8 earthquake in order to explain the present amount of offset. Parts of the displacement or the hole lot is due to the vertical loading and unloading from the Late Weichselian ice sheet.

3 To-day's situation is shown as it was demonstrated to us by Robert Lagerbäck at Trench P2 of the Molberget site.

The only way to check the amount of displacement derived from this new model of creating the vertical displacement, is to dig trenches at sites above the highest shore line. In the report by Lagerbäck (1988) SKB TR 88-25 he presents results of some trenches above the highest shoreline but they were incomplete in length and did only expose one side of the fault scarp.

Regarding item 6 "Present movements", the sliding micrometer measurements are interesting but a number of uncertainties have to be sorted out, e.g. averaging procedure of readings, influence of digging, influence of changes in groundwater level. SKB is strongly recommended to keep these measurements going for a couple of years (5 years) and if possible supported by surface levelling and precision polygon measurements of the heads of the boreholes or fixed points. It is a strong wish from the science community to try to keep one trench open for future revisits and studies. One of the trenches instrumented with sliding micrometer instrumentation would be a good choice.

Is the Lansjärv area with its PGFs anomalous to the rest of Fennoscandia?

My firm answer is still, YES! The formation of the "graded till" at L Telmträsket, Pokölen and Furuträsket needs to be explained. A couple of model experiments conducted in a soil mechanics laboratory is recommended. Many of the new evidences for paleoseismics, manifested in the sedimentary structures around the Lansjärv fault, can be explained as due to gravity instability. The size, wavelength, amplitudes of many of the convolutes are controlled by the ratio of layer thickness, density, and viscosity and the pore pressure. The triggering mechanism can be a minor disturbance of the substratum. This creates a deviatoric state of stress and establish the gravity instability and form the sedimentary structures. SKB is recommended to send the most recent report by R Lagerbäck to a couple of experts on paleoseismic sedimentary structures and ask for their comments.

I have suggested several times that rock stress measurements is a way of detecting plausible late glacial faults at a potential site. In order to prove this we need more stress data from PGFs and other faulted areas. SKB is recommended to support stress measurements in the borehole to be drilled this autumn at Stuoragurra in Norway.

TALBOT'S COMMENTS AFTER LANSJÄRV FIELD EXCURSION JUNE 17--18, 1991

Christopher Talbot

Congratulations and many thanks to all those involved in organizing the very successful field excursion to the Lansjärv region 1991-06-17--06-18. Participants were asked to write a few pages of comments on what they thought about what they saw. Here is my contribution.

General

In combination, the trenches at Molberget and Furuträsket, and the landslide at Elmaberget, clearly demonstrated all the main points that Robert Lagerbäck has ever claimed. However, they may have gone further in some respects that I discuss below.

Geoscientists will be arguing about the details of the PGFs for as long as there are geoscientists. An important point for SKB is that the PGFs in Lapland are currently the most spectacular and largest Holocene fault displacements known on this planet. That means that SKB need only prime the pump to concentrate world attention on them. That was probably done with the latest excursion, it now become a rush to see who publishes about them first in the front line journals. But you can expect an editorial or article about the PGFs in Terra Nova before the end of this year (edited by Robert Muir-Wood).

One or more shocks along the Lansjärv PGF?

Trenches 2 and 3 at Molberget raise the possibility of more than earthquake in the (few?) hundred years between the rise of the fault scarp and the retreat of the highest marine shore-line. Robert Lagerbäck (reasonably and informally) attributed the few dm of grey compacted sand that overlies the faulted till stratigraphy on the foot wall to a seismically driven flow unit. The dewatering structures in the yellow sandy silts above he also attributed to seismic shock. There are also dewatering structures in the few dm of fine yellow-brown (clayey?) silts beneath the compact grey unit. Indeed in part of trench 3 at Molberget, the fine grained brown unit intrudes up into, even through, the compact grey unit in a number of irregular pipes approximately a metre apart.

So about a metre of the young sequence in trench 3 is disturbed by dewatering structures. This metre includes the brown (clayey?) silt, the grey compact sand and the yellow laminae and beds above. The timing of these three units and their disturbance (hours, a day, or hundreds of years?) might well be controversial for years to come.

If I were Robert Lagerbäck, I would start reading text books on volcanic eruption facies. I would try thinking of the grey unit as a base surge that lasted something like ten to twenty minutes and the overlying sands as the swashing tsunami facies that may have lasted a few hours (along any one PGF). I would test by observations the idea that the brown clays and silts are the fines that were pumped up from the underlying tills and accumulated (as one or more intrusive sills?) locally beneath the compacted grey surge facies and locally burst through it. If this approach has any success, then we are probably still dealing with a single shock of enormous magnitude (eg. Mn 8) along each PGF.

Graded till facies

The graded tills are a major new phenomena. I guess many of those on the excursion were as shocked as I was to learn that Robert has been studying this phenomenon for ten years and has only published a brief note in GFF. Robert Lagerbäck's picture of graded tills as a new facies of seismite is already supported by his evidence. I would guess that he only needs to map the shallow depressions poor in surface boulders that "sound distinctive to stamping feet" within a km of a PGF on its hanging wall before he submits a major paper to the Journal of Sedimentology (or somesuch).

It would also be useful to look for structures in the partially graded tills in the hope of establishing how the large (and therefore dense) clasts sank while the (finer materials were displaced upwards). It would be useful to document the size fractions (and densities of the clasts below sand size) that come out of different levels of some of those trenches. This would allow quantification of the size fraction that was removed after grading and thereby constrain the height of the waves that followed. Another mapping tool that has promise would be seismic refraction. The graded units are depressed because they have lost their fines and compacted to greater densities and therefore faster P wave transmissivities. A combination of the depth of the depression, the thickness of the graded unit, its seismic velocity and its grain-size truncation has great potential for mapping energy in-put. This is also the sort of information necessary for the next phase of study which is surely experimental (incidentally, if the brown silts under the grey compacted sands on the foot wall did rise from below, then the underlying tills also lost their fines without, apparently, sorting by size).

As with the other seismite facies (surface collapse and flows, in-situ disturbance, intrusion, extrusion and dewatering in-situ facies etc), the main unknown about the graded till facies is the energy necessary and its timing. A series of simple but well designed dynamically scaled models should be able to answer such questions as:

- How much water has to be present to allow grading of a till ranging in size from 1.5 metre boulders to clay? Is that initially within the till sufficient or must there be throughput from the bedrock (which would imply that the graded sunken facies may be localized over steep fractures in the bedrock)?

- What was the energy input and rate? The energy input must have been capable of lifting all the material with less than the median grain size (or is it the median mass or depth?). There must have been considerable temporary dilation (> 30%?) to allow such extraordinarily efficient local sorting. One shock is known to be sufficient to dewater and compact substantial sequences of rapidly deposited (cubic packed) sand, but does the first shock also mass sort an initially mixed unit? I strongly suspect that simple experiments would soon demonstrate that mass-sorting requires vigorous fluidisation that in turn requires cycling loading by either ground shock (which is only likely for a few minutes or, with aftershocks, perhaps episodically over a few weeks) or repeated passage of tsunami waves overhead (seishing in an enclosed basin for a few hours?).

Fault gouge at Molberget

Since Robert Lagerbäck and Herbert Henkel first flew me along all the Swedish Post-Glacial Fault Scarps (PGFs) in the autumn of 1986, I must have spent many field weeks, if not months, looking at PGFs, and studying the bedrock outcrops along them and their older precursor deformation zones. But it was not until the 17th June 1991 that, at last, I saw a fault gouge.

No gouge survived the brutal excavation of the first trench at Molberget. Consequently those who studied it could not understand the apparent disparity between the majority of slickenlines exposed in the "PGF" scarp being subhorizontal (strike slip) even though the post-glacial displacement was obviously vertical. Some dip-slip slickenlines are exposed on some small facets dipping about 50 degrees towards the hanging wall in a sheared amphibilite sheet, but the vast majority of slickenlines are horizontal or oblique-strike-slip in chlorite veins that are obviously much older than the post-glacial movement.

The second trench at Molberget was excavated with commendable care. As a result, some dm of the clay gouge along was left undisturbed along the post-glacial fault. As might have been anticipated, all the polished slickenlines in the clay gouge are dip-slip and account for the vertical (and locally normal) displacement.

This simple but important observation emphasises the importance of sampling the soft clay gouges along our Swedish deformation zones of all ages. The clay gouges have always been eroded from natural exposures, washed out of all our exploration drill holes, and removed while excavating the trenches. Trench 2 at Molberget demonstrates that the clay gouge can be sampled if there is sufficient motivation and sufficient care is taken. Everyone involved in the excavation of trench 2 are to be congratulated for at last sampling the delicate and extremely valuable direct record of the end glacial movement along the Lansjärv fault. Careful attention must now be paid to the mineralogy, structures, fabrics and age of all components in this gouge with its multiple slip surfaces.

Clay gouges elsewhere in Sweden

Clay gouges are conspicuous by their absence along most of the fault zones exposed in the surface trenches at Äspö. It is possible (but hardly likely) that clay gouges exist **only** along those faults that moved in post-glacial times. And yet we have been washing away the gouges that we know to have existed in several faults at several SKB study sites (including Äspö). **It cannot be overemphasised that these gouges, together with the displacement(s) of the fault scarp, are the only direct record of the latest movements along the faults that contain them.**

In letters and reports to SKB since 1986, I have been advocating that we use well tried techniques to sample the fault gouges in exploration holes drilled for SKB. It is not as though materials just as soft as clay gouges have not already been sampled in exploration holes in Sweden for they have; Boliden Mineral used the necessary triple-tube core barrels long ago. Nowadays we could find (and wash away) the gouge zones by standard drilling of vertical holes, establish the orientation of gouge bearing faults by radar, then withdraw twenty or fifty metres and drill any number of side-track holes to intersect the gouge twenty or fifty metres away from where we have already disturbed. This could be done using triple-tube core barrels (that have a non-rotation plastic liner inside the flushing circuit). As the side track holes would be inclined, there should be little difficulty in drilling **undisturbed** core across the entire thickness of the loose breccia and gouge zone(s).

Strain measurements at Molberget

It is good to see such work being done, but important that it be done in such a way and for sufficiently long that we know what is happening. That means a control hole well away from engineered disturbance and the fault (e.g. in the foot wall). It is a well known geodetic "law" that strains occur on every scale that they are measured. As an example, I installed (photoelastic) strain gauges across fractures in a road cut in Scotland and measured strains on a monthly basis. I then became suspicious and found significant strains over weeks, then days and eventually hours. On an Iranian salt extrusion in 1977 or 1988, I found the same phenomenon (see Talbot & Rogers, EA., 1980: Seasonal movemements in a salt glacier in Iran, Science, Wash., vol 208, p. 395-397, copies available). Eventually I abandoned strain gauges and just used tape measures and an alidade because the phenomenon was so exaggerated (in salt). The joints opened and closed because the mountain swelled and shrank with the temperature, the humidity and (I expect) the daily, monthly and annual tides. Thus the 7x2x1.5 km salt mountain swelled up to five cm every morning at dawn, and shrank the same amount every evening (when the salt was dry). The mountain shrank a cm and regained the same cm in about ten minutes when a small cloud crossed in front of the sun!

In other words, I suggest that the strain measurements at Molberget are so accurate that they are monitoring the pulse of the bedrock in the area due to the weather (wind, air pressure, temperature, humidity and tides etc). The trivial test of this will emerge after a few years of monitoring at Molberget - with a local standard hole. A more accurate test would be to install three of the longest available continuously recording vibrating-wire strain gauges (e.g. two horizontal and one vertical) at a test site near a weather and/or geodetic or tide station far away from Molberget (e.g. at LMV in Gävle or the geophysics lab at Kiruna). The complete strain field could then be monitored almost continuously and compared to the such phenomena as the weather, tides etc. The signal at Molberget varies from place to place because the bedrock is flawed by the PGF and distorts unequally. There may well be a drift in the readings with time, but a simple test of their validity would be to take readings from one of the boreholes continuously for a 24 hour cycle and plot all the readings (±).

Something close to the strain monitoring station I advocate above may well already exist elsewhere (California, various major dam sites etc???).

This is my contribution to the summary of impressions from the field excursion and meeting in Norrbotten, 17-18 June, 1991, concerning the post-glacial faults in the Lansjärv area.

Eva-Lena Tullborg

The evidence of post-glacial faults in the Lansjärv area

The fault scarps of the Lansjärv system can be easily traced on aerophotos as vertical displacements in the order of 2 to max. 10 m. This was the way they originally were discovered and considered as post-glacial fault movements. Disturbances in till stratigraphy as well as a number of other features interpreted by quaternary geologists, support this idea and also indicate that these vertical displacements are closely related in time to the retreat of the last landice. Vertical striae in clay/chlorite minerals on the fault scarp were found in one of the trenches carefully excavated for the excursion.

It has, however, not been possible to find any evidence of late movements by the mineralogical investigations (carried out on drillcore samples and surface samples from two other trenches). This could be due to the loss of soft minerals, like e.g. clay minerals, during the drilling by flushing of the drilling fluid but is also due to the problem to distinguish potential presence of small volumes of "post-glacial minerals" from major parts of hydrothermal and low temperature minerals produced during earlier periods of alteration.

The causes of post-glacial movements

The importance of deglacial stresses compared to plate tectonical stresses are debatable and many different points of view were presented during the meeting. Earthquakes occur obviously also in areas that haven't been glaciated, on the other hand most quaternary geologists seem to agree that the recent faulting in northern Fennoscandia took place shortly after the deglaciation (which can be interpreted as faulting trigged by the post-glacial up-lift). Interesting discussions on this theme were held but no convincing evidence for a single theory was proposed at the meeting.

Are the post-glacial faults reactivated?

The Lansjärv fault zone is penetrated by drillholes at two different localities (Molberget and Mäjärvberget). Mineralogical investigations comprising drillcore samples as well as surface samples from these localities show that the faults follow older, preexisting fault zones which contain hydrothermal minerals (probably of Proterozoic ages). Concerning the Lansjärv post-glacial fault zone there is, thus, no evidence or signs of new fracturing in undisturbed rock at the localities investigated (including the excavated trenches). It is, however, not possible to exclude the occurrance of new fracturing in minor parts of the fault system.

From the field observations in the washed trenches (Molberget) it is clearly seen that the earlier, major movements, which have resulted in striae in hematite and chlorite minerals on the fault scarp, are strike-slip to oblique in direction.

POST-GLACIAL FAULTS IN THE LANSJÄRV AREA, NORTHERN SWEDEN

Paavo Vuorela

Meeting in Överkalix in June 17-18, 1991

A group of international experts was invited by SKB to participate in discussions and a field excursion in the Lansjärv area. The main results of the research project into post-glacial faulting in Lansjärv between 1986 - 1989 were presented and a number of field localities showing fault scarps, landslides and seismites were visited. A further aim of the meeting was to discuss post-glacial faulting with special emphasis on its implications for the disposal of radioactive waste. Participants were asked by SKB to write some comments concerning sites visited and to provide answers to some related questions raised at the meeting.

Comments concerning sites visited

Localities were all situated along a c. 50 km long zone marked by post-glacial fault scarps.

1 Risträskkölen

The site visited is a 20 m high corner of a bedrock block, adjacent to a smooth swamp area. General opinion was that the formation is probably not post-glacial. However, there was no visible evidence of age, and location of the scarp on air photos and determination of its relation to other scarps may help in interpretation. I think that it's very probable that this kind of block has been involved in post-glacial movements.

2 Molberget

The Molberget site included several deep trenches excavated perpendicularly to the fault scarp. The first exposure showed red coloured brecciated and fractured granite, which changed on the northern side to unbroken granite, in between was a dark coloured dike, which had been identified as dolerite or probably metadiabase. This observation is very interesting because a diabase dike in trending parallel to the fault scarp suggest a very great original age for the earliest movement on the fracture zone. In other excavations further north, over a distance of five or ten metres of the scarp, zones of fracture cleavage parallel to the main fault were present, while mineral assemblages in small fracture fillings (epidotes etc.) represented PT conditions, which must be of great age. However the fault scarp was very clearly indicated and represents in my opinion a post-glacial movement.

3 Furuträsket

The Furuträsket site included a depression containing deformed sediments, double till beds and disturbances, which could be attributed to earthquake activity presumably of high magnitude. Another possibility which was discussed was gravity sliding, since the magnitude of an earthquake required to cause sliding and slumping of liquefied sediment is like to be much less. Digging of long trenches seemed to be an economic and practical way to study the sedimentary stratification.

4 Elmaberget

Elmaberget was well known on account of a clearly indicated land slide. Lagerbäck considered that a high earthquake magnitude would be required because, as he said, this type of soil material is more cohesive. The slide was very clearly visible on an air photo taken by Lagerbäck.

At the end of the excursion John Adams presented studies of post-glacial faults in Canada. Interesting seismic profiles were drawn across the lakebottom sediments where sudden disturbances were indicated. Turbulent layers and enrichment of heavy mineral fractions were indicated, similar results as Lagerbäck had told earlier.

<u>Comments on questions presented</u>

1 Post-glacial faults - new or reactivated?

Reactivation is clearly evident at all excursion sites. It is logical that new fracturing could occur to some extent during bedrock movements but its also reasonable that faulting follows the pre-existing weakest zones in the bedrock. Even a complete change in the stress field does not necessarily require a completely new system of fractures if we are dealing with previously fractured material. We must also take into account that the orientation of regional stresses has been almost constant in northern Fennoscandia for quite a long period of time.

2 Causes of post-glacial movements.

Extension at the Mid-Atlantic ridge and landuplift process act together. NW-SE trending old transcurrent faults and NE-SW reverse faults are related to each other. Both fracture systems are old, with the repeatedly activated repeated NW-SE transcurrent system dating back at least to proterozoic.

3 Why do the post-glacial faults trend NE-SW?

Clear relation to NW-SE transcurrent faults. An interesting observation by Stephansson was the anomalously low stress field below the Lansjärv fault scarp. If this were also the case generally with other fault scarps it might tell something about the relation between these movements and the existing stressfield.

4 How deep are post-glacial faults?

Maybe they dip at low angles, but I see no reason why they could not be deep at least the transcurrent fault zones are very deep (several kilometres).

5 Are northern regions of Fennoscandia exceptional with regard to post-glacial faults?

These faults have been actively searched for in different places and especially in the southern part of Finland, appeal to geologists was even made in the Finnish Geological Society Newsletter, but the results have been very poor, the only faults found being small, with displacement less than 4 cm high cutting the bedrock surface. In the southern parts of Finland ancient fracture zones hundreds of kilometres in length occur and are indicated as lineaments. These zones are often covered with thick layers of sediments (30-40 m clay deposits) and lakes and rivers commonly follow them. During landuplift process they have certainly been active. Some information concerning current vertical movements along these zones has been obtained by precise levelling measurements. In these large zones earthquake activity is almost absent, faults are probably creeping. Post-glacial fault scarps have, however, not been found.

6 What are the implications of post-glacial faults for the disposal of nuclear waste?

We know that the amount of landuplift has been several hundreds of metres. We also know about block movements in the bedrock. Studies dealing with bedrock structure and stability are important. If the conclusion is that post-glacial faults follow old fracture zones, there must be evidence of it and the Lansjärv studies have brought new light on that question. We ought to identify the fracture zones in order to avoid them. Most clearly identifiable are the transcurrent faults, but difficulties may exist in recognizing low angle faults. Answer to the question: after carefully made regional structural analyses and site selection, a probability, that a post-glacial fault affects waste canisters seems to be small. Also must be mentioned, that very small faults and fractures are insignificant, since they have no effect on waste canisters, even though small changes in groundwater flow may take place.

SUMMARY OF IMPRESSIONS FROM THE INTERDISCIPLINARY LANSJÄRV PROJECT AND THE MEETING AND EXCURSION IN ÖVERKALIX AND THE LANSJÄRV AREA ON JUNE 17-18, 1991

Rutger Wahlström

The description below addresses some of the matters discussed in Överkalix last June, such as causes of movements, orientations of faults, their extension at depth, and present movements.

The Seismological Department, Uppsala University, operated a seismic network with 6-7 stations, mostly 3-component, digital, in the Lansjärv area in the summers and autumns of 1987 and 1988 to monitor the microearthquake activity near the late-glacial fault (LGF) segments. It was the first time such a dense network has operated during such long periods in Sweden. On the average, about one local earthquake was recorded weekly and where accurate locations could be made the focal depth is confined to 7 km - 10 km. The majority of the events were located east of the LGF segments and it is difficult to determine whether they are associated with these - in which case the LGF:s have to slope eastward at a low angle to these depths - or with perpendicularly oriented faults which are older but have experienced documented neotectonic movement. A similar discrimination has been discussed for the thoroughly investigated Stuoragurra LGF in northern Norway.

The seismicity from the last three decades recorded with the ordinary Swedish seismograph network also points to a certain concentration of seismicity in the area east of the Lansjärv LGF:s (Wahlström and Kulhanek, GFF 1983). However, lacking comparative investigations from other parts of Sweden or the Baltic Shield, the field-station recorded microearthquake activity may not be higher than the general background seismicity in the shield.

As suggested by the geological data and demonstrated by the seismic disturbances in some of the excavated sections near the LGF:s visited during the excursion, the faults were created instantaneously or during a very short time span (order of a few decades) at the last phase of the last deglaciation. This implies major seismic activity with earthquakes possibly as large as magnitude 8.

The stress anomaly near the LGF:s is low at the present time. Different hypotheses for the underlying mechanisms to the sudden and powerful stress release are:

a   relief of plate-tectonic generated stresses accumulated during the ice age but prevented to be released by the heavy ice sheet;

b   tectonic stresses were released during the glaciated period, and at the deglaciation there were therefore predominantly vertical movements due to previously locked an now freed vertical stresses.

The NNE trend of the faults in Lapland fits the current stress pattern of predominantly horizontal compressive stress propagated from the North Atlantic Ridge.

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