FIELD VISIT TO SITES OF POSTGLACIAL FAULTING

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John Adams

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Geophysics Division
Geological Survey of Canada
Energy, Mines and Resources Canada
1 Observatory Crescent
Ottawa, K1A 0Y3, Canada

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INTRODUCTION

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

The four areas visited were:

1. Postglacial faults and moraines in the Stockholm area.

2. Postglacial 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, Skogso, and Ragnorok, claimed by Mörner to represent postglacial fracturing of the bedrock and/or postglacial 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 postglacial 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 earthquke shaking from the varve stratigraphy should be collected rigorously.

2. Postglacial Faults in the Kiruna area

I went on a 2-day field trip led by Robert Lagerbäck, from Lulea 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 Tarendo.

An esker, of very fresh and postglacial 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 ($\approx$ 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 Tornetrask. 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 that 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.

Risträskkölen

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 postglacial faults of northern Sweden and applied in southern Sweden, where there are as yet no mapped faults of similar postglacial 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 postglacial 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 (Postglacial 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 postglacial 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 futher 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 postglacial 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 postglacial 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 unidirectional 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 futher work needed.

The following items are critical to the interpretation of the postglacial faults and their future importance:

Have the mapped postglacial 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 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 postglacial 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 postglacial faults? How deep do the faults extend? It would be interesting to attempt to discern the regional deformation caused by the postglacial 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 postglacial 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 Tornetrask 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 postglacial sedimentation in Sweden, with the aim of finding the sedimentary record caused by the postglacial 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 postglacial faults
- Lack of similar evidence for earthquakes in more recent times (confirming the hypothesis that the mapped postglacial 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 postglacial 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 postglacial 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.