Postglacial Fault Drilling in Northern Europe: Workshop in Skokloster, Sweden, October 4–7, 2010

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Introduction

The majority of Earth's earthquakes are generated along plate margins, and the theory of plate tectonics provides the explanation for the occurrence of these earthquakes. However, a minority of earthquakes occurs within continental plates and the theoretical understanding for these earthquakes is largely lacking (Stein and Mazzotti, 2007). The general assumption is that intraplate earthquakes tend to be relatively small in size. This workshop was devoted to a special type of intraplate earthquake generating faults, postglacial (PG) faults that to date have been observed only in Northern Europe.

Altogether, there are 14 well-known PG fault structures in northern Sweden, Finland and Norway with fault scarps up to 160 km in length and up to 30 m in height (Figs. 1 and 2; Lagerbäck and Sundh, 2008; Kukkonen et al., 2010). Assuming that these distinct faults were formed in single events, they would represent earthquakes with magnitudes of up to 7-8 (Bungum and Lindholm, 1997; Kuivamäki et al., 1998). This estimate is supported by numerous observations of massive landslides associated with these structures and dated to have occurred at the last stages of the glaciation. PG faults represent earthquakes with considerable contrast to the present seismic activity in continental northern Europe, where earthquakes are usually smaller than magnitude 4 M_W.

All known PG faults are located in old reactivated zones of weakness in the crystalline rock, and so far, no PG faults have been identified in intact rock. The PG faults are usually SE dipping, SW-NE oriented thrusts. The last major reactivation of these faults is believed to have occurred during the last stages of the Weichselian glaciation (*ca.* 9,000–15,000 BP). The earthquakes are believed to have been triggered by the combined effects of tectonic background stresses and rapidly changing stresses from glacial loading by the shrinking Weichselian ice sheet (Johnston 1989, Lund, 2005; Lund et al., 2009).

From what is known today, these large-scale types of PG faults appear to be restricted in occurrence to northern Fennoscandia. In other previously glaciated areas, such as Canada, postglacial faults are significantly smaller in size (Adams, 1989). It remains to be determined whether large-scale PG faulting are unique for northern Fennoscandia, or if they are hidden under sedimentary cover in other parts of the world. All structures are hosted by Precambrian crystalline rocks of the Fennoscandian Shield and covered by a thin (typically a few meters thick) veneer of Quaternary sediments.

Seismology data reveal that the PG faults are currently seismically active, and that small earthquakes are associated to these structures over a significant depth range (down to 37 km depth; Bungum and Lindholm, 1997; Arvidson, 1996). They are obviously structures of crustal dimensions and relevance, but not thoroughly understood at the moment (Arvidson, 1996).

Postglacial faulting has important implications for predicting the behavior of fault zones during future glaciations. Therefore PG fault research is expected to significantly contribute in planning the disposal of spent nuclear fuel, CO_2 and toxic waste into bedrock that currently is prepared in the Nordic countries. Other fields of applied geoscience which may benefit from PG fault research are mineral exploration and mine stability estimation as some of the faults are located in areas which host Au, Cu and Ni mineralizations in northern Fennoscandia. A gold mineralization has been found along the Suasselkä fault in northern Finland. Major hydropower and tailing dam complexes in northern Sweden and Norway may also be influenced by PG faults and their current earthquake activity. Here the main question is what the long-term effect of small-scale dynamic loading from frequent earthquake activity has on the internal erosion of hydropower and tailing dams. An improved understanding of the prevailing *in situ* stress, Plio-Pleistocene erosion, uplift and sedimentation has also implications for the understanding of offshore fluid migration and sealing properties of petroleum reservoirs on the Lofoten-Barents margin.

Methods applied in PG fault research so far include bedrock and Quaternary field geology, trenching, seismicity, airborne and ground geophysics, and shallow drilling to about 500 m level (see references in Kukkonen et al., 2010). Revealing the mechanisms and processes related to PG faulting is highly relevant for understanding seismicity in these intraplate areas. Several disciplines and approaches can be used to improve our understanding of PG faults, for example through earthquake seismology, stress field measurement and modeling, as well as geodetic surface monitoring of fault activity. Scientific drilling and coring is the only way to obtain direct core samples from PG faults at depth, and the resulting boreholes provide direct access to the fault structures for geophysical, hydrogeological, and biological sampling, monitoring and in situ experiments. Our aim is to initiate a new ICDP project "Postglacial Fault Drilling Project" (PFDP) which would drill one or several deep boreholes into these structures.

We organized the ICDP-supported international workshop "Postglacial Fault Drilling in Northern Europe" in Skokloster, Sweden, 4–7 October, 2010 with thirty nine participants representing eight countries. At the workshop, the status of PG fault research was presented with 28 presentations and posters, and plans were made towards developing a realistic drilling plan. Participants represented basic research, applied geosciences, relevant industries and the radiation authorities.

Major Scientific Issues and Problems

The major scientific questions and tasks of PG fault research were identified as follows:

1. What is the tectonic style, deep structure and depth extent of the PG faults?
2. Are PG faults still active?
3. What are the paleoseismic implications of postglacial faults?
4. Did PG faults reactivate more than once? Is it possible to provide quantitative ages of the tectonic systems hosting PG faults?
5. What are the present and paleostress fields and pore pressure of PG faults?

6. How has the faulting affected the rock properties, structure and deformation in and near the fault surface?

7. What are the hydraulic properties of PG faults, and how did they control fresh glacial meltwater recharge?

8. What is the composition of groundwater (chemistry, salinity, pH, Eh, gas content) in PG faults?

9. Is there a deep biosphere in PG faults?

One of the relevant issues of PG faulting is whether their current appearances really are the result of single earthquake events. The risk and implications of PG faulting to intraplate seismicity in general, and waste disposal repositories in particular, is highly dependent on this. Previous investigations by Lagerbäck and Sundh (2008) suggest that massive land-sliding and seismites in soft sediments occurred concurrently with the faulting. Lagerbäck and Sundh (2008), who based their arguments mainly on the relatively small erosion of the Weichselian glaciation, presented that such dramatic faulting which generated the great PG faults in northern Sweden, very probably did not occur in glaciations earlier than the Weichselian. This interpretation inherently assumes that the ice sheets of previous glaciations have been identical with the latest glaciation in respect of their spatial distribution, extent and duration of ice load. These factors, however, have varied between the Early/Middle Weichselian and Late Weichselian ice sheets (Svendsen et al., 2004), and older corresponding fault structures may be unrecognized.

Workshop Presentations

The workshop presentations can be roughly subdivided into four sub-groups: (1) Geology, tectonics, age determination studies; (2) Seismic structures, seismicity and other geophysics; (3) Stress field, land uplift and plate tectonic forces; and (4) Hydrogeology, hydrochemistry, geothermics and deep biosphere. The participants subsequently discussed the major scientific tasks within these four sub-groups. Prior to these thematic presentations, brief introductions to the PFDP, the Swedish Deep Drilling

Program (SDDP), and ICDP were given by I. Kukkonen, C. Juhlin, and T. Wiersberg, respectively. In addition, S. Hickman gave a presentation of the San Andreas Fault Observatory at Depth (SAFOD) project, and P. Jonsson gave an update on the status of the acquisition of a Swedish core drilling platform. Finally, A. Luukkonen gave a presentation on the regulatory perspective of glacial faulting with reference to disposal of spent nuclear fuel in bedrock.

Geology, Tectonics, Age Determination Studies

O. Olesen provided a review of PG faulting in Norway with special emphasis on the Stuoragurra fault which seems to occur within a Paleoproterozoic duplex structure along the Mierujavri-Sværholt shear zone. A dextral component of the dominating reverse postglacial faulting is indicated by an offset esker and a sag pond between two overlapping fault segments. F. Riis showed results from the Barents Sea on the link between erosion, gas leakage and pore pressure reduction. New observations of land-slides in the area of the Suasselkä PG fault were presented by R. Sutinen. Several talks focused on age determination studies and their potential application to the PFDP by H. Zwingman, J. Jacobs, and G. Viola. Although it is clear that age data is necessary to constrain the history of faulting, these presentations also revealed that there are several difficulties associated with the methods concerning, for example, the rock types and paleotemperatures of the PG faults.

Seismic Structures, Seismicity and Other Geophysics

Available seismic studies presented at the workshop include both active and passive experiments (C. Juhlin, C. Lindholm, B. Lund, I. Kukkonen). B. Lund indicated that some of the faults are associated with current seismic activity with about 80-130 microseismic events/year (*e.g.*, Pärvie and Burträsk faults in North Sweden), whereas others are surprisingly passive (Röjnöret fault). Initial results suggest that focal depths of events extend from the surface to about 30 km in the Pärvie fault, and roughly follow a dip of about 70°SE. Reflection seismic surveys (2D) by C. have indicated distinct reflectors which correlate with known surface expressions of PG faults but there are also reflectors with no obvious PG fault expressions at surface. These may represent a flower structure which joins into one deep fault at 10-20 km, but the seismic reflection data does not extend this deep. Furthermore, the reflection structure may also be complicated with no obvious alternative for the fault plane as in the case of Suasselkä PG fault (I. Kukkonen). This may reflect that faulting has taken place in an environment rich of older zones of weakness. C. Lindholm discussed seismicity in Northern Norway and seismic arrays designed for improving the threshold and quantity of recorded events. J.S. Rønning presented results from ground geophysical investigations of the Stuoragurra faults in addition to new and improved techniques such as 2D resistivity profiling and well logging tools adequate for future studies of postglacial faults.

In addition, S. Dineva showed results from the neotectonic stress field from earthquakes in Canada and T. Torvela presented results on the detection of steeply dipping faults with reflection seismics. C. Lindholm and S. Olaussen presented results from ongoing study on CO_2 storage in Longyearbyen.

Stress Field, Land Uplift and Plate Tectonic Forces

The available stress data from boreholes penetrating or adjacent to postglacial faults is limited to one study in Landsjärv in the 1980's (Bjarnason et al., 1989). C. Pascal presented results from studies of rock displacement at road cuts and blast holes in Norway and obtained a remarkable correspondence to the tectonic stress field. H. Steffen presented modeling theory and results from evolution of stress and fault stability in glaciated areas, with focus on resolving the conditions that lead to earthquake rupture. B. Lund followed with a similar modeling approach on studying glacial isostacy in Sweden. S. Hickman provided interesting views from methodology and results of stress measurements in SAFOD, and S. Dineva showed stress orientations from earthquakes in Canada.

Hydrogeology, Hydrochemistry, Geothermics and Deep Biosphere

T. Wiersberg presented different techniques and results on sampling and monitoring fluids and gas from fault zones during and after drilling, especially from the San Andreas Fault. R. Sutinen presented new data on water geochemistry (elevated As contents) in springs in the immediate vicinity of the Suasselkä fault suggesting a connection with surface discharge and neotectonic structures. PG faults show sometimes strong hydrogeological activity at surface level. A spring of water with anomalous high copper-content occurs along the Stuoragurra fault (Olesen et al. 1992). No other vegetation than the flower *Viscaria alpina* grows in the heavily contaminated soil downstream from the spring. I. Thorseth discussed the biosphere in deep subsurface environments. A key question is which carbon, nutrients and energy sources actually support the deep biosphere. M. Itävaara reviewed a number of deep biosphere studies in crystalline bedrock in Finland, with a special emphasis on the 2.5 km deep Outokumpu deep drill hole. Microbes seem to be ubiquitous in crystalline rocks, but proper sampling techniques and avoiding of surface contamination are essential issues in drilling projects. Geothermal and hydrogeological studies of deep boreholes are important in revealing the flow conditions in the borehole as well as the in the formation and are the key in assessing the dominant heat transfer mechanisms (conduction vs. advection) in the formation.

Workshop Discussions and Views

The workshop participants share the consensus that the main aim for drilling is to penetrate a fault which presently is seismically active. It is also commonly agreed that it would be useful to compare an active fault with a passive one. When defining drilling targets it will be important to locate the fault exactly at depth, but this may be difficult. Even in the shallow drilling of the Lansjärv fault in the 1980's it was not easy to decide where the PG fault actually was because the rock was generally very fractured and broken (Bäckblom and Stanfors, 1989). The PG fault structures at depth are still uncertain and far from being understood.

One of the desires of the participants was to drill into the seismogenic zone of a PG fault. Although the macroseismic activity in Fennoscandia seems to be characterized by focal depths of 10–20 km (Ahjos and Uski, 1992; Bungum and Lindholm, 1997) the present seismic activity of PG faults seems to start from surface, at least in the case of the Pärvie fault (B. Lund, workshop presentation). B. Lund stressed that the data were preliminary, which implies that focal depths may be reinterpreted, and that the shallow data probably include non-seismic events, for example thermally induced noise rather than true microseismicity. Nevertheless, his results indicate that a drilling target into microseismic depths in the Pärvie fault may be at much shallower depths than 10-20 km. The need of seismic monitoring of several faults was considered relevant before the best candidate for drilling can be identified. Many of the PG faults in Sweden have been monitored with microseismic arrays, but there is no such monitoring data of the major faults in Finland and Norway. However, the workshop community foresaw the possibility of arranging new seismic arrays and obtaining new data in the next couple of years. The participants discussed the major scientific tasks in the four sub-groups mentioned above.

Objectives for Geology, Tectonics, and Age Determination Studies

Geological studies should include detailed description of fault rocks and damaged zone. Identification of fault kinematics and individual deformation phases represent critical components. An important aim is to define the pre-fault history by age dating techniques such as Ar-Ar and apatite fission track analysis (AFTA). Later alteration of the fault rocks to clay minerals is also an interesting aspect. In this respect, existing core from shallow drillings could be utilized to provide some base line information. Delineation of the glaciation and deglaciation history is an essential piece when putting together the puzzle of the fault generating mechanism. Limnological studies of lake sediments are expected to provide interesting information for dating of the fault movements.

Objectives for Seismic Structures, Seismicity and Other Geophysics

The workshop session on seismic structures, seismicity and other geophysics attracted the largest group. The conclusion was that determining the mechanics of rupture of PG faults is the major scientific task. In order to resolve this, the geometry, stress state and physical properties such as friction, cohesion, pore pressure/permeability on the fault and in its vicinity needs to be examined. Drilling should be targeted to hit an active part of a PG fault, but a comparative study between active and non-active faults is also an option. It would probably be possible to sidetrack a main borehole to penetrate both types of target in a single fault. In a first attempt, 1–3 shallow boreholes (~1 km) would be instrumented for seismic monitoring, and together with a dense surface network, a high resolution 3-D survey of seismic events would be recorded for defining the final drilling target in a deep (≥2 km) drilling. Assuming that the fault is steeply dipping, the main borehole should be subvertical in the upper part but deviate into the fault at depth. Geophysical studies other than seismic studies would be essential in pre-drilling surveys in characterizing the drilling sites. Standard magnetic and EM airborne low-altitude maps, deep EM soundings and gravity surveys should be utilized. Downhole logging is necessary to provide a representative data set on the magnetic, density, electrical and seismic velocity variations with depth.

Objectives for Stress Field, Land Uplift and Plate Tectonic Forces

Discussions regarding the goal for stress field, postglacial rebound and plate tectonic forces focused around three themes: effective stress field and rock properties, importance of geographic location, and geohazard risk. A suite of objectives were defined within each theme. In addition, we concluded that PG fault drilling will provide general improvements in methods for measuring stress and deformation, and in integration methods. Important geoscientific problems regarding the theme on effective stress field and rock properties are: (1) What are the sources of stress driving PG faulting (e.g., ridge push, uplift, sedimentation); (2) What is the role of PG faults in fluid transport in the crust; (3) How does fluid pressure and permeability vary within PG faults over glacial interglacial periods; (4) How are fluids interacting with faulting; (5) What are the physical controls on timing, magnitude and location of intraplate seismicity; (6) Are these faults unique in time? If so, what was the state of stress and tectonic setting at their formation? Is the crust suffering from fatigue? (8) Can we demonstrate that some PG faults are active, whereas others are not? (9) What physical and chemical controls on current activity (microseismicity and creep) of PG faults (variations in fluid pressure, frictional properties, state of stress, and broader crustal scale rheological properties); and (10) The geometries of these faults are not optimal for the current stress field. Which type of stress field created the faults? What type of faults will be reactivated and why?

Important questions regarding the importance of geographic location are: (1) Is it only Fennoscandia which hosts these types of faults? Are they hidden or non-existent in other countries; and (2) What is the parallel to the Canadian shield, Antarctica, Greenland? The discussion within the geohazard risk theme focused on predicting the potential risk for seismic hazard, and to investigate how factors such as global warming and reglaciation influence the activity of PG faults.

Objectives for Hydrogeology, Hydrochemistry, Geothermics and Deep Biosphere

Hydrogeology, deep biosphere and geothermics were considered to have so much in common that these studies should be carried out in close co-operation. One of the fundamental questions raised was how and at what depth level the surficial diluted fluids change into saline fluids, and what are the hydraulic properties of the faults. Finding out the residence time (age) of groundwater at depth is a fundamental task for hydrogeochemical studies. The current fluid flow in the fault and hosting formation should be modeled and taken into account in deciding the drilling sites. Topographic lows (likely discharge areas) would be more preferable than sites on topographic highs. A deep biosphere is expected to exist in PG faults as microbes seem to be common in crystalline rocks in general wherever proper sampling is carried out (Havemann and Pedersen, 1999; Kieft et al., 2005; Frederickson and Balkwill, 2006). A major issue would be to find out how the microbial life forms vary with depth along the fault plane. The fault may be speculated to have acted as pathway for microbes. Faulting may actually be a fundamental means to open pathways for migration of microbes in the crust. Microbial and hydrogeological studies require special care in selecting cement for borehole stabilization (if required) as well as casing materials. Traditional steel casing releases hydrogen to borehole water when corroded, and the presence or lack of natural hydrogen (a potential source of energy for microbes) is one of the fundamental issues to be solved in hydrochemistry. Contamination cannot be completely avoided but it can be monitored with tracers added to drilling fluid. Geothermal studies in a deep borehole to 2 km depth are expected to reveal considerable vertical variation in heat flow, mainly due to climatic variations in ground surface temperatures during the past 100 ka (Kukkonen and Jöeleht, 2003).

Pre-Site Investigations

A major issue that may be addressed before the start of drilling is if surface studies can reveal whether the fault scarps were formed by one big earthquake of be several smaller ones. Closer inspection of the fault scarps themselves, as well as investigations of the sediment cover using traditional trenching coupled with (C-14) dating would help address this question. Bungum and Lindholm (1997) and Kuivamäki et al. (1998) did comparative studies of the relationship between fault length and fault scarp height of PG faults in Scandinavia, and compared the data with recent large earthquakes. Their approach may be pursued to investigate what the scale effect is for the fault, *i.e.*, if there is a relationship between the size of the earthquake and the size of the fault scarp. Furthermore, drill cores would reveal whether there has been paleodynamic weakening effects (thermal pressurization, frictional melting, *etc*.) related to major periods of faulting in the geological history.

Site survey data that needs to be collected include 2-D and 3-D reflection seismic surveys to identify the geometry of PG faults, passive seismic network data to identify earthquake activity and tomography studies. In addition, additional geophysical measurements such as ground penetrating radar, 2-D resistivity measurements, gravity, magnetotelluric soundings, as well as high resolution topographic surveys with laser scanning (LIDAR) is also needed. Seismic reflection surveys exist for the Pärvie, Suasselkä and Burträsk PG faults, and local seismic networks have been in operation over five years the in the Pärvie and Burträsk PG faults. Drilling of shallow and relatively inexpensive pilot holes may allow characterization and identification of the fault at shallow depths and installation of instruments monitoring microseismicity, which is also recommended for inclusion in the site survey. It is important to expand the seismic surveys and seismic networks to as many of the remaining faults as possible to allow the selection of the best candidates for drilling.

In addition, use of existing data may also improve an ICDP drilling proposal, *e.g.*, synthesizing results on existing cores and their mechanical properties, and reinterpretation of the state of *in situ* and paleo-stresses. Finally, site investigation data can be utilized to calibrate and improve viscoelastic ice sheet numerical modeling within the site survey areas.

Challenges for Drilling

Different strategies of drilling geometry were outlined in the workshop. Assuming that drilling takes place on one fault site only, the alternatives would be (1) to drill only shallow (<1 km) boreholes located on a profile perpendicular to the fault plane, or (2) drill one deep borehole (2-5 km) penetrating the fault at great depth, (3) drill a deep borehole with several shorter boreholes deviating from the main borehole at 1.5–2 km depth, or (4) combine 1–3 shallow boreholes and a deep (2–5 km) one. All alternatives have their pros and cons. Shallow drilling has already been done in several cases (see Kukkonen et al., 2010 for references) and would be an economic and technically relatively easy alternative, but would probably not make a major step forward in PG fault research. On the other hand, drilling only one deep borehole has the risk that we would not necessarily know where the fault really is (unless it is distinctly seismically active), and moreover, in the case of technical failure and uncontrollable borehole instability, the scientific results would be limited. Deviating boreholes (alternative No.3) would be a tempting strategy to collect information of the fault to a distance of a few hundred meters from the main borehole. However, branching boreholes cannot be easily used for logging and cross-hole experiments. Therefore, a possible strategy could be built using option No. 4, which would allow learning while drilling, *i.e.,* modification of drilling plans of the main borehole would be possible from the experience gained in the shallow ones. Such a drilling geometry would also allow cross-borehole experiments and various sampling and monitoring activities *in situ*, and would provide good control of fault properties with depth.

We identified a range of criteria that is helpful to determine the best site for drilling. At the site of drilling, the selected PG fault should: (1) be seismically active over a depth interval that can be reached by drilling and beyond: (2) reveal contrasting geology across the fault to allow unambiguous determination of the fault location; (3) be a site with good logistics capacity; and (4) pre-drilling investigations should suggest the site has a very good scientific capacity, *i.e.,* the majority of research hypotheses should have a good chance to be tested with drilling.

The workshop participants were quite unanimous that drilling into PG faults should be core drilling. However, savings in money and time could be achieved by coring completely only pilot hole(s) (~1 km), whereas a deeper borehole would be cored only at depths greater than the pilot hole. To reach depth, continuous coring is not necessary. On the other hand, core samples are required in many investigations planned, which implies that a carefully balanced drilling plan is needed. It is quite certain that PG faults can be expected to be a technically challenging drilling environment. Previous experience from shallow boreholes has shown that the faults are located in very fractured, sheared and damaged rock. In such conditions, obtaining decent core recovery and securing borehole stability will be a challenge. In practice, wire-line drilling is required with dual/triple tube techniques.

In order to address the scientific problems, a detailed drilling and testing program needs to be developed. The program should include the collection of oriented cores, borehole logging, fluid sampling, stress measurements, and long-term monitoring of strain/tilt, microseismicity, fluid pressure and temperature. Preferred core tests include physical properties (petrophysics), rock mechanical determinations, deformation microstructures, mineralogy and geochemistry, and dating. Good quality and sufficient amount of logging data will be required to allow as complete characterization of the fault as possible. This includes image logs (UBI, FMS), density, resistivity/induction with varying penetration depths, magnetic logs, full waveforms (dipole sonic), and spectral gamma logs.

Unstable boreholes are commonly stabilized with cementing, but cement is problematic for groundwater chemistry and microbial studies. Borehole stability is a limiting factor for many post-drilling activities, such as downhole logging, groundwater sampling and installation of downhole monitoring instruments. Probably a casing needs to be installed at most difficult sections, but casing also limits the access to the rock. Further, casing material may be important for microbial studies as discussed above.

Knowledge of the state of effective stress, especially the orientation of horizontal stresses and their magnitudes would be useful in planning of an optimally stable borehole trajectory.

After drilling the most important measurements are stress measurements, strain/tilt- and microseismic monitoring, fluid pressure and temperature monitoring, borehole image logging and geophysical logging. Hydrogeological and microbial studies require post-drilling time for long-term pumping of fluid and gas. Important laboratory investigations include geological logging, petrophysical measurements, rock mechanic testing, core studies of deformation and fault related microstructures, and to link them to geochemical studies of the core (*e.g.*, fluid inclusion if it exists) and geochronology. These data would help improve the models and quality of viscoelastic ice sheet modeling within the site survey area. The possibility for induced seismicity tests should be investigated.

Potential Drilling Targets

The workshop participants could already identify several potential drilling targets. At the moment the most promising ones would be structures which have long surface scarps, thus indicating crustal scale relevance. The targets should preferably be seismically active, and whose structures have been sufficiently imaged with various geophysical techniques. Seismicity has been monitored already in a number of faults (*e.g*., Pärvie, Burträsk) with arrays designed for PG faults, but many major faults lack monitoring at the moment (*e.g*., Stuoragurra, Suasselkä). An interesting option would be to compare two structures, one showing seismic activity and one devoid of any activity, where the Burträsk and Perviä fault represent active faults, and the Röjnöret fault appears to be inactive.

Identification of the scientifically most optimal drilling targets was not possible with the present data available, and more site-specific studies are needed. Particularly, the Suosselkä and Pasmajärvi faults in Finland, and Stuoragurra fault in Norway would need seismic arrays and networks to be run for about one to two years to be able to decide whether they are active or not. In addition, geodetic monitoring should be started to observe any creep of the faults. Previous work on geodetic leveling and GPS measurements of the Pasmajärvi PG fault, and a regional lineament constraining the fault (Kuivamäki et al., 1998, Poutanen and Ollikainen, 1995) did not show any measurable bedrock movement over a monitoring period of about ten years. Either there is no movement at all, or the movement is below detection limit in the time frame monitored. The result does not necessarily indicate a complete stagnation of the fault, particularly as some earthquakes are located close to the Pasmajärvi area (Kuivamäki et al., 1998).

Conclusions and Road Map Forward

The workshop community considered drilling into postglacial faults a feasible scientific initiative which would lead to a research project with important societal implications. The present state of the art in PG fault studies is very promising for developing an ambitious drilling project. Many PG faults are seismically active, and they may represent structures which release the current plate tectonic stresses accumulating in the Fennoscandian continental plate. Seismicity of PG faults and its temporal and spatial variations were considered key phenomena influencing the scientific aims and future drilling strategy. A concept for the project would be to define a target fault which is presently seismically active, and where the preliminary results of seismic monitoring may suggest that the upper parts of the seismogenic zone could be reached with boreholes shallower than about 3 km. The fault would be investigated with both shallow boreholes (< 1 km) and a deep borehole (maximum 2–5 km). Core drilling is essential for a representative sampling of the rocks at least in the expected depth levels of the fault. Furthermore, a combination of several boreholes would allow a variety of downhole experiments, logging, samplings and monitoring after drilling.

Defining the best drilling site still requires seismic monitoring at several PG faults. Also geodetic monitoring of creep should be carried out, and is expected to provide interesting results on possible creep of the faults. Pre-drilling research is therefore required in these fields, and plans were made in the workshop to realize these goals in the next field season.

The existing shallow cores on Stuoragurra, Pasmajärvi, Suasselkä and Lansjärv faults (see references in Kukkonen et al., 2010) should be re-examined with modern mineralogical and isotope methods. The results would provide important data for borehole planning and predictions of expected conditions at depth. The existing borehole sites should be visited and checked for present condition of boreholes. Open boreholes could be re-logged and the data extended. Pre-drilling science should include re-analysis of stress field measurements which were done in the Lansjärv fault (Bäckblom and Stanfors, 1989; Bjarnason et al., 1989). The original data has been located, saved, and will shortly be reinterpreted (D. Ask, written comm., 2010). In addition, field studies for reconstructing paleostresses of some of the Swedish PG faults is in the planning (A. Bäckström).

Pre-drilling science and gathering of site-specific data sets is estimated to take 2–3 years before a well-defined drilling proposal can be compiled. In the meanwhile information will be disseminated on the Postglacial Fault Drilling Project in international conferences, and working group meetings are planned to be organized in association with the EGU and AGU conferences. The session 'SM2.12 Intraplate faulting and seismicity with special reference to the Fennoscandian postglacial fault province' is arranged at the European Geosciences Union's General Assembly in Vienna, Austria, 3–8 April 2011. We continuously encourage interested scientists to join the project.

Workshop Participants

Workshop participants are shown in Table 1 and a group photo of the participants is shown in Fig. 3.

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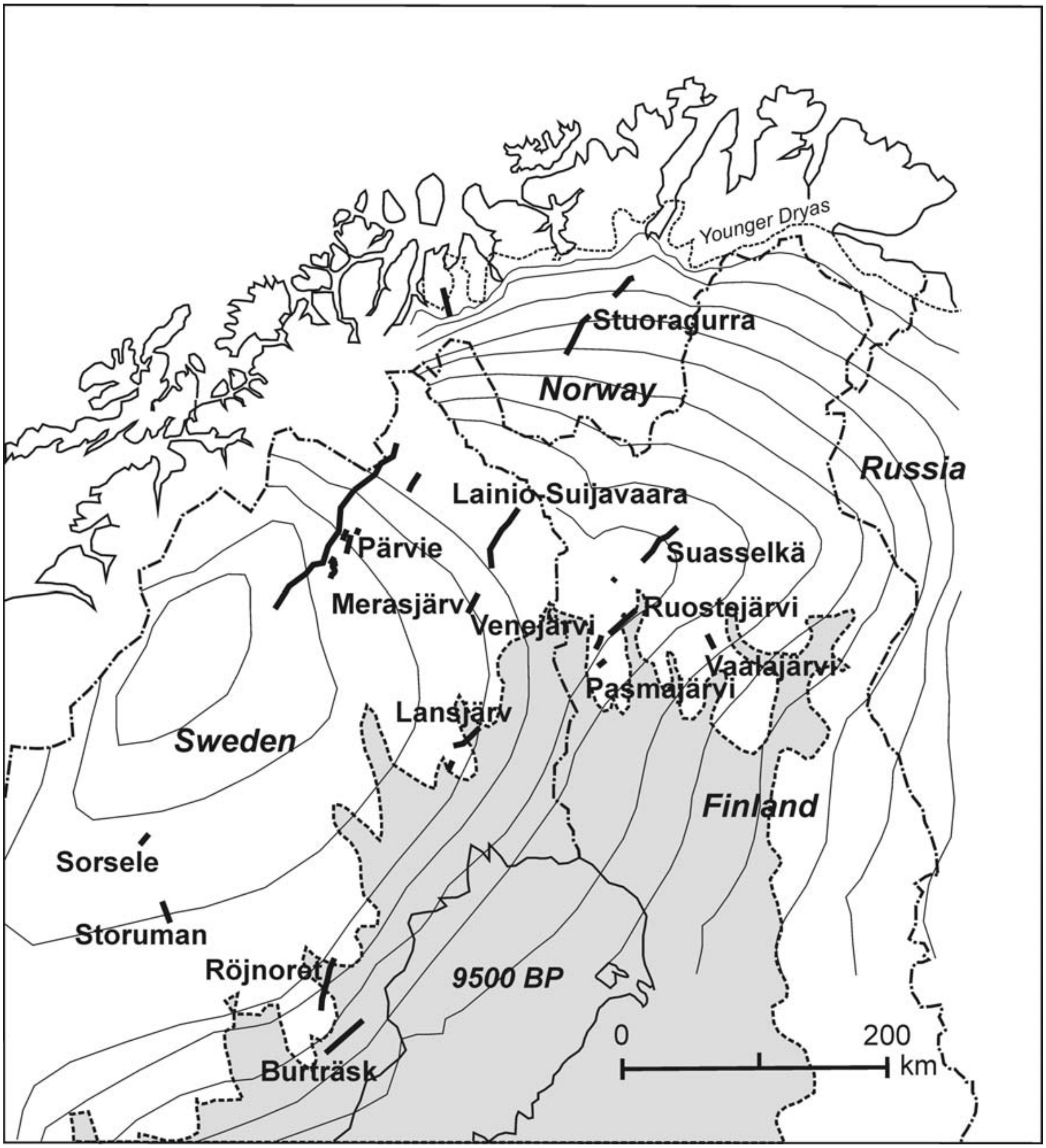

Figure 1. Location of PG faults in northern Fennoscandia (thick lines), and successive ice-marginal lines between ca. 10,000 and 9,000 years B.P. (thin lines). The grey area shows the highest shoreline of the Baltic. Adopted from Kukkonen et al. (2010)

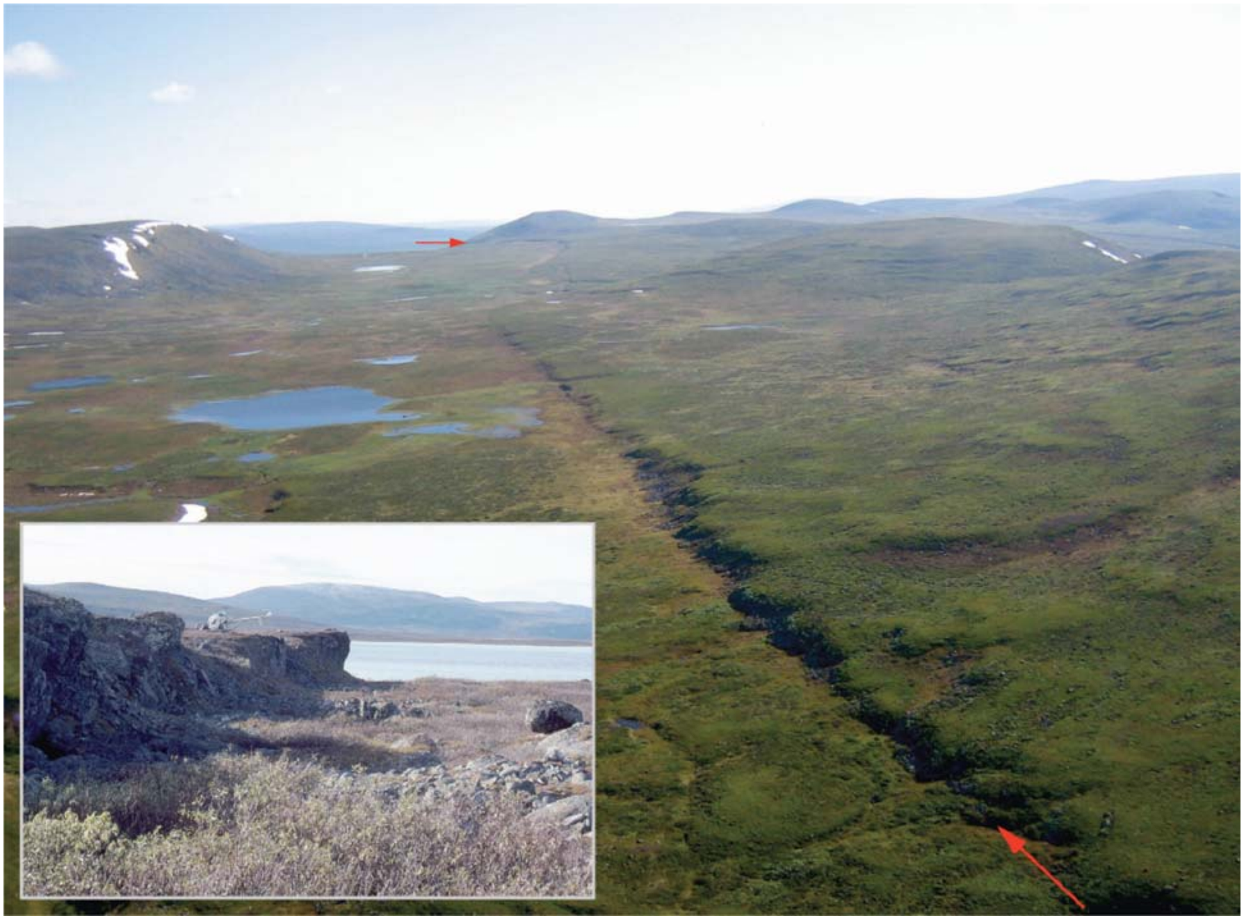

Figure 2. Helicopter view of the southwestern part of the Pärvie PG fault (see Fig. 1 for location). The red arrows show the trace of the fault scarp. The insert shows the fault scarp from the ground surface, about 85 km to the northeast of the location of the large photo, including a helicopter for scale. Photo courtesies: Björn Lund, Uppsala University, Sweden (large photo); and Roger Lagerbäck, Geological Survey of Sweden (insert photo).

Figure 3. Workshop participants

Table 1. Workshop participants

Name	Association	Country
Horst Zwingmann	CSIRO Perth	Australia
Holger Steffen	University of Calgary	Canada
Savka Dineva	Queens University	Canada
Ari Luukkonen	STUK	Finland
Asko Käpyaho	Posiva Oy	Finland
Ilmo T. Kukkonen	Geological Survey of Finland, Espoo	Finland
Juha Karhu	University of Helsinki	Finland
Jussi Mattila	Geolocical Survey of Finland	Finland
Merja Itävaara	Technical Research Centre of Finland	Finland
Pekka Heikkinen	Institute of Seismology, University of Helsinki	Finland
Raimo Sutinen	Finnish Geological Survey	Finland
Hendrik Vogel	University of Colonge	Germany
Thomas Wiersberg	GFZ-Potsdam	Germany
Christophe Pascal	Geological Survey of Norway	Norway
Conrad Lindholm	NORSAR	Norway
Giulio Viola	NGU	Norway
Ingunn Thorseth	Center for Geobiology, University of Bergen	Norway
Odleiv Olesen	Geological Survey of Norway, Trondheim	Norway
Snorre Olaussen	UNIS, Longyearbyen	Norway
Björn Lund	University of Uppsala	Sweden
Christopher Juhlin	University of Uppsala	Sweden
Daniel Ask	Vattenfall Power Consultant	Sweden
Eva Lindblom	University of Uppsala	Sweden
Hans-George Scherneck	Onsala Observatory	Sweden
Maria V.S. Ask	Luleå University of Technology, Luleå	Sweden
Raymond Munier	SKB	Sweden
Taija Torvela	University of Aberdeen	UK
Stephen Hickman	USGS	USA