Veðurstofa Íslands
Report

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Chapter 1

Summary

1.1 Main objectives of the workprogramme

PRENLAB is a two years multinational project of earthquake prediction research, starting early 1996. In this project multidisciplinary European technology and science are applied in a common action aimed at progress in earthquake prediction research and at reducing seismic risk. The questions are "where, when and how" large earthquake ground motions will occur. Answers are sought by studying the physical processes and conditions leading to large earthquakes. Iceland, sometimes called a Natural Geophysical Laboratory, is the test area for the project. The significance of the multidisciplinary approach of the PRENLAB project can be seen in the light of the following. The classical hazard assessment as it has been applied in Iceland and more countries is based mainly on historical documentation and limited information from instrumental earthquake catalogues of this century and a general knowledge of where the earthquake generating plate boundaries are. Although such hazard assessment is extremely useful in many aspects, it has the obvious limitations that it is only based on a few hundreds of years of history, and in fact assumes that we should only expect hazards that are comparable to those which have happened within this short history. Also it does not take into consideration the exact position of and the interaction of faults that are expected to move in earthquakes or earthquake sequences. It integrates effects over large areas in time and space while it is well known that by far the largest destruction is related to the proximity of the faults which are activated in the earthquakes each time and to the areas where the faults rupture the surface.

Hazard assessment based mainly on catalogues of earthquakes and their magnitudes has come to the state that it cannot have more progress:

- Until a better modelling of the fault processes has been achieved.
- Until we can recognize better the involved faults and monitor their movements and interaction.
- Until we can monitor better the stresses in the adjacent area and understand better the rheological properties and the role of fluids in the crust.

For a progress in earthquake hazard assessment and in general for progress in earthquake prediction research we must aim at creating dynamic models which can explain multiplicity of observations, which means that many disciplines of geosciences must be involved.

This is the basis of the PRENLAB project. It is a multidisciplinary approach in earthquake prediction research (Figure 1).

The dynamic models to be created must comply with a multiplicity of observations in time scales ranging from seconds to millions of years, ranging from historical seismicity to

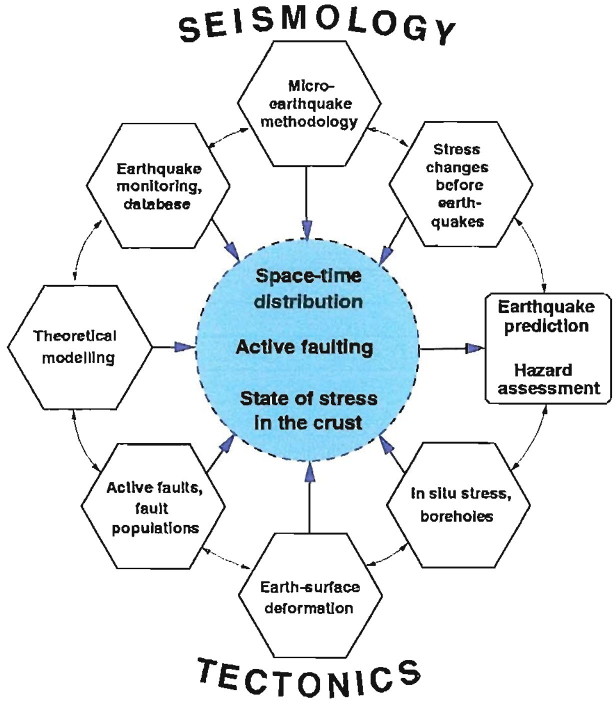

Figure 1: *In the project multidisciplinary European technology and science are applied in a common action aiming at progress in earthquake prediction research and for reducing seismic risk. Scientists from 9 institutions in 6 European countries participated in the project as contractors or associated contractors, and in addition scientists from several other institutions.*

microearthquake information, ranging from geological field observations to observations of deformation with space technology methods and borehole observations. The PRENLAB project collects information, developes methods and models to base further observations on to create a basis for a more general multidisciplinary modelling.

In the workprogramme of PRENLAB the overall objectives were summarized as follows:

- To develop methods for automatic extraction of all information available in the frequent microearthquake recordings, including fault mapping, rock stress tensor inversion, and monitoring of crustal instability.
- To make use of information from microearthquakes, geological information, historical as well as older seismological information for physical interpretation of and modelling the tectonic processes leading to earthquakes.
- To improve the understanding of the space and time relationship between earthquakes and other observable features associated with crustal deformation.
- To apply this knowledge for improved real-time evaluations and alert systems and for improved hazard assessments.

1.2 How the project was carried out

Starting time of the PRENLAB project was March 1, 1996. A start-up workshop was held in The Hague, May 7, 1996, coinciding with the XXI EGS (European Geophysical Society) General Assembly there. The first steps of the project were discussed and the work schedule for the year was detailed. It was very successful to have the contractor meeting coinciding with the EGS meeting at this very start, where the contractors presented their methods and got them tested in the general discussion among the geophysicists of Europe.

The project had a good start. Some subprojects started already March 1 and all got started during 1996, well before the contractor meeting, which was coinciding with the XXV ESC General Assembly (European Seismological Commission) in Reykjavík, September 9–14, 1996. Papers reflecting the progress of all the subprojects were presented there at the various symposia of the conference. The contractors met twice formally, September 10 and 12.

A PRENLAB workshop was held during the ninth biennial EUG meeting in Strasbourg, March 23-27, 1997. Results of PRENLAB were demonstrated in several sessions of this meeting and in Union Symposium 16, about mitigation of geological hazards, the majority of the papers was about the PRENLAB project.

A two days PRENLAB workshop was held in Paris, October 24–25, 1997.

Participants in PRENLAB have attended several meetings besides those mentioned above, in some cases especially invited, to describe results of the project.

The PRENLAB project has been carried out in accordance with the workprogramme. There have been minor changes in priorities of work which are to a large extent do to unexpected increase in data collection capabilities. Thus refinement and easy access to databases lags behind the hopes expressed in the workprogramme. On the other hand much more data have been collected which is extremely significant for the progress of the PRENLAB project and its continuation PRENLAB-2.

The subprojects of PRENLAB have all been finalized in accordance with what was planned in the workprogramme. There were no significant delays in carrying out the projects except Subpart 4B, *Radon related to seismicity in the South Iceland seismic zone*, which was associated to Subproject 4, *Borehole monitoring of fluid-rock interaction.* Task 1 of Subpart 4B, *Build an improved LSC apparatus to measure the radon content of water and gas samples*, was funded by EC. For various reasons this work was delayed compared to what was planned in the workprogramme. It has been successfully finalized now. However, the delay caused delay in reviving the the radon sampling program in South Iceland within the time limits of PRENLAB. This part of reviving of the radon program is cost by Icelandic sources. However, it must be added that significant research work was carried out on the available old radon data for the region, and this work creates a good basis for reviving the regular sampling program, which now can start.

It is of a great significance for the project how successfully the SIL acquisition system has been expanded from the 18 stations that were available for the project at the time of application, to the 33 stations that are now in the permanent network. Although this expansion was not cost by EC funding the existence of the PRENLAB project and the powerful research planned, helped greatly in obtaining the necessary funds for the extension. This adds considerably to the database which is available for the project, and makes Iceland to a much more significant „laboratory" for earthquake prediction research also for other projects. Another addition of a similar type is that 29 broad-band seismic stations are operated temporarily in Iceland during the period of the PRENLAB project and until end August 1998. This is a part of the Iceland Hotspot Project which is run in cooperation between the University of Durham, Princeton University, and the Icelandic Meteorological Office. Geographically the Iceland Hotspot stations are complementary to the permanent SIL network, so it is of a significant benefit for the PRENLAB project to have access to these data.

The PRENLAB project will be directly continued by PRENLAB-2 which started on April 1, 1998. PRENLAB-2 is based on the results of PRENLAB and is a continuation of it.

1.3 Financing and support from other sources

Originally the support requested for this project from EC was 2.2 MECU, but only 500.000 ECU could be provided by EC to a revised project. The question was raised, of course, if it would be right to cut out significant parts of the project to be better able to make progress on other parts of it. It was, however, agreed that it was more worth to keep the multidisciplinary character of the project, so all the main projects were kept in. Evidence has shown that this decision was correct. Among significant items that had to be cut from EC fundings was building of new seismic stations in the existing seismological acquisition and evaluation system, i.e. the SIL system. It showed to be possible to achieve funds from other sources to extend the seismological system, gradually even far beyond the what was planned in the EC proposal. Among others, Icelandic communities and civil defence funds, the Icelandic Government and the Icelandic Research Council could provide a significant contribution to extend the SIL system. The PRENLAB contractors succeeded to obtain financial guarantees from the various institutions and funds for being able to plan realistic projects falling within the objectives of the original multidisciplinary proposal and thus to compensate partly for the cutting of the requested EC support.

1.4 Some significant results

The results of PRENLAB research during 1996-1998 are listed task by task in Chapter 3, related to the projects and tasks as these were described in its workprogramme.

In the following a few significant results are summarized:

- The multidisciplinary cooperation in PRENLAB is a significant progress to be reported. It is not so usual that seismologists, other geophysicists and geologists have cooperated on such a wide basis in projects aiming at seismic risk. In future this cooperation will be still deepened, and gradually more disciplines taken in.

- It has been demonstrated in several studies involving work of seismologists, geologists and geophysicists that it is possible on basis of microearthquakes to map subsurface faults with a great accuracy. A good agreement is between such studies within the project based on microearthquakes and the results of studying the faults on the surface when these are exposed. But new faults have been found and their tilts and sense of motion found in many cases. There are indications that arrangements of individual fault planes of microearthquakes along faults express fluid activity in the faulting process.

- It has been demonstrated that stresses inferred from microearthquakes coincide generally very well with what can be expected, based on paleostress studies of the geologists in this project, and in agreement with results gained from the borehole experiment. One of the problems of interpretation of double-couple focal mechanism solutions of earthquakes is to distinguish between the fault plane and the auxiliary plane of the solution. Methods for doing this have been developed with three different approaches, by comparison with geological fault data, by basing the selection on groups of solutions on the same fault and by applying stability criteria on the possible fault plane solutions for each earthquake.

- Among significant new results that can be reported is that changes of shear-wave splitting at one of the SIL stations in the South Iceland seismic zone (SISZ) indicate changes of deviatoric stress with time. It has been proposed that this may be attributed to the preparatory stage of the eruption in Vatnajökull which started on September 30, 1996. An increase of deviatoric stresses was indicated, starting at the seismic station SAU inside the SISZ about 5-6 months before the eruption, at 160 km distance from the eruptive site. The increase in stress continued until around the start of the eruption. It was suggested that intrusive activity at great depth under the eruption site caused the stress changes. Volumetric borehole strainmeters at two sites in the same area also indicated change in strain rate during the same period of time. The more general interpretation of these findings is that these changes indicate a strain wave going through Iceland during these 5-6 months. These indications may be of enormous significance for understanding strain waves and how these are transmitted. Strain waves have been defined in Iceland on basis of historical observation of clustering in time of large earth activity in an area spanning several hundreds of kilometers. The main problems with explaining interaction between stress release events over long distances are that in the most used earth models, i.e. elastic half space models and similar models, the stresses will attenuate so strongly with distance that the daily changes caused by earth tides and changes in atmospheric pressure would be more effective in triggering earth events than stress changes from earthquakes at a large distance. Therefore it has been proposed that strain waves should be attributed to common source of large intrusive activity deep in the brittle crust or below it which trigger events at sites which are ripe for release. To understand strain waves has relevance both for understanding their sources as well as how they are transmitted. The observations above may be a key to this understanding.

  To be able to explain strain waves physically opens the possibility to predict increased probability for triggering of earthquakes based on monitoring of stress changes from outside of the seismic zones. It is to be pointed out that one of the main pillars for using Iceland as a test area for earthquake prediction was that it would be possible to monitor stress or strain changes caused by measurable pulsations of the Iceland plume. It was pointed out that such understanding would have a consequence in general for understanding how stresses are transmitted in the crust anywhere.

- The geological field studies and interpretations have revealed significant variations in the direction of stress fields in the same area. Such changes have also been indicated in evaluating microearthquakes. Former modelling of historical activity also shows the significance of such changes in time and space.

- A result of a great significance is that it has been shown that it is possible to use satellite radar interferometry for monitoring stable plate motion during a period of a couple of years in the favourable conditions that prevail in Iceland. The relative average plate motion being only of the order of 2 cm per year. This is of enormous significance for constructing a dynamical model of stress build-up in an earthquake area.

  A semicontinuous GPS station in the middle of the SISZ shows significant relative plate motion, compared to a station outside the zone during the first year of the experiment, of 11.5 mm. The motion appears to be in the same direction during the one year of observation, averaging to 1 mm per month. No significant earthquakes have occurred during this time, i.e. the motion is stable for the time being. The result shows how a powerful and significant tool continuous GPS monitoring is in the area. Because of noise with period of the order of days, continuous measurements allow us to see much smaller changes than measurements which are made only on a long-term basis. The results obtained highlight how significant it is to increase the number of GPS with continuous monitoring in the area, both for modelling of the motion around the plate boundary as well as a for alerting about changes that may occur in the stable motion, and to look for concentration in time and space of the observed motion.

- It has been demonstrated on two occasions by observations and modelling how fluid intrusion may trigger earthquakes. In one case this was a magnitude 5.8 earthquake, in the other it was an intensive earthquake sequence. This may be a key to explain or understand foreshocks which are frequently reported before large earthquakes in Iceland.

- The high ongoing seismic activity in the Hengill area indicates many kinds of patterns that may characterize source areas of large earthquakes, like foreshock-mainshock relations and migration of activity. Study and modelling of such patterns in this area may be a key to understand premonitory activity and nucleation patterns in large earthquakes.

- The multidisciplinary observations within the frame of the PRENLAB project are focussed in modelling work of many kinds. Modelling work has been carried out with the purpose of interpreting observations in various fields. An example of this is the modelling of observed tension gashes on the surface following an earthquake, based on knowledge of the upper crustal structure. By this modelling it was concluded that it is possible to draw conclusions about the underlying stress field from open fissures striking a few degrees away from the fault strike.

  Modelling work has been carried out also with the aim of adapting and developing existing methods for the special conditions in Iceland, with its rifting, time dependency of stress field, etc. A model has been created which describes magma intrusion into two layered crust, where the lower layer is of much lower rigidity than the shallower layer. This model which is an earth realistic model for some areas favours the ideas that stress changes from faulting or rifting may cause more significant stress changes at distance than previously assumed.

1.5 Presentation of results at symposia, workshops and in papers

The results already obtained within the PRENLAB project have been demonstrated very thoroughly, as mentioned above, at the XXI EGS General Assembly in The Hague, May 6–10, 1996, and at the XXV ESC General Assembly in Reykjavík, September 9–14, 1996. These conferences gave a good opportunity to demonstrate the first steps taken and the obtained results within the project and to have them discussed among European geoscientists. There were special workshops of contractors and co-workers during both of these assemblies.

There were papers given on all the subprojects of PRENLAB at the ninth biennial EUG meeting in Strasbourg, March 23–27, 1997, especially in Union Symposium 16, *Mitigating geological hazards (risks)*, where 10 oral presentations were directly linked to PRENLAB. A special PRENLAB workshop was also organized during the symposium.

Several results of the PRENLAB project were presented at the 29th IASPEI (International Association of Seismology and Physics of the Earth's Interior) General Assembly in Thessaloniki, August 18-28, 1997. A PRENLAB contractor meeting was also organized there, however, only attended by the seismologists.

A two day PRENLAB workshop was held in Paris, October 24–25, 1997. It was an intensive workshop, where 25 papers were given, followed by discussion.

Before the end of the PRENLAB project abstracts were prepared for the XXIII EGS General Assembly in Nice, April 20–24, 1998. A PRENLAB workshop was organized there to overview the results of PRENLAB and to prepare the first steps of PRENLAB-2 which started as a continuation of PRENLAB, on April 1, 1998.

Some parts of the PRENLAB project or the project as a whole have also been reported at several other symposia and conferences. Besides conferences mentioned here can be mentioned AGU meetings, symposia of Nordic seismologists and a symposium on Long-term Evaluation for Earthquake Occurrence in Japan.

Available papers and reports, which are based on the research within the project have already been published or submitted as can be seen in the publications lists in Chapter 4.

A PRENLAB webpage was opened for presenting especially internal reports or abstracts among the participants. The location is http://bjarg/jar_inn/prenlab.

Main achievements and responsible institutions

2.1 IMOR.DG: Icelandic Meteorological Office, Department of Geophysics

IMOR.DG coordinated the PRENLAB project and was responsible for Subproject 1, *Real-time evaluation of earthquake-related-processes and development of database.* The comitments of the PRENLAB workprogramme as a whole have been fulfilled as detailed below.

The coordinator and contractor was Ragnar Stefánsson. IMOR.DG was responsible for a significant extension of the seismic network available for the project and for operating it. It has done extensive work in extending, refining and standardizing the earthquake databases as well as related databases on slow changes, where continuous borehole strainmeters were most significant. It served the other subprojects with data from these databases. It is also responsible for projects in mapping of active faults, in studying seismicity patterns, in enhancing the alert system in Iceland, for installing and testing new algorithms for data acquisition and for enhancing the automatic evaluation processes. It cooperated closely with all the other subprojects, and through its coordination all the subprojects were well linked together.

Work has been carried out on all tasks according to the time schedule of the workprogramme, although the needs of other partners for an easy access to parts of a new and refined database are ahead of the intensive work going on with refining it. On the other hand the database which it has collected and which it is working on to make it more easily accessible is much larger than originally expected.

2.2 UUPP.DGEO: Uppsala University, Department of Geophysics

UUPP.DGEO was responsible for Subproject 2, *Development of methods using microearthquakes for monitoring crustal instability.*

The contractor Reynir Bödvarsson, UUPP.DGEO, has fulfilled its commitments in the workprogramme, although experience during the period and obtained results have influenced the priorities on individual tasks. Most of the tasks of the project (Tasks 1, 3, 4 and 6) have been finalized some with results beyond expectations. Task 2, *Methods for monitoring the crustal wave velocities based on microearthquake monitoring*, has been very successful in discovering anomalies in the 3-dimensional wave velocity structure which are of enormous significance in understanding the physics of the earthquake zones. This is also a good basis for being able to see possible changes in velocity from microearthquakes, and to understand such possible changes. Task 5, *Methods for statistical analysis of the space/time distribution of microearthquakes and earthquakes*, has had good results as far as concerns the studies of several datasets in some areas. However, the delay in having an easily accessible database available, especially for all the 7 years of the SIL system, still delays pattern recognition work in the dataset as a whole. Thus the approach has been more a physical approach rather than that of discovering general patterns in the dataset. Besides the defined tasks of the workprogramme the contractor has provided significant work in software upgrading of the seismic system which was necessary because of the enormous extension of the SIL acquisition and evaluation system both geographically and in collection of data. This work is very significant for the PRENLAB project as a whole and its continuation.

In all tasks above the closest cooperator was IMOR.DG. Especially concerning continuous GPS the NVI has been the close cooperator, and there has also been much cooperation with UEDIN.DGG in studying shear-wave splitting.

2.3 UEDIN.DGG: University of Edinburgh, Department of Geology and Geophysics

UEDIN.DGG was responsible for Subproject 3, *Monitoring stress changes before earthquakes using seismic shear-wave splitting*. The contractor was Stuart Crampin. UEDIN.DGG has fulfilled its commitments in the workprogramme. It cooperated closely with IMOR.DG. Other significant cooperators were UUPP.DGEO and GFZ.DR.DBL which will contribute by providing data from borehole experiments.

All tasks of this project have been finalized according to workprogramme.

2.4 GFZ.DR.DBL: Stiftung GeoForschungsZentrum Potsdam, Division 5 - Disaster Research, Section 5.3 - Deep Borehole Logging

GFZ.DR.DBL was responsible for Subproject 4 as a whole, *Borehole monitoring of fluid-rock interaction*. Commitments of the workprogramme have been satisfactorily fulfilled.

Subproject 4 was divided into Subpart 4A, managed by contractor Frank Roth of GFZ and Subpart 4B, managed by associated contractor Páll Einarsson of UICE.DG (see 2.8).

All the tasks of Subpart 4A, *Geophysical loggings*, have been carried out in accordance with the workprogramme. Main cooperator with GFZ on Subpart 4A was Valgardur Stefánsson from the Icelandic Energy Authority (OS).

Subpart 4B, *Radon related to seismicity in the South Iceland seismic zone*, was a minor associated part to Subproject 4. One task of Subpart 4B was cost by EC, i.e. *Build an improved LSC apparatus to measure the radon content of water and gas samples.* For various reasons this task was delayed compared to what was planned in the workprogramme. However, it has now been successfully finalized. However, this delay caused delay in reviving the the radon sampling program in South Iceland within the time limits of PRENLAB. This part of Subpart 4B is cost by Icelandic sources. However, significant research work has been carried out and reported on the available old radon data for the region, and this work creates a good basis for reviving the regular sampling program, which now can start.

Subpart 4B of Subproject 4 has been finalized as concerns EC funding. The delay in reviving the regular radon monitoring in the SISZ has been compensated by significant research work on old radon data.

2.5 CNRS.DTP: Centre National de la Recherche Scientifique, UPR 0234 – Dynamique Terrestre et Planétaire

CNRS.DTP was responsible for Subproject 5 as a whole, *Active deformation determined from GPS and SAR*. CNRS.DTP has fulfilled its commitments in the workprogramme.

The Subproject was divided into two Subparts, 5A and 5B.

Subpart 5A, *SAR interferometry*, was managed by contractor Kurt Feigl of CNRS.DTP in close cooperation with Freysteinn Sigmundsson of NVI (see 2.6), and Páll Einarsson of UICE.DG (see 2.8). A very significant collaboration was also with Didier Massonet and Helene Vadon at CNES in Toulouse. Subpart A has been carried out and finalized in accordance with the workprogramme.

Subpart 5B, *GPS geodesy*, was managed by associated contractor Freysteinn Sigmundsson of NVI (see 2.6), cooperating with Reynir Bödvarsson of UUPP.DGEO (see 2.2) and with IMOR.DG. The work has basically been carried out in accordance with workprogramme although there was some reorientation of priorities between the two tasks in accordance with obtained results.

2.6 NVI: Nordic Volcanological Institute

NVI was responsible for Subproject 6, *Formation and development of seismogenic faults and fault populations*, and has fulfilled its commitments in the workprogramme. Subproject 6 was divided into Subpart 6A and Subpart 6B.

Subpart 6A, *Paleostresses*, was managed by associated contractor Francoise Bergerat of CNRS.TT (see 2.9). Cooperative partners have been NVI and IMOR.DG. Rennes in France have also cooperated with CNRS.TT on this project. Other and subpart 6B, *Field and theoretical studies of faults and fault populations*, was managed by contractor Ágúst Gudmundsson of NVI.

Subpart 6B, *Field and theoretical studies of fault populations*, was managed by Ágúst Gudmundsson of NVI. Cooperative partners were IMOR.DG and UUPP.DGEO. Other cooperators have been Helgi Torfason of the Icelandic Energy Authority and UBLF.DF. This subpart has been carried out as planned. There has been more priorities given to South Iceland seismic zone than the Tjörnes fracture zone than indicated in the workprogramme. This was in accordance with obtained results and in accordance with guidelines from the PRENLAB group in general.

Thierry Villemin, Université de Savoie, and Olivier Dauteuil, Geoscience Rennes, both in France have cooperated with CNRS.TT on both subparts of this project.

2.7 UBLG.DF: University of Bologna, Department of Physics

UBLG.DF was responsible for Subproject 7, *Theoretical analysis of faulting and earthquake processes.* This subproject was divided in two Subparts, 7A and 7B.

Subpart 7A, *Crust-mantle rheology in Iceland and Mid-Atlantic Ridge from studies of post-seismic rebound*, was managed by contractor Maurizio Bonafede of UBLG.DF. Close cooperation has been with Maria Elina Belardinelli and Antonio Piersanti of ING in Rome. Subpart A has been finalized in accordance with the workprogramme.

Subpart 7B, *Modelling of the earthquake related space-time behaviour of the stress field in the fault system of southern Iceland*, was managed by associated contractor Frank Roth of GFZ.DR.DBL (see 2.4). Close cooperation was with IMOR.DG.

All parts of Subpart 7B have been finalized in accordance with the workprogramme.

2.8 UICE.DG: University of Iceland, Science Institute

Associated contractor Páll Einarsson (see 2.4).

2.9 CNRS.TT: Université Pierre et Marie Curie, Département de Géotectonique

Associated contractor Francoise Bergerat (see 2.6).

Methods and results

3.1 Subproject 1: Real-time evaluation of earthquake-related-processes and development of database, and coordination of the project as a whole

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Einar Kjartansson was especially hired as a researcher for the project from March 1, 1996, and has been working on it full time from the very beginning. The other researchers mentioned are staff members of the Department of Geophysics. They have carried out 96 manmonths of work for the project during the two years period of the project, paid by IMOR.DG.

3.1.1 Task 1: Database, development and service

Start: March 1996 (month 1)
End: February 1998 (month 24)
Responsible partner: IMOR.DG

3.1.1.1 Task 1.1: Data collection

A very significant achievement within Task 1 is the increase of number of operating seismic stations. In the original application to EC, 12 SIL type seismic stations were requested, to be integrated in the SIL system in Iceland. The SIL system is an automatic acquisition and evaluation system for earthquake data, developed in Iceland during 1988–1995 as a part of an earthquake prediction research project of the Nordic countries, i.e. the so-called SIL project [77]. The cutting of the EC application for the PRENLAB project, however, did not permit any new stations according to our own evaluation. However, it showed to be possible to arrange funds from other sources to build 15 new permanent SIL stations. These stations are as other permanent stations of the SIL network available for the PRENLAB project and are of great significance for it. However, they do not fully complement what was asked for in the original application as they are not all at sites most preferable for the project.

Anyhow, since the start of the PRENLAB project in March 1996, the number of SIL stations in operation has increased from 18 to 33. The new stations are funded by Icelandic communities, hydrothermal and hydroelectrical power companies, civil defence funds, a private tunnel-digging company, the Icelandic Research Council, and indirectly by research groups carrying out tomographic studies, which can make use of the powerful SIL acquisition system. The largest supporter of this build-up project of the SIL system is IMOR.DG/the Icelandic Government, which besides contributions to the initial costs guarantees the operation cost of the system [44, 66, 9, 65].

Preparations are going on to install 5 new permanent SIL type stations in the area around Vatnajökull, i.e. central and SE Iceland, within short. The 1996 eruption in this area including the preparation stage was very well monitored by the SIL seismic system. This made it possible to obtain funds from the Icelandic State to operate 5 permanent stations around the area and thus to fill in a gap in the Icelandic seismological network. Two of these stations are in a very remote area and request special facilities for operation. It is planned that these stations will become operative and an integrated part of the SIL system during summer 1998.

Since summer 1996 to end August 1998, 29 extra digital broad-band stations are operated continuously at remote places not covered by the SIL system, mainly for collecting teleseismic data. This is a part of the Iceland Hotspot project, lead by Gillian Foulger, University of Durham. Among other participants are Princeton University, with Jason Morgan and Guust Nolet, and Bruce Julian of the U.S. Geological Survey, besides IMOR.DG. The waveform information from these stations will be included into the SIL evaluation processes, especially as concerns the local seismic activity. This is a significant addition to the data that according to the original plan can be approached for the PRENLAB project. As the Hotspot Project stations are operated at sites where we have only a few SIL stations they can provide us with a much more general overview about the stress conditions in the country as a whole than would be possible with the SIL system only [27, 28]. Figure 2 shows the locations of the seismic stations operated in Iceland during the period of the later part of the PRENLAB

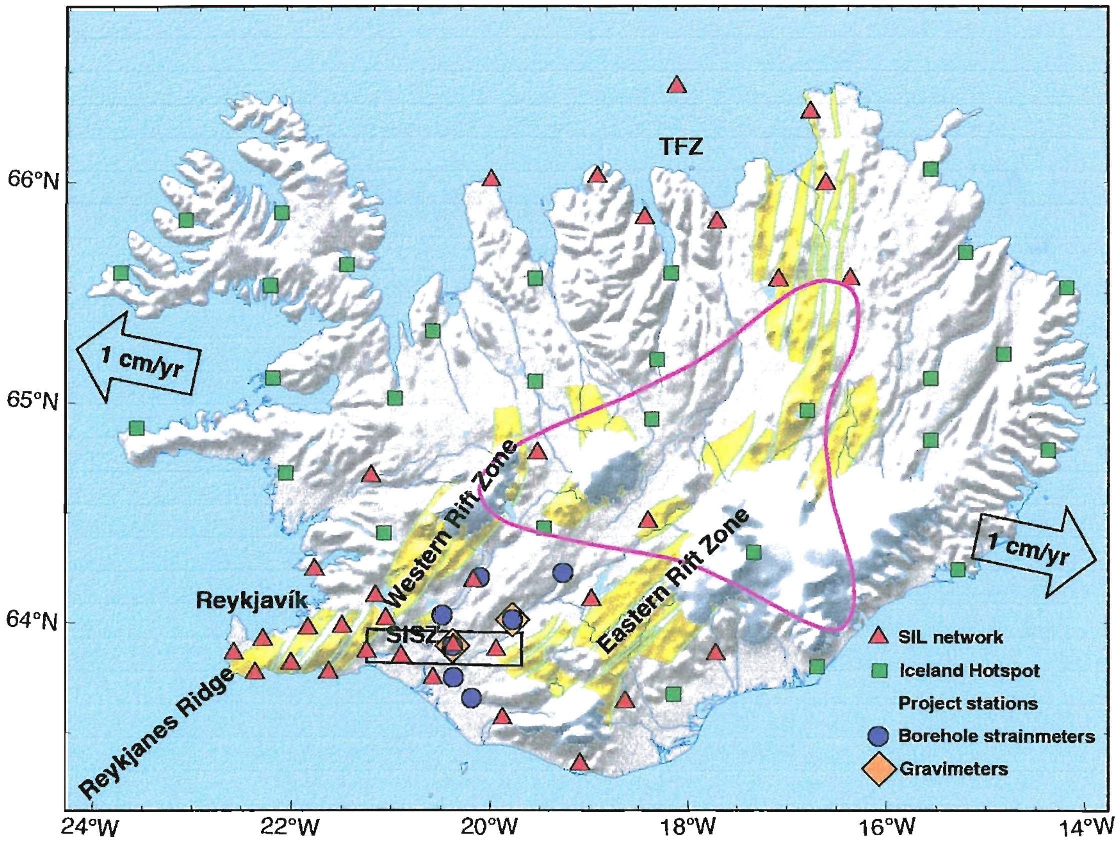

Figure 2: *The available 3 component digital earthquake monitoring in Iceland. The Mid-Atlantic Ridge goes through Iceland from the Reykjanes Ridge along the South Iceland seismic zone (SISZ), the rift zones to the Tjörnes fracture zone (TFZ) in the north. The most destructive earthquakes occur in the transform zones, SISZ and TFZ. The outlines of the Iceland mantle plume at depth are shown in purple. The Iceland Hotspot project stations are operated during 1996–1998. Other stations are permanent. Some other seismological and hydrological monitoring stations are operated too.*

project.

Besides the seismic networks the operation of borehole strainmeters is the most significant continuous monitoring within PRENLAB. 7 Sacks-Evertson volumetric strainmeters have been operated in boreholes in and near the South Iceland seismic zone (SISZ). This is in cooperation with the Carnegie Institution of Washington [5, 8, 80].

An alert system relating to activity in 30 areas within Iceland is in continuous operation.

It is mostly based on the automatic evaluation of the seismological network. The purpose of it is to inform the seismologists instantly if there are changes in the seismic activity which might be a premonitory activity before larger earthquakes or volcanic eruptions. It also serves the purpose of making the data collection better, because sometimes it is necessary to take special actions when activity increases in some area. The functions of the alert system are gradually improved as a result of experience and outcome from the ongoing scientific research [6].

3.1.1.2 Task 1.2: The database access

Here we discuss in general the availability of data which are significant for PRENLAB research, and which are collected and evaluated by IMOR.DG. Also we discuss ongoing work in making these data gradually more easily available.

A refined and easily accessible database for SIL data is under construction. Since 1991, 100.000 earthquakes have been recorded by the SIL system. The data were automatically evaluated and manually corrected. Facilities have been developed to store all the data on-line on hard disks. Because of the enormous amount of data they have to be compressed very much, to make this practically possible. Seismogram data in digital form is stored using packed binary format, where only the number of bits that is required to store sample to sample variation is stored. Parameter data of events are stored in relational database tables, which contain all parameters of the events, both observed parameters like onset time of phases and amplitudes as well as calculated parameters such as hypocenter location, magnitude and fault plane solution.

Other data is stored in relational database tables. Station parameters such as coordinates, instrument characteristics and time corrections are stored in separate tables. This information is incorporated into headers when data are extracted from the database [51].

In order to insure against loss of data, procedures and facilities have been developed to back up all data onto magnetic tapes. All new data and modifications are written to tape each day and all data are written to tape approximately every two weeks. Periodically, a set of tapes is moved for storage to a different site. As magnetic tapes only last a few years, and the long-term stabilty of optical storage media is not well established, this is possibly the most effective way to permanently preserve the data, and it has the advantage that the data is always readily accessible.

An interface to the database through the World Wide Web is in operation. Currently anyone with access to the Internet can search through a list of over 65.000 earthquakes that have been manually checked since January 1, 1995.

Data from the SIL database have been provided to the various projects of PRENLAB as requested. It has not yet been possible to provide data in standardized form covering the whole of the SIL period, i.e. since 1991. This is, however, very significant for pattern recognition research. It is aimed at that this will be possible shortly and for this purpose reevaluation of old automatic data is being speeded up as much as possible.

Work has been carried out for a new, reevaluated and refined catalogue of earthquakes in Iceland since 1926. The catalogue from 1926–1963 has been reevaluated and put on digital form. The refinement of the more recent catalogues is in progress [39].

Work has been carried out for refined estimation of magnitudes and locations of historical earthquakes as well as felt events, not instrumentally detected since 1926 [36].

A long-term overview (since 1979) of 7 volumetric strainmeters in the SISZ has been worked out. Methods have been developed for correcting the strainmeter record for weather influences [5]. As a result of this work change in strainrate 5–6 months before the start of the 1996 eruption in Vatnajökull was discovered, which has been proposed to be caused by magma intrusion there, i.e. more than 150 km from the strainmeter stations [79].

Basic evaluation was carried out on the seismic activity related to the volcanic eruption in Vatnajökull, especially as concerns hypocenters and mechanism of the earthquakes. Much effort was put in saving data on this remarkable eruption from the seismic networks, both earthquake data as well as data on volcanic tremor. Vatnajökull is directly above the center of the Iceland mantle plume and changes of the plume activity greatly affect the seismicity along all of the plate boundary in Iceland, and is thus of a great significance for the PRENLAB objectives [78].

Although the SIL system is a seismic data acquisition system, that is primarily designed for automatic acquisition and evaluation of data from local microearthquakes, it can also be used for collecting teleseismic and regional data for deep structure studies. It broadens the scientific use of the network and has made it easier to obtain funds for extending the network to a large part of the plate boundary in Iceland. The SIL station software has now been modified allowing for selection of waveform data at 20 and 4 samples per second in addition to saving data at 100 samples per second, which is routinely done. This makes it economically possible to save long time intervals of seismological data from the SIL stations. An automatic procedure has been developed to select and store teleseismic data in the SIL system, based on USGS/NEIC information on teleseismic events in the whole world, which are measurable in Iceland. From USGS/NEIC we receive E-mail messages with a single-line information on earthquakes they have determined, the so-called „E" type messages. A selection program reads the messages and selects events that fulfill certain criteria of magnitude and epicentral distance. The program uses the IASPEI91 model to compute the first arrival time at each station. The teleseismic body wave data are fetched with a sampling rate of 20 samples (in some cases 100 samples) per second and the surface wave data with sampling rate of 4 samples per second from the 1–3 days long ringbuffer of the SIL site stations. Since mid-year 1996 waveform data from 230 teleseismic events have been stored by this automatic procedure [34].

A real-time filter has been introduced into the on-line process of the SIL system, to be tuned for detecting harmonic tremor and signals which now are not identified automatically. The continuous seismic signal at the SIL site stations is bandpass filtered at 0.5–1 Hz, 1–2 Hz and 2–4 Hz and the 1 minute mean amplitude is scanned and sent to the SIL center. Visual presentation of this data gives a useful indication of the multiplicity of activity in real-time. This data has been calibrated and procedures developed to estimate magnitudes of local events larger than magnitude 2, independent of the waveform processing [52].

The extension of the SIL system into the highlands of Iceland has lead to many problems in the automatic detection and analysis which are gradually being solved. The SIL system was developed for use in the seismic zones. Automatic monitoring in the highlands revealed in many ways new problems because the crustal structure is not as well known and the earthquake sources are often more complicated. Much work has been carried out to lower the detection threshold for earthquakes in Central Iceland to be able to acquire more information from microearthquakes in this area. The new real-time filter mentioned above is significant for this purpose as well as further tuning of all detection parameters [41].

Work has started on a method to use cross-correlation of waveforms to accurately and automatically determine onsets and classify earthquakes in cooperation with UUPP.DGEO. There has been close cooperation with Uppsala in various other fields, such as stress tensor inversion procedures and mapping of faults.

Work has been carried out to overview the state of knowledge and modelling in the areas of catastrophic earthquakes in Iceland, the SISZ, the Reykjanes Peninsula and the north coast of Iceland [81, 82, 83].

3.1.2 Task 2: To map seismically active minifaults of the seismic fault systems

Start: March 1996 (month 1)
End: February 1998 (month 24)
Responsible partner: IMOR.DG
Cooperative partners: UUPP.DGEO, NVI

Provided the time accuracy of the seismic data of the SIL system, close to 1 millisecond, active faults can be mapped with accuracy of the order of 10 meters. Fault plane solutions based on spectral amplitudes of P- and S-waves are then used as a part of the mapping to reveal the sense of the fault motion. Several special fault mapping efforts have been carried out related to ongoing earthquake sequences in other parts of the country, so gradually information on fault arrangement in different parts along the plate boundary is being collected [68].

Very significant results have been obtained in using seismological data for mapping active earthquake faults in the Tjörnes fracture zone at the north coast of Iceland (Figure 3). The method used is a multievent method based on cross-correlating similar signals at the same seismic station [67, 63].

Similar research has been carried out for the Hengill triple junction in SW-Iceland. Fault plane solutions of more than 20.000 earthquakes have been studied in the area and faults have been mapped by multievent location procedure (Figure 4) [64].

3.1.3 Task 3: To search for time and space patterns in the multiplicity of information in the SIL data

Start: June 1996 (month 4)
End: February 1998 (month 24)
Responsible partner: IMOR.DG
Cooperative partners: UUPP.DGEO, NVI

Results have been obtained on basis of investigation of recent high seismic activity near the Hengill triple junction in SW-Iceland, spatial and temporal variations of activity have been studied and migration within the area (Figure 4) [64, 69].

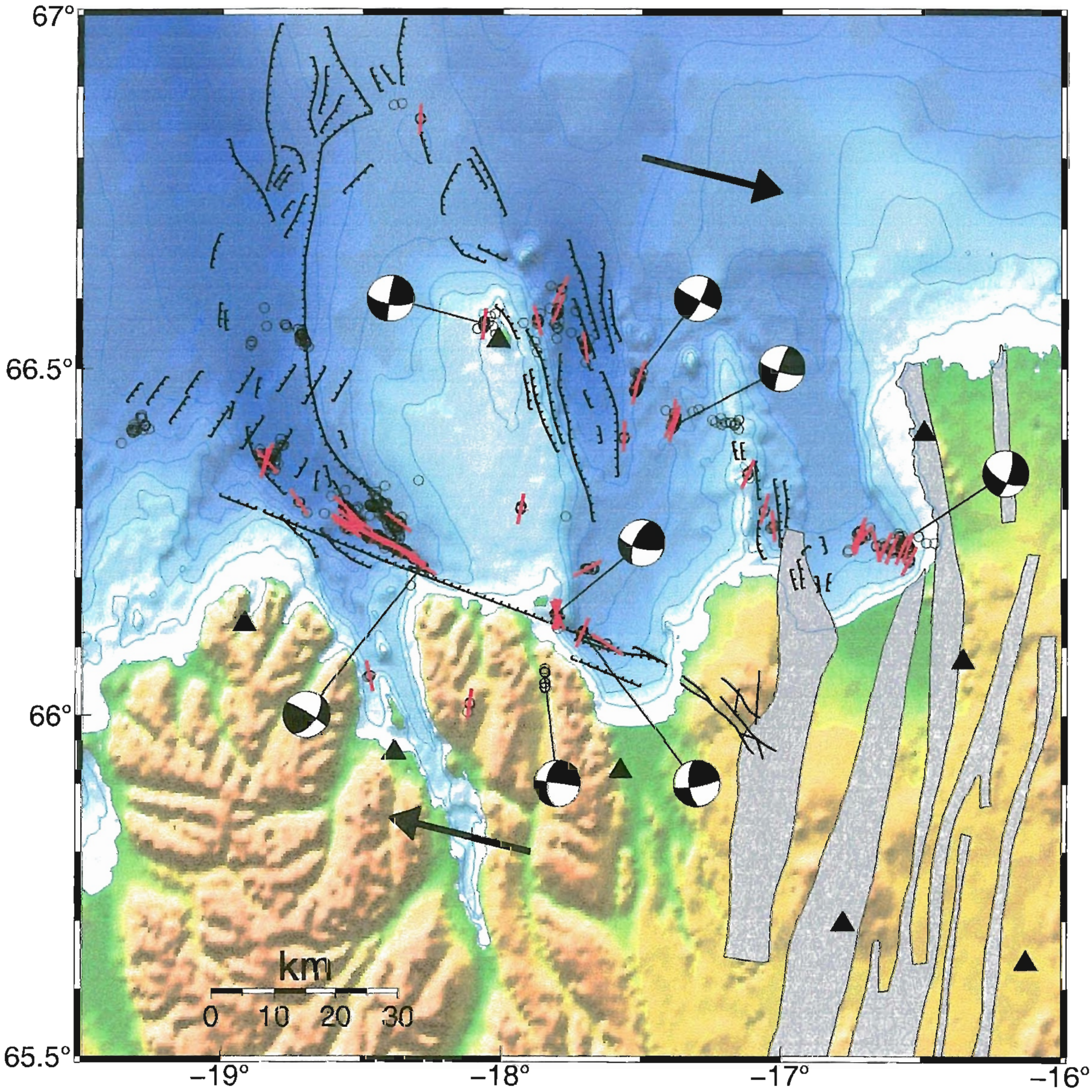

Figure 3: *Mapped faults within the Tjörnes fracture zone off the north coast of Iceland. Black lines indicate faults mapped with conventional reflection seismic methods or by direct observations on-land. Red lines are 60 active fault segments mapped using accurate relative locations of microearthquakes recorded by the SIL network. Seismic stations are denoted by triangles. Grey patches are fissure swarms in the Eastern volcanic zone. The depth contour interval is 100 m.*

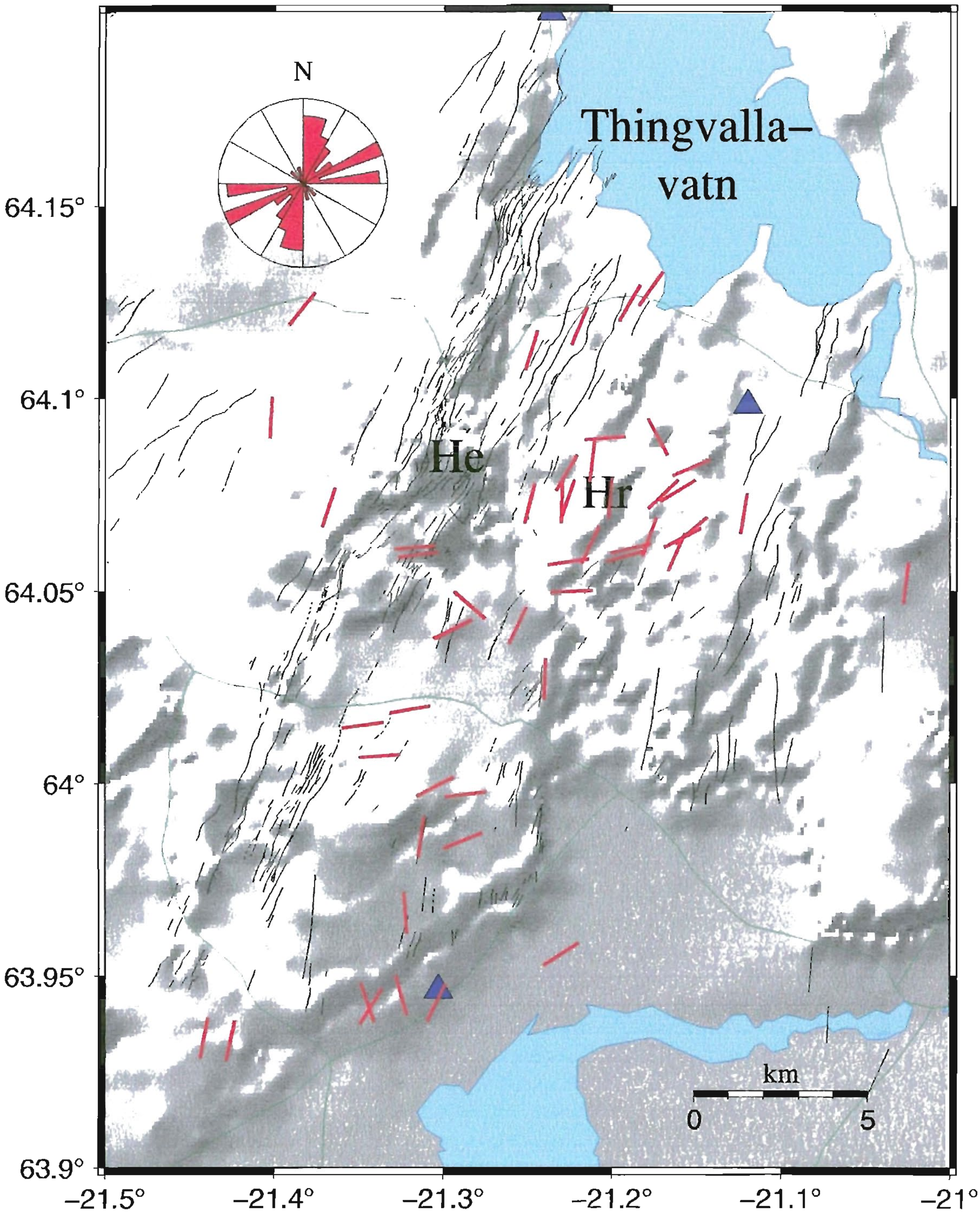

Figure 4: *Earthquakes in the Hengill volcanic area, SW-Iceland. The red lines show the location and orientation of fault planes estimated from the relative location of earthquakes. The black lines are mapped surface faults, green lines are roads. The inset rose diagram shows the orientation of the faults mapped using accurate relative locations of earthquakes.*

The seismicity of Katla volcano which is beneath the Mýrdalsjökull glacier has been studied. Eruptions in Katla pose a considerable danger because of enormous water- and mudflows which accompany the eruptions. It is one of the objectives of the SIL network and the attached alert system to help to warn for the the future eruptions [33].

Spatial changes in seismicity have been studied in an area along the Reykjanes Peninsula, the South Iceland Lowland, into the eastern volcanic zone, and off coast of North Iceland [37, 55, 71].

Work has been carried out to find 3–D crustal velocity structure in SW-Iceland from local earthquake tomography in cooperation with UUPP.DGEO [86, 87].

Based on historical data and recent historical data research work has started on known earthquake premonitory changes [75].

Much work has been carried out in interpreting data from volumetric borehole strainmeters, which has lead to very significant results. Premonitory and coseismic changes, volumetric strain, and foreshocks of the magnitude 5.8 earthquake at Vatnafjöll, near the eastern end of the SISZ, have been studied. These can be interpreted and have been modelled as magmatic fluids intrusion coinciding with the foreshocks and the main shock [5, 8].

3.1.4 Task 4: Introduction of new algorithms into the alert system and other evaluations of the SIL system

Start: June 1996 (month 4)
End: February 1998 (month 24)
Responsible partner: IMOR.DG
Cooperative partner: UUPP.DGEO

The basic option of the SIL seismic system techniques is to use microearthquakes to bring to the surface information from the source areas of earthquakes. Based on detailed microearthquake analysis it is possible to monitor active faults and movements on these, as well as stresses and stress changes in their surroundings. The smaller the earthquakes are which can be used the closer we are to continuous monitoring of such features, and the more detailed information we obtain of the spatial conditions. Therefore it is so significant to be able to obtain automatically as detailed and secure information as possible [41, 43, 22].

A new software tool is being developed, ACIS, to be introduced into the automatic procedures of the SIL system. ACIS is an acronym for *Reducing manual checking by Automatic Correlation of Incoming Signals.* As has been shown in the work on multievent analysis for detailed mapping of faults most seismic events correlate well with each other within some areas. A geographically indexed database is being created where different classes of earthquakes are stored. As new earthquakes are recorded by the network, the system automatically looks for similar waveforms in the database, and if found, takes the onset and the first motion direction picks from there. If no existing entry in the database correlates with the new event, the event is checked interactively by the network operators. This approach will improve the accuracy of the automatic analysis and reduce the need of work for interactive checking of the data without loss of useful signals. Preliminary testing has demonstrated that the approach described here is possible. It is expected that the first version of the algorithm will be ready for testing within the SIL system in October 1998. It is the intention that after testings it will be introduced in the routine procedures of the SIL system and thus become a basis for enhanced alert detector algorithms. One of the consequences of a more accurate real-time hypocenter location is that real-time fault plane solutions will be much more reliable, making real-time monitoring of stress changes from microearthquakes possible in practice [22].

Work has been carried out for studying and refining the alert thresholds for the SIL related alert system in Iceland. An alert detector monitoring directivity, large amplitudes and background noise in both unfiltered and filtered bands of the seismic waveform data is operated on all the SIL stations. It has been tuned for different types of sensors as the SIL system operates according to need with 1 second, 5 seconds and broadband sensors [6, 7, 42].

The continuous seismic signal at the SIL site stations is bandpass filtered in three channels and the 1 minute mean amplitude is calculated and sent to the SIL center, where the interpretation of characteristics of the tremor is carried out and linked to the alert system. These frequencies show to be useful in discriminating noise of different origin. The lower frequencies are typical for harmonic volcanic tremor, while the highest frequency seems to be expressing noise created by very intensive activity of very small earthquakes, although these are not discriminated as such. Such an activity is more typical in the approaching of an eruption and may possibly be of significance in the introductionary phase of earthquakes. Much work remains to be done to analyze the noise and how it is related to other activities of the crustal forces. This noise monitoring is already now used to monitor volcanic activity [52].

The experience described above also provides a good basis for ongoing work in designing a new detector in the SIL system which will be aimed at detecting and automatically evaluating complicated earthquakes (i.e. slow quakes having corner frequencies of the order of 1 Hz or earthquakes which appear as composed of low and high frequency motion) which are often observed in Iceland, especially from areas close to the volcanoes. A graphic tool has been developed to help visualizing the effects of changing the triggering parameters and algorithms of the detector. This tool is very significant and efficient for the ongoing development of the new detector algorithms. This work is carried out in close cooperation with UUPP.DGEO.

3.1.5 Meetings and conferences

Here the research workers at IMOR.DG are listed and which PRENLAB workshops and other scientific meetings they attended during the period of PRENLAB. At these occasions they presented results of PRENLAB and participated in discussions about the PRENLAB work.

Ragnar Stefánsson attended the XXI EGS General Assembly in The Hague, May 6–10, 1996, and the PRENLAB contractor meeting which was held there.

Ragnar Stefánsson attended the XXV ESC General Assembly in Reykjavík, September 9–14, 1996 (president of the Local Organizing Committee), and one of the two PRENLAB contractor meetings held there. He was a convenor of the special EC seismic and volcanic hazard meeting which was held there including coordinators of other ongoing EC seismic risk projects. Besides him the following researchers at IMOR.DG attended the second contractor meeting of PRENLAB in Reykjavík: Sigurdur Th. Rögnvaldsson, Páll Halldórsson, Kristján Ágústsson, Einar Kjartansson, Gunnar B. Gudmundsson and Steinunn S. Jakobsdóttir. All these PRENLAB researchers also attended in general the ESC Assembly and presented papers there.

Ragnar Stefánsson attended the ninth biennial EUG meeting in Strasbourg, March 23-27, 1997 and a PRENLAB workshop which was organized there on March 27. In fact Union Symposium 16 of EUG 1997, *Mitigation of Geological Hazards*, was a part of the PRENLAB workshop as majority of the papers at this session was about or related to PRENLAB. This session was partly based on an initiative of the PRENLAB coordinator, Ragnar Stefánsson.

Ragnar Stefánsson attended the 28th Nordic Seminar on Detection Seismology in Helsinki, June 16–18, 1997, and met with the PRENLAB contracor of Subproject 2 in Uppsala for discussions on the way.

Sigurður Th. Rögnvaldsson cooperated in Uppsala, from May 30 to June 8, 1997, with researchers within Subproject 2 for development of the ACIS software.

Ragnar Stefánsson, Steinunn S. Jakobsdóttir and Kristján Ágústsson attended the 29th IASPEI General Assembly in Thessaloniki, August 18–28, 1997, and a seismologist PRENLAB workshop which was held there on August 26.

Ragnar Stefánsson was invited by Science and Technology Agency of the Prime Ministers Office, Japan, to attend a symposium on Long-term Evaluation for Earthquake Occurrence held in the Prefecture of Shizuoka, Japan, October 20–22, 1997.

Ragnar Stefánsson, Páll Halldórsson and Sigurdur Th. Rögnvaldsson attended a two day PRENLAB workshop in Paris, October 24–25, 1997.

Ragnar Stefánsson attended the workshop Development of a Multiborehole Observatory which was held in Athens, October 26-28, 1997.

Ragnar Stefánsson attended Review Meeting on Seismic Risk in the European Union in Brussels, November 27-28, 1997.

Einar Kjartansson attended the American Geophysical Union fall meeting in San Fransisco, December 8–12, 1997.

3.2 Subproject 2: Development of methods using microearthquakes for monitoring crustal instability

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The SIL microearthquake system produces detailed results of automatic analysis of large number of microearthquakes. To be able to work efficiently with this kind of information a special interactive program had previously been created. During the PRENLAB project, this software has been developed further and now accepts the results from single event location, multievent location, fault plane solutions and from rock stress tensor inversion as input. The program can be used for steering results from one analysis to another, for example the relative locations can give constraints on the fault plane orientation which can be used in the input for both fault plane solutions and rock stress tensor inversion. The development of this interactive software has also required modifications in all other software to facilitate the information flow between the different algorithms. In addition to what is written below, the UUPP.DGEO research group has been involved in further development of the SIL data acquisition system ranging from further development of the phase detector at the sites to the on-line multistation analysis and the multievent analysis. A new approach is being taken regarding the automatic operation of the network based on the positive results of the correlation techniques used in the relative location algorithm. Work has been initiated within the PRENLAB project to develop software for using cross-correlation of neighboring events to automatically determine the onsets of P- and S-phases with accuracy comparable to or better than achieved in the interactive analysis. The aim is to reduce the need for manual inspection of seismograms from local and regional earthquakes and to improve the quality of the readings in the microearthquake database [22]. This work is done in cooperation with the research group at IMOR.DG.

3.2.1 Task 1: Methods for subcrustal mapping of faults

Start: March 1996 (month 1)
End: July 1996 (month 5)
Responsible partner: UUPP.DGEO
Cooperative partner: IMOR.DG

The algorithm for absolute and relative location of microearthquakes has been implemented in the SIL system routine analysis. The software has been applied in a search of crustal faults, both in the Tjörnes fracture zone (TFZ) and the South Iceland seismic zone (SISZ). This work has been in cooperation with geologists within PRENLAB. Faults found from the microearthquakes show a remarkable agreement with the fault information available from sea bottom and land surveys [67]. These studies also indicate the power of the multievent location technique for discriminating the fault plane and the auxiliary plane. An example of the results using this algorithm is shown in Figures 3 and 4.

3.2.2 Task 2: Methods for monitoring crustal wave velocities from microearthquakes

Start: July 1996 (month 5)
End: October 1997 (month 20)
Responsible partner: UUPP.DGEO
Cooperative partner: IMOR.DG

Selected from the SIL seismic database, 6200 local earthquakes have been used in a tomography study of the 3-D P- and S-wave velocities and hypocentral locations beneath SW-Iceland [86, 87]. The study region is a 224×112 km^2 rectangular area. Major tectonic features within the study region include the SISZ, the Hengill volcanic system, the Western volcanic zone (WVZ), and the Reykjanes volcanic zone (RVZ). The velocity model block size used was 4×4 km horizontally and 1 km vertically, resulting in detailed velocity models. The resulting velocity structures are well constrained down to depths of 10–12 km. Figure 5 shows a horizontal slice through the models between the depths of 6 and 7 km. The main results of the interpretation are:

- A large low-velocity anomaly is found at depths between 4 to 12 km beneath the Hengill volcanic fissure system. Both P- and S-wave velocities are low, but the reduction in the P-wave velocity is larger than in the S-wave velocity, suggesting that the anomaly is not caused by large portions of partial melt. The observed anomaly is interpreted as a heavily fractured volcanic fissure system and the low velocities are caused by supercritical magmatic fluids (CO_2 and H_2O) which are migrating in the fracture system. Theoretical calculations of the elastic moduli for a porous medium, using both magma saturated pores and supercritical water, support this interpretation.

- The SISZ has normal velocities with a tendency towards lower than normal V_p/V_s ratios (1.75). A slight increase in the depth to the lower crust (P-wave velocities of 6.5 km/s) is observed along the SISZ from west to east, from less than 4 km to below 5 km.

- In the depth range 5–7 km, lower than normal P- and S-wave velocities are observed in the center of the RVZ. A tendency to increased V_p/V_s ratios is observed at 4–8 km depth beneath the Krísuvík volcanic system, which might be caused by elevated temperatures.

- The depth to the base of the brittle crust in the study area, defined as the depth above which 90% of the earthquakes occur, varies from about 5 km in young (0–0.7 My) crust near the RVZ and WVZ to about 12 km near the eastern end of the SISZ. This corresponds to the estimated depths of the 600°C isotherm.

- Clusters of earthquakes deeper than the base of the brittle layer occur beneath the Hengill and Eyjafjallajökull volcanoes. These earthquake sequences may be associated with periods of unusually high strain rate in the roots of the volcanic systems.

3.2.3 Task 3: Methods for monitoring the local rock stress tensor

Start: July 1996 (month 5)
End: January 1998 (month 23)
Responsible partner: UUPP.DGEO
Cooperative partners: IMOR.DG

New methods and software have been developed to estimate a regional or local stress tensor based solely on microearthquake focal mechanisms and locations [53]. The inversion method is based on the work of Gephart and Forsyth [29] with significant changes in the treatment of focal mechanisms and in the criteria of choosing the correct fault plane from the two nodal planes. The inversion algorithm is implemented in the SIL system environment, takes full advantage of the SIL software for focal mechanisms [62] and for absolute and relative location [73] and is compatible with the visualization software.

We invert the focal mechanisms to obtain the directions of the three principal stresses and, $R = 3D(\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$, a measure of the relative magnitude of the intermediate principal stress. We use a grid search over the lower hemisphere for the directions of the principal stresses and the size of R. For each stress tensor the direction of shear stress on the

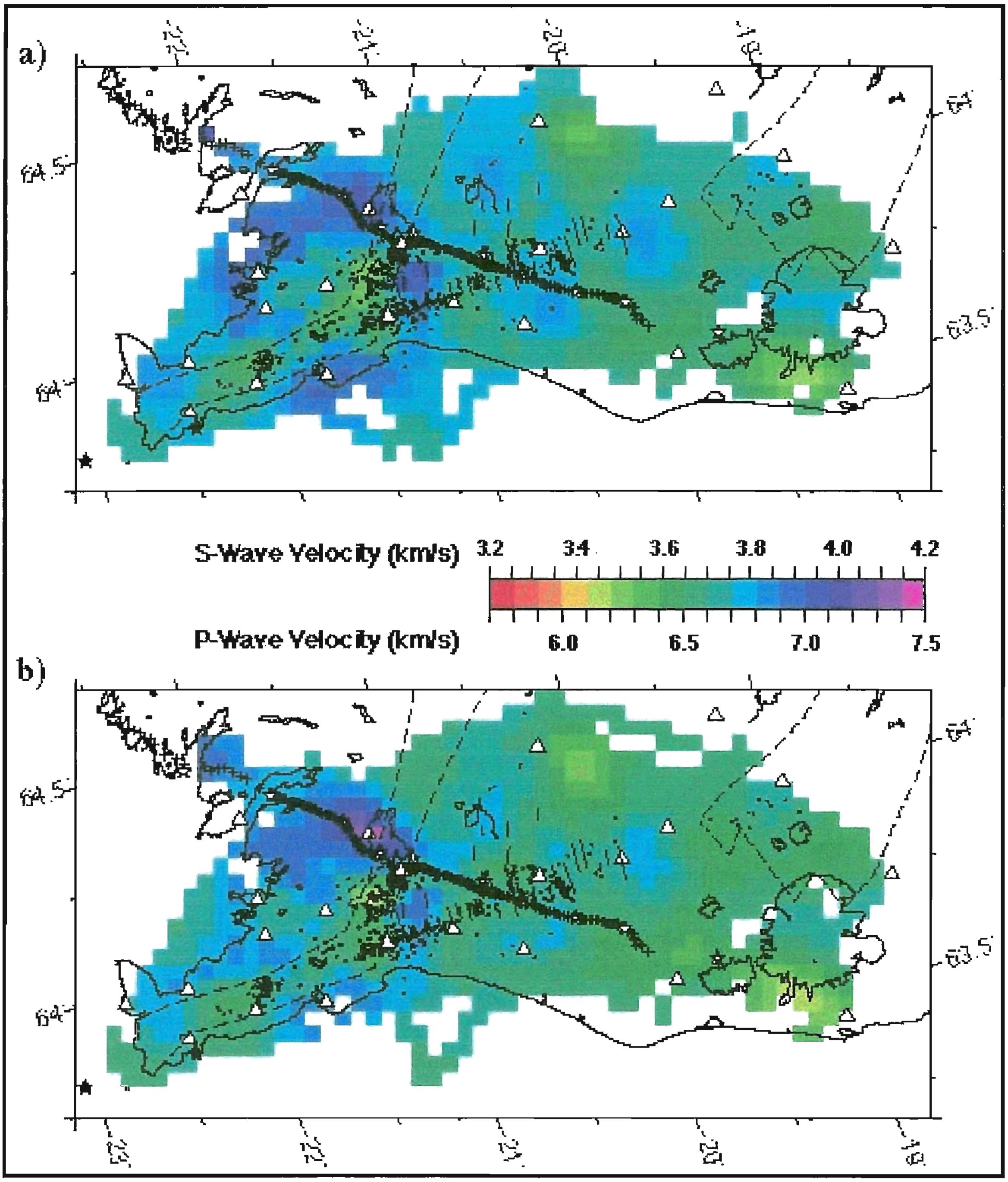

Figure 5: *Horizontal slices through the models at 6–7 km for a) the S-wave velocities and b) the P-wave velocities. Model blocks without any ray travelling through them are white. Earthquakes occurring within the layer are shown. The thin stippled lines outline the volcanic zones.*

nodal planes are calculated and we minimize the angle, in the plane, between the observed slip direction and the theoretically calculated shear stress direction in the inversion. The misfit angle is used as the objective function to be minimized and can be weighted with the amplitude errors on the focal mechanisms, with dynamic source parameters such as the moment and can also be constrained to consider angles less than a certain value equal to that value to prevent overfitting the data. The misfit and confidence levels are calculated in a one-norm sense, following [29], and the confidence levels are further constrained using only non-redundant focal mechanisms [54].

To account for the uncertainties in the focal mechanisms we use the facilities provided by the SIL fault plane solution algorithm [62]. The algorithm provides a range of acceptable fault plane solutions for each event, in the same way as a 95% confidence level, where each fault plane solution has a specific amplitude error. The amplitude error is used as a weight in the misfit calculation. We include the whole range of mechanisms for each event and calculate the misfit of each focal mechanism, in the end choosing the mechanism which gives the lowest misfit. This significantly improves the stress tensor inversion (Figure 6). For each tested stress tensor all acceptable focal mechanisms are thus tested, the best fit mechanism is chosen for each event and all the chosen misfits added to a final misfit for that stress tensor.

The crucial point of choosing which nodal plane to include in the inversion, i.e. choosing the fault plane, has been tackled with three different methods (Figures 6 and 7):

- Slip angle. The most common method today is to choose the nodal plane that shows the smallest misfit, i.e. the smallest angle between observed slip and estimated shear stress, in the tested stress field.

- Instability. We designed a new method of choosing the most unstable nodal plane in the current stress field. Using a simple Mohr-Coulomb failure criterion we define instability as $I = 3D\tau - \mu\sigma_n$, shear stress minus the product of the coefficient of friction and the effective normal stress. We showed that the dependence on μ, which is a potential problem, can be handled consistently without assuming a local coefficient of friction. The instability criterion is appealing from a physical view point but gives slightly higher misfits than the slip angle method.

- Pre-defined fault plane. Using the SIL algorithm for absolute and relative location [73] we can sometimes, with very high accuracy, locate a cluster of events to a common fault plane. For the events in the cluster only fault plane solutions in agreement with this fault plane are used in the stress tensor inversion, i.e. we have a pre-defined fault plane. This criterion is used together with either the instability or slip angle criterion for the events without pre-defined plane.

We want to emphasize that these methods *only* choose the fault plane! They are not part of the objective function and do not add to the misfit. The objective function is calculated on the chosen nodal plane. The methods to choose a nodal plane have been tested with both synthetic data and geological fault slip data where the correct fault plane is known. The slip angle and instability methods generally return similar stress tensors but the chosen fault planes vary significantly. Our tests indicate that instability method chooses the correct fault plane more often than the slip angle method.

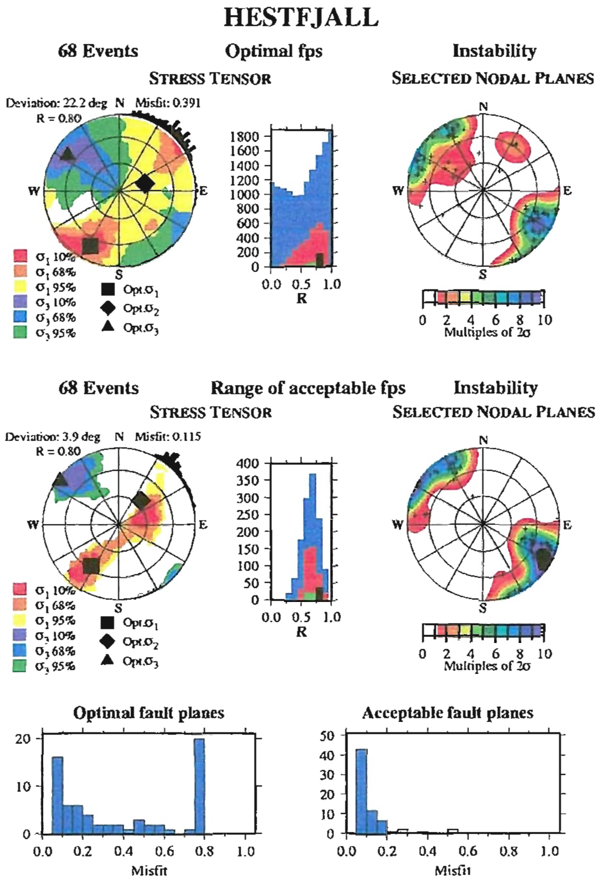

Figure 6: *Results of stress tensor inversion of 68 microearthquake focal mechanisms in Hestfjall, Iceland. The upper two rows show lower hemisphere equal area projections, in the left column are the resulting principal stress directions with 10%, 68% and 95% confidence limits and the optimal solutions marked by a black square (σ_1), a black diamond (σ_2) and a black triangle (σ_3). Deviation is the average angle between observed slip and estimated shear stress and misfit is the weighted deviation, both for the optimal solution. R is the relative size of the intermediate principal stress. The black rose diagram around the circle is the 95% confidence limit for the direction of maximum horizontal compression. The middle column histogram shows the confidence regions for R and the right column shows the nodal planes that the inversion algorithm picked as fault planes. The plus signs are the poles to the individual planes. They are overlayed by a Kamb contour diagram. The upper row shows the result when only the optimal fault plane solutions (FPS) were included in the inversion and the middle row is the result when a range of acceptable FPS were used for each event. The third row shows histograms over the misfits of the individual FPS. Both inversions were performed with the instability plane selection criterion. The misfit is reduced significantly and the confidence limits shrunk markedly when using the range of acceptable FPS.*

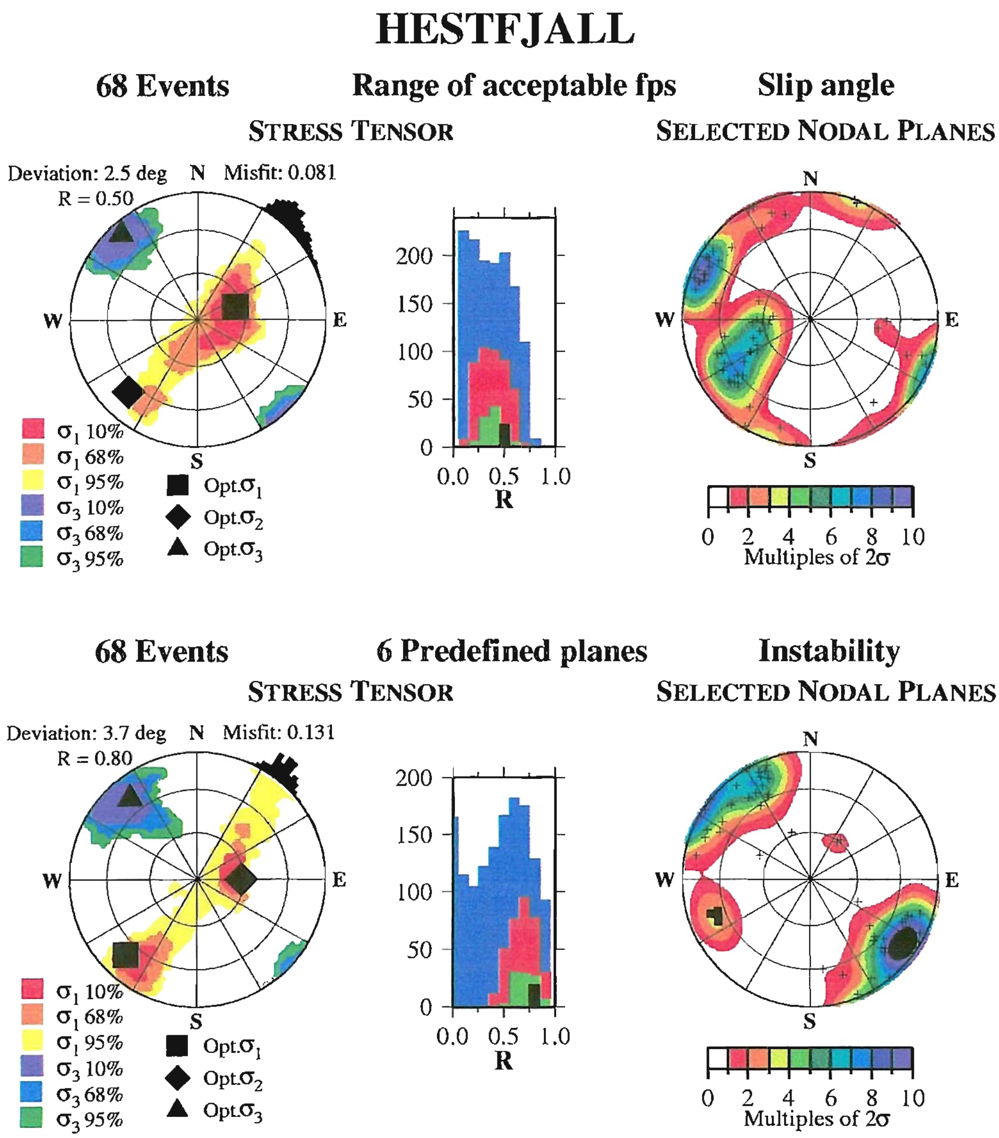

Figure 7: *Same 68 microearthquakes as in Figure 6 but now inverted with different nodal plane picking algorithms. Both examples in this figure have been inverted with acceptable fault plane solutions (FPS). In the upper row we have used the slip angle plane selection criterion to determine the fault planes. In the bottom row the plane with lowest stability, calculated using a simple Mohr-Coulomb failure criteria, was chosen as the fault plane. In addition six events have been located to a fault plane and thus constrained to only use FPS with the same direction as that plane. The slip angle inversion favours a normal faulting stress regime, although there are strike-slip regimes within the confidence levels. When inverting with predefined planes the stress tensors are more strongly polarized into a strike-slip and a normal faulting regime, both equally probable. The slip angle method selects very different fault planes from the instability inversions. We infer that the correct stress tensor can be distinguished only with knowledge of which planes slipped.*

We have applied our stress tensor inversion scheme to data from Hestfjall in the SISZ. Figures 6 and 7 show different stages in the inversion of 68 microearthquakes, ranging in local magnitude from -0.36 to 1.38 with a median at 0.24 and in depth from 3.2 to 7.4 km with the median depth at 5.7 km. It is evident from Figure 6 that using a range of acceptable fault plane solutions significantly improves the fit and accuracy of the inversion. The overall misfit is reduced by more than a factor three, the 95% confidence level shrinks to show two distinct stress states, either strike-slip or normal faulting, and the direction of horizontal compression, the black histogram on the perimeter, is concentrated at N40°E. Also the range in R is reduced. Both inversions choose mainly subvertical nodal planes striking NNE-ENE. At the bottom of Figure 6 we see the histograms of the individual misfits on the selected nodal planes and there is a marked change to lower misfits for the acceptable focal mechanism inversion. The lack of misfits between 0.0 and 0.05 is due to a lower bound on the misfit corresponding to 3° between observed slip and estimated shear stress.

The results of using the three different criteria for choosing the fault plane can be seen in Figure 6, which shows the instability criterion inverse in the lower half, and in Figure 7, which shows the slip angle criterion on top and the pre-defined plane criterion, with instability for most of the events, below. All three inversions have been performed using the acceptable focal mechanisms. As expected the slip angle method gives the lowest misfit, since it has the largest freedom to choose well fitting planes. The pre-defined inversion has worse misfit than the instability inversion, also due to the lower degree of freedom when six of the events have fixed planes. All inversions yield approximately the same direction of maximum horizontal compression, N40°E, and all inversions have 95% confidence levels allowing both strike-slip and normal faulting regimes. The slip angle inversion, however, strongly favours normal faulting whereas the other two have almost equal misfits for the best fitting strike-slip and best fitting normal faulting stress tensors. The planes chosen by the different criteria vary markedly. The instability criterion choose mainly subvertical planes striking NNE-ENE, with some planes having lower dips, for the strike-slip stress state. The slip angle inversion choose both subvertical and subhorizontal planes with main strike directions of NNE and NW, which is similar to the planes the instability inversion choose for the normal faulting regime. Including pre-defined planes with the instability criterion yields even more subvertical planes but with an added group of NNW striking planes.

These 68 Hestfjall microearthquakes are thus compatible with both a strike-slip and a normal faulting state of stress. The strike-slip regime requires mainly NNE-ENE striking subvertical fault planes and the normal faulting regime requires some subhorizontal fault planes. Knowledge of the fault planes is thus necessary to distinguish between the two stress states. This can be gained either through a larger data set with more events with predefined planes or through extrapolation of surface fault mapping to the conditions at 5 km depth. We feel that the methods developed here have improved our chances of correctly identifying the state of stress in the crust through earthquake focal mechanisms.

3.2.4 Task 4: Methods for monitoring of stable/unstable fault movements

Start: October 1996 (month 8)
End: February 1998 (month 24)
Responsible partner: UUPP.DGEO

Cooperative partner: IMOR.DG

The work in this field has been concentrated in developing tools for handling the large amounts of data produced by the PRENLAB network. Examples will be given in a number of figures from the TFZ transform fault north of Iceland. The activity from August 1, 1997 onwards will be used in this demonstration. This analysis is based primarily on a multievent location algorithm [73] and fault plane solution inversion using spectral amplitudes and first motion directions [72, 62].

The activity during August 1–9, 1997, is shown in Figure 8. Figures 9 and 10 shows fitting of planes to different grouping of these events. One should note that accurate locations are produced although the closest station is more than 20 km from this rather shallow activity. The magnitudes of these events are mostly in the range M_L=0.5–1.5. The estimated relative location uncertainties are about 10–30 m.

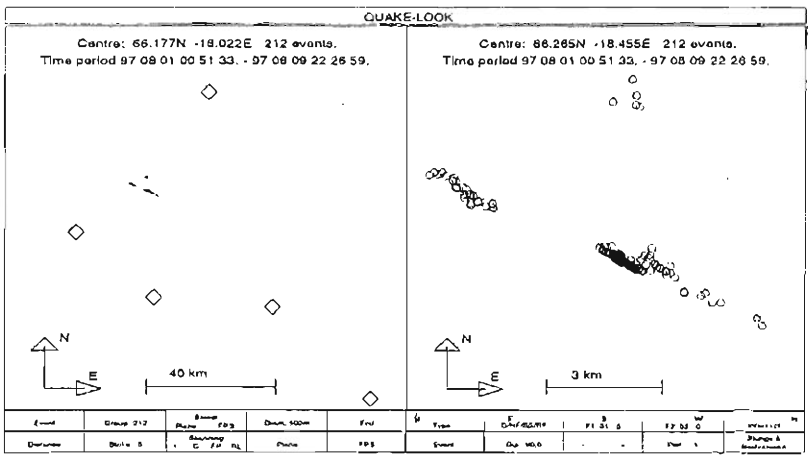

Figure 8: *The left map is an overview showing the stations as diamonds and the events of the swarms on August 1–9, 1997, are shown as circles with diameter 500 m. The closest station in the analysis is about 22–28 km from the events. The events have been located by multievent analysis and the blow-up to the right gives a clearer picture of the epicenters. The diameter of the event circles in the right map is 200 m. Note that the multievent location gives accurate locations although the ratio closest station distance to depth is about 3.*

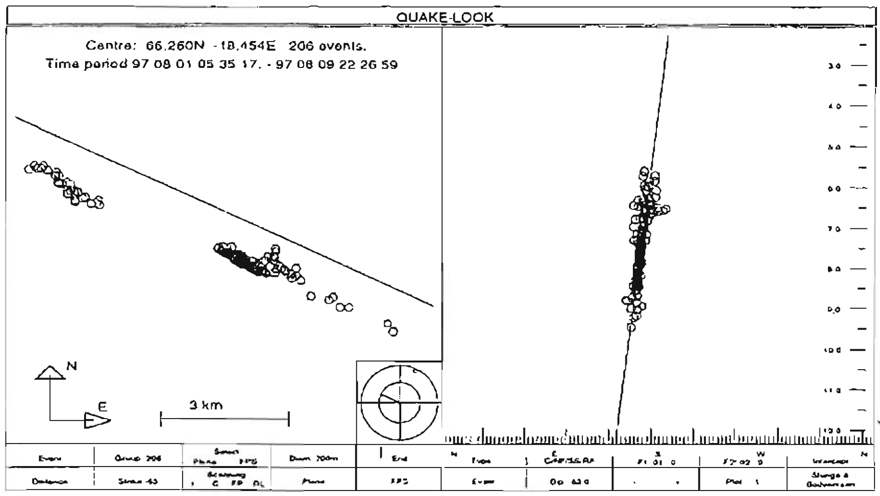

Figure 9: *The left map shows the again the epicenters while the right part is a depth view along the strike of the plane fitting the hypocenter locations of the events. The surface interception of the best fitting plane is shown in the left map. The RMS deviation from the plane is 88 m. This is larger than the estimated uncertainty of the relative locations of these events. The sizes of the event circles are 200 m and the depth scale of the right part is in kilometers.*

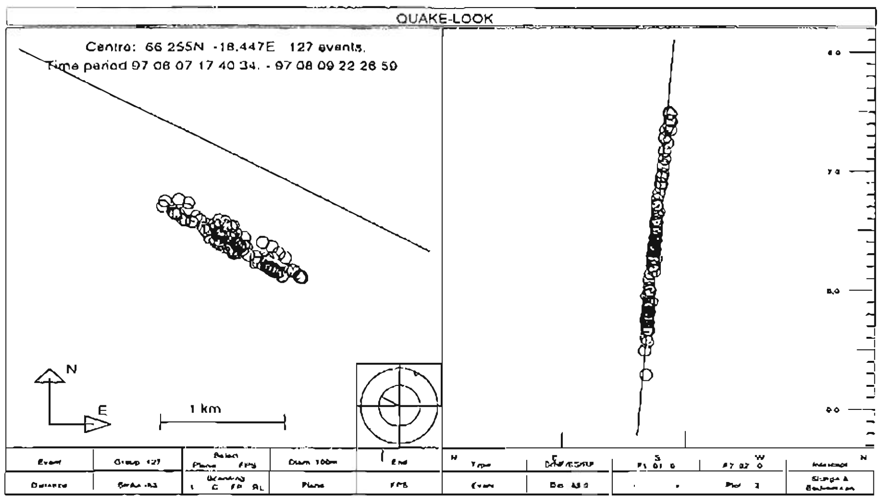

Figure 10: *This is a slight blow-up of the central densest group of events. The sizes of the event circles are here 100 m. The RMS deviation from the best fitting plane is 12 m which is in agreement with the estimated uncertainties of the relative locations of the events. This illustrates that rather accurate locations are achieved even with only few stations and with no station very close to the epicenters.*

The consistency between the multievent locations and the routine fault plane solutions of the SIL network is illustrated in Figure 11 which shows the best fitting fault planes from

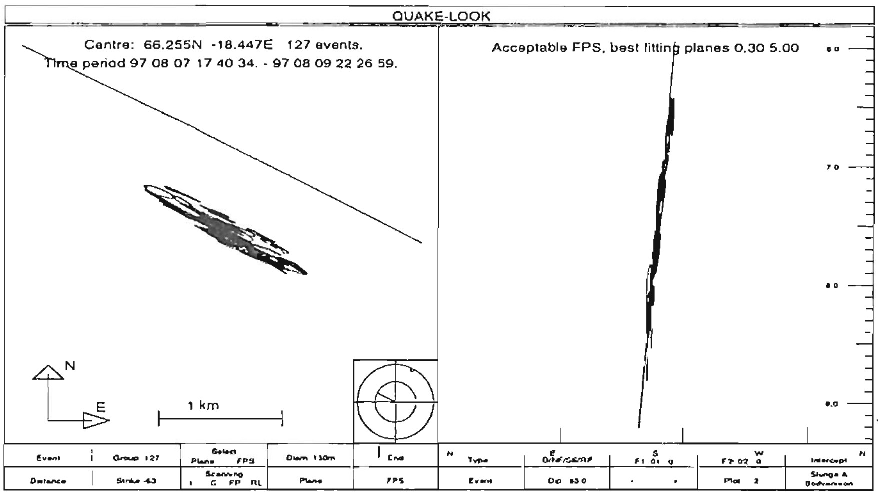

Figure 11: *This figure is the same as Figure 10 but here the events are shown as disks. The radii are the estimated fault radius of each event. Among all fault plane solutions (FPS) having an acceptable fit to the observed spectral amplitudes and first motion directions the one having one of its two possible fault planes closest to the orientation of plane fitting the hypocenter locations has been chosen. For each event the disk shows the orientation of that FPS plane. The median deviation from the hypocentral plane is* 4° *which is reasonable as the grid step in the FPS analysis is* 6°. *This figure indicates a reasonable consistency between the multievent locations and the FPS inversion.*

the results of the fault plane solutions. A reasonable conclusion is that the plane marked in the figure well approximates the slipping fracture.

Figure 12 shows how the microearthquakes are distributed over the fault area. The sizes of the earthquakes are estimated from the corner frequencies. One can see that the seismicly slipping parts do not cover the whole active area and also that some parts slips seismicly several times during the two days of this activity. In addition the peak slips (not shown in this figure) varies between 0.03 and 3 mm which gives a remarkable different size of total slip over the area during this concentrated activity.

The group in Figures 10, 11, and 12 is very close to other events, see Figure 13. To get some indications about the reality of the slight location differences the distributions of their dynamic parameters (seismic moment M_0 and peak slip sl) are shown in Figure 14. There is a clear difference in b-value and also in the distribution of the peak slip. This supports the indication by the multievent location that the additional events do not belong to the same fracture as the starting group.

The activity along this fault has continued after August 9, 1997, and the main features of this activity are summarized in Figure 15 which shows the locations of all major swarms after August 1. The figures close to the central parts of the swarm fault areas indicate their relative times in days. One can see that later activity tends to occur in parts of the faults that are close to immediate previous major faults. The simplest guess is that the swarm activity is caused by an increased velocity of the stable slip of that part of the fault. There

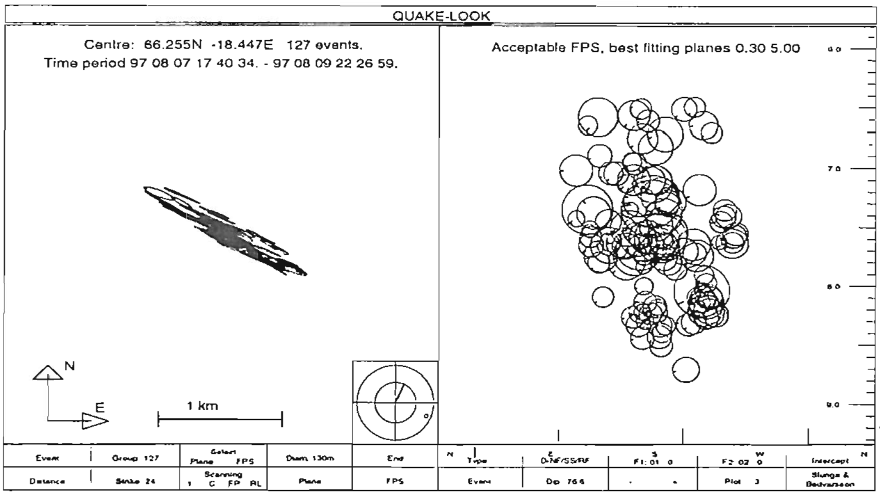

Figure 12: *This figure shows the same disks as Figure 11 but now the depth view to the right is normal to the strike of the hypocentral plane. The slight marks at the peripheries of the circles show the slip direction of the bedrock of the visible side of the disks. This slip direction pertain for each event to the chosen acceptable FPS. Interesting aspects of this figure is that parts of the active area has no detected seismic event and that parts of the area slip seismicly several times during the two days of this activity.*

seems to be a complicated episodic migration of the stable slip along the fault.

The recent state- and rate-dependent models for fault stability may be valuable tools in the analysis and in understanding of of fault behaviour as illustrated in these figures.

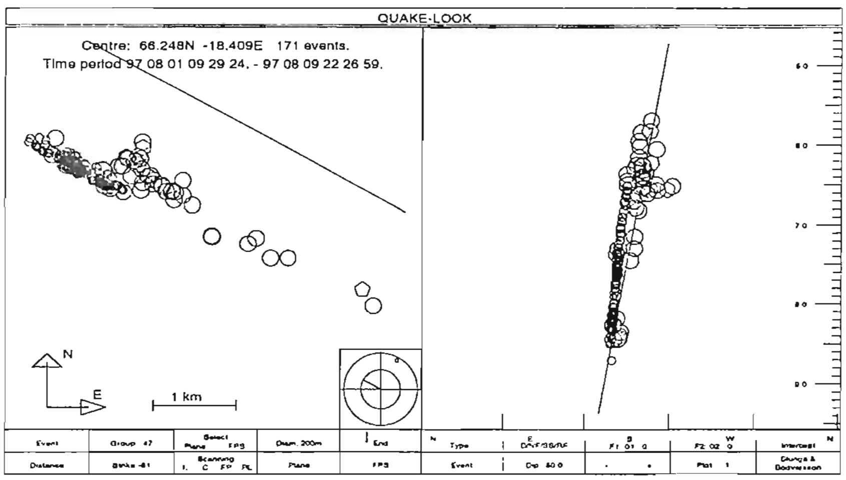

Figure 13: *This figure shows the group of the previous figures with small circles while the larger circles show the other close events. The sizes of the larger circles are 200 m. An obvious question is if the small location differences are real.*

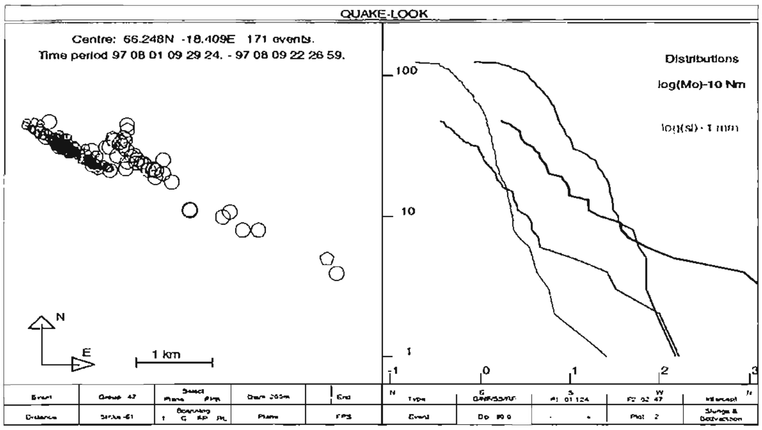

Figure 14: *The distributions of two dynamic parameters of the two groups of events, the seismic moment M_0, and the peak slip sl. In the right part the distributions are shown in a log-log plot. The small circle group contains 124 events and the great circle group contains 47 events. For each group the right curve shows the distribution of log(M_0) and the left group shows the distribution of log(sl). For the log(M_0) distribution the horizontal scale is approximately the local magnitude M_L. For log(sl) a value 1 means an estimated peak slip of 1 mm, 0 means a peak slip of 0.1 mm, etc. The two groups have different b-values (slope of log(M_0)) and also different slip distributions. This gives some support to the different hypocenter locations.*

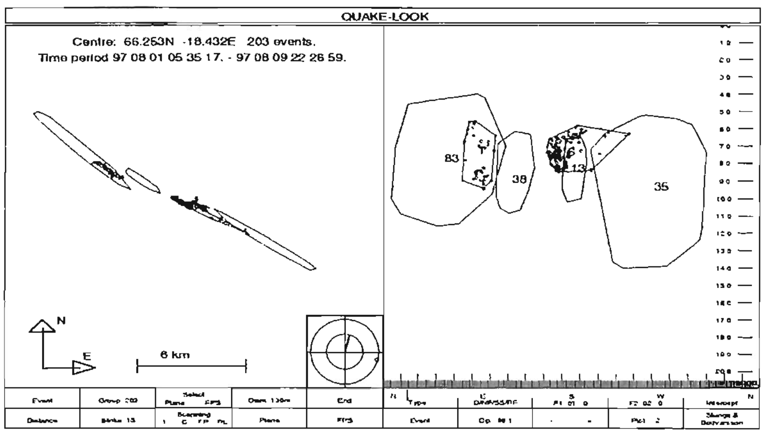

Figure 15: *The locations of swarm activity along the fault after August 1, 1997. To each major swarm a plane containing most of the events has been fitted. In the depth view to the right (normal to the strike) the figure close to the central part of each plane gives the day number of the swarm activity (typically they last for a week or more). The first swarm is marked by day 1. The swarms marked 1 and 6 are based on multievent locations and for these two groups the individual event locations are shown. The remaining groups are based on single event locations which explains there wider depth distributions. The activity migrates in such a way that calm areas close to active areas are likely areas of next activity. Note that plane marked 13 overlapping plane marked 6 "avoids" the most active part of plane marked 6 in agreement with this statement.*

3.2.5 Task 5: Methods for statistical analysis of the space/time distribution of microearthquakes and earthquakes

Start: May 1997 (month 15)
End: February 1998 (month 24)
Responsible partner: UUPP.DGEO
Cooperative partner: IMOR.DG

The work on this task has been integrated with the work within Task 4 and is reported in Chapter 3.2.4.

3.2.6 Task 6: Development of a method for acqusition of continuous GPS data at the SIL stations

Start: May 1996 (month 3)
End: February 1998 (month 24)
Responsible partners: UUPP.DGEO, NVI
Cooperative partner: IMOR.DG

The work on this task was a part of Subproject 5, Section 3.5.2.2.

3.2.7 Meetings and conferences

Here we list the research workers at UUPP.DGEO and which PRENLAB workshops and other scientific meetings they attended during the period of PRENLAB. At these occasions they presented results of PRENLAB, and participated in discussions about the PRENLAB work.

Reynir Bödvarsson and Ragnar Slunga attended the XXI EGS General Assembly in The Hague, May 6-10, 1996, and the PRENLAB contractor meeting which was held there. Reynir Bödvarsson, Ragnar Slunga, Björn Lund and Zaher Hossein Shomali also attended the XXV ESC General Assembly in Reykjavík, September 9–14, 1996. Reynir Bödvarsson attended the ninth biennial EUG meeting in Strasbourg, March 23-27, 1997 and the PRENLAB workshop organized there on March 27.

Reynir Bödvarsson and Ragnar Slunga attended a two day PRENLAB workshop in Paris, October 24-25, 1997.

Reynir Bödvarsson, Ragnar Slunga and Björn Lund attended the 29th IASPEI General Assembly in Thessaloniki, August 18–28, 1997, and a seismologist PRENLAB workshop which was held there on August 26.

On many occasions the members of the UUPP.DGEO research group visited IMOR.DG in Iceland working with the research group there.

3.3 Subproject 3: Monitoring stress changes before earthquakes using seismic shear-wave splitting

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3.3.1 Task 1: Identify optimal stations and search for precursors

Start: June 1996 (month 4)
End: February 1997 (month 12)
Responsible partner: UEDIN.DGG
Cooperative partner: IMOR.DG

Shear-wave splitting is sensitive to changes in stress, for example, changes prior to a large earthquake. The two principal arrivals identifiable on local earthquake records are the direct compressional P-wave, and transverse shear-wave. In anisotropic media, such as triaxially stressed microcracked rock, the shear-waves split into two orthogonally polarized waves that propagate with slightly different velocities. Careful examination of seismograms can identify the polarization direction of the first (or fast) shear-wave, and the time-delay between the two arrivals (Figure 16). The time-delay is particularly sensitive to changes in the anisotropy.

We have used earthquake data provided by IMOR.DG to ascertain which of the SIL stations record sufficient numbers of events suitable for shear-wave splitting analysis, and which of those are suitable for looking for precursory changes. Figure 17 shows those stations with polarization measurements during the period January 1996 to May 1997, inclusive.

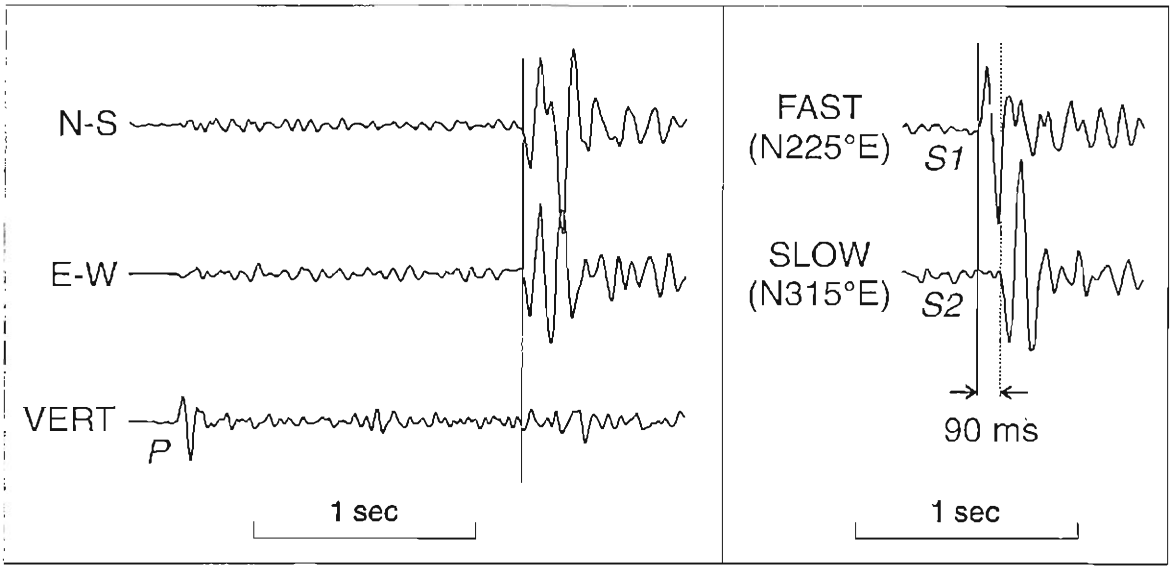

Figure 16: *Example of shear-wave splitting at station SAU. On the right-hand side are the three recorded components. On the left hand side, the rotated horizontal components clearly show the time-delay between the two shear-wave arrivals. This event occurred at 07:28:30.4, July 10, 1996, at 9.8 km depth, 5 km from SAU.*

Many of the stations show a good alignment of polarizations, indicative of seismic anisotropy with transverse isotropy and a horizontal axis of symmetry. The polarizations show the average direction of the maximum horizontal stress is NE-SW.

During the first year, time-delay analysis was concentrated on station SAU as it is close to a seismically active area, and at the easternmost end of the South Iceland seismic zone (SISZ) where a larger earthquake might be expected. Data was initially analyzed from May 1996. The results appeared to show a trend in the time-delay results associated with the eruption beneath the Vatnajökull ice cap in October 1996 (as reported previously). This study has now been continued, at SAU and at other stations, as described under Task 2.

3.3.2 Task 2: Station/EQ relationship

Start: March 1997 (month 13)
End: February 1998 (month 24)
Responsible partner: UEDIN.DGG
Cooperative partner: IMOR.DG

Time-delays and polarizations have been measured for all suitable data in the period January 1996 – May 1997, inclusive. Suitable events are those recorded with station-to-epicenter distance less than hypocentral depth. These are within the shear-wave window which ensures that the shear-waves are not distorted by surface conversions. This constraint places a severe restriction on the number of events that can be used for shear-wave splitting analysis. Also,

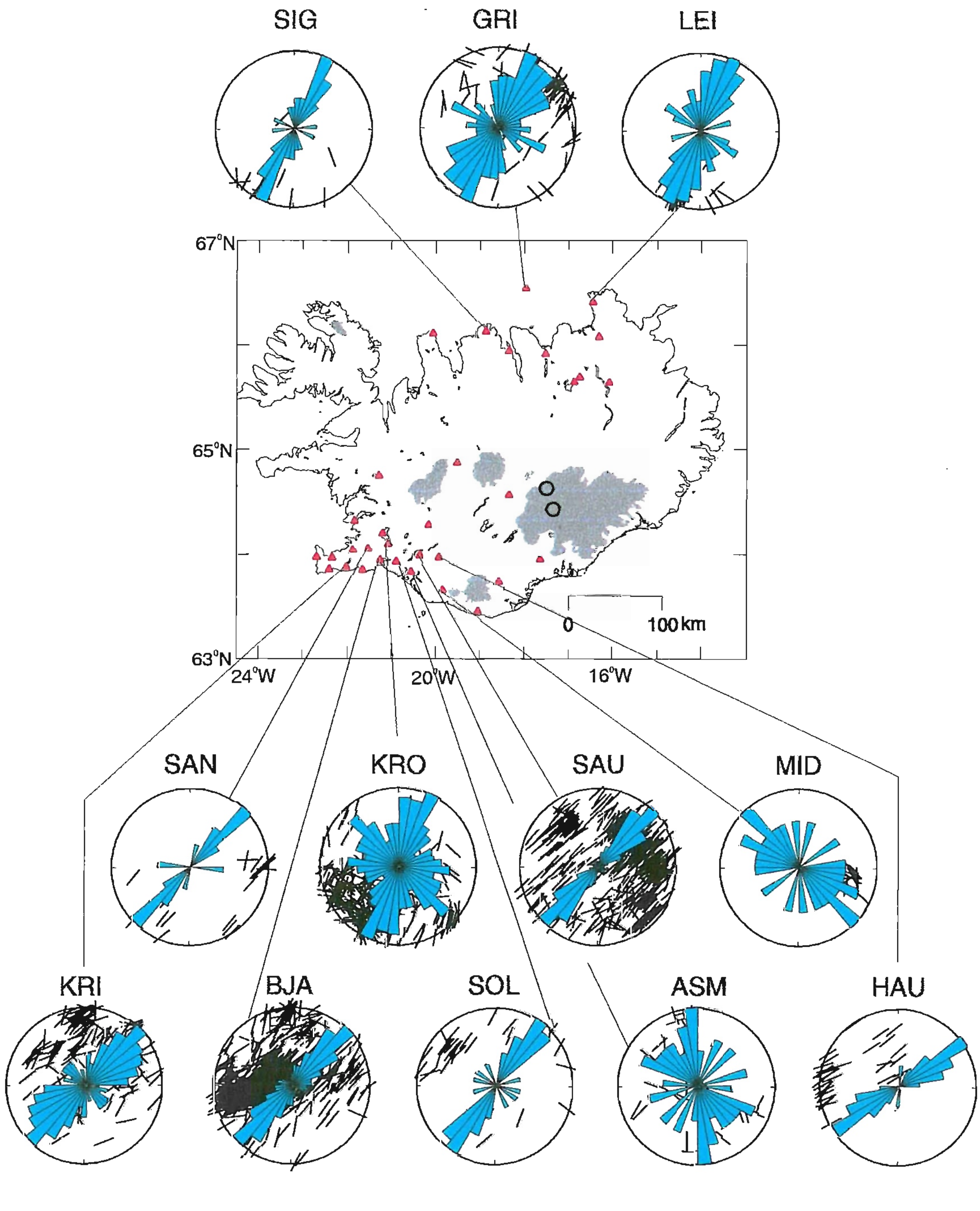

Figure 17: *Shear-wave splitting polarizations measured at SIL stations. All data are within the shear-wave window (45°), January 1, 1996 - June 1, 1997.*

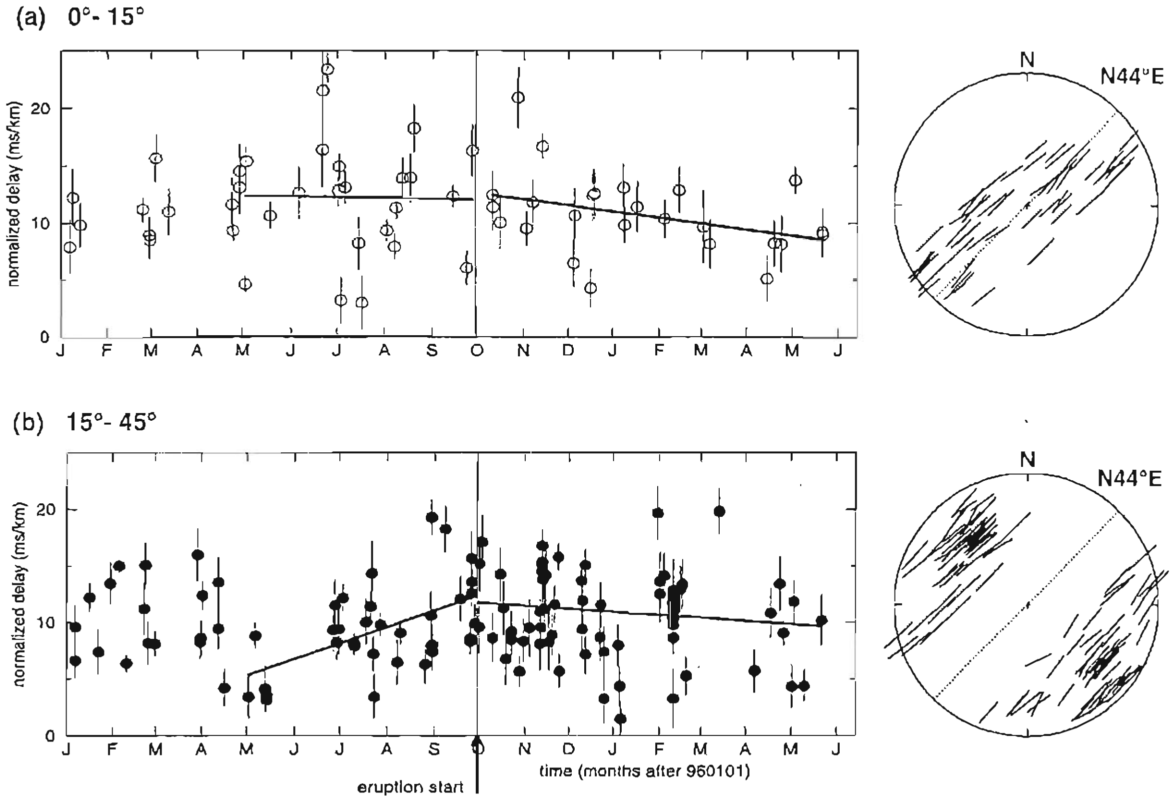

Figure 18: *Shear-wave splitting at SAU from January 1, 1996 to June 1, 1997. Variation of normalized time-delays with time, and polar equal-area maps out to 45° of shear-wave polarizations with dotted line indicating average direction, for (a) ray paths in bands with incidence 0° to 15° to the crack face (sensitive to crack density), and for (b) ray paths in bands with incidence 15° to 45° to the crack face (sensitive to aspect ratio). Lines are linear least-square fits to data before and after the Vatnajökull eruption (October 1996). Error bars are approximate.*

to identify temporal trends, there needs to be sufficient activity, spread in time, near the station. These criteria were only fulfilled at stations SAU and BJA.

Time-delay measurements are analyzed for temporal trends in Figures 18 and 19. At each station, the mean circular polarization direction is calculated, and time-delay measurements with polarizations within the standard deviation of this direction are selected (at SAU and BJA this is polarizations N44°E ± 20°). The time-delay measurements (normalized over straight-line path distance) are then separated into two bands. The bands are defined by incidence to the vertical plane of symmetry parallel to the mean polarization direction (interpreted as the strike of aligned near-vertical cracks), previous studies have shown that the outer band of time-delays is expected to be the most sensitive to changes in crack aspect-ratio, the result of increasing stresses. At SAU, there is a clear increase in time-delays from about May 1996 to the beginning of October 1996 in the outer band of measurements. After

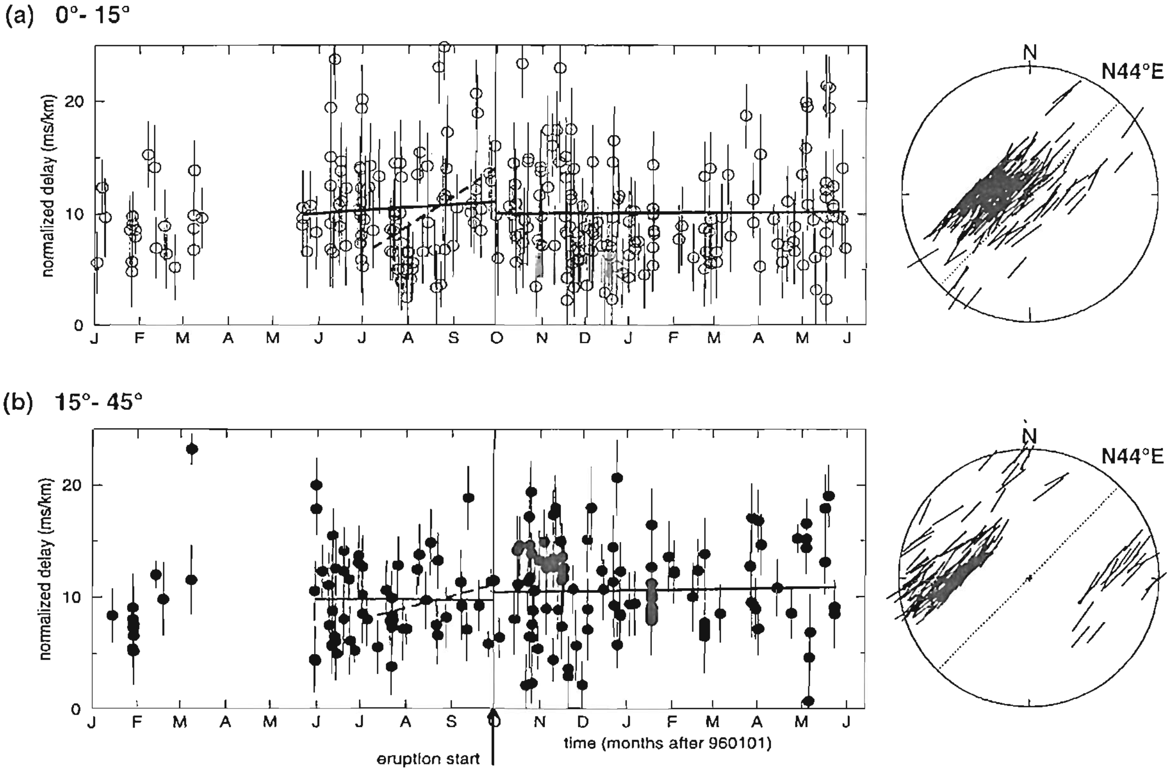

Figure 19: *Shear-wave splitting at BJA from January 1, 1996 to June 1, 1997. Diagrams as for Figure 18. The dashed lines are linear least-square fits for a shorter time period. The absence of data for March, April and May 1996 is due to instrumental problems.*

this time, the delays gradually decrease. During the same period, the delays in the inner band remain roughly constant. This suggests that the change in delays could be a result of increasing aspect-ratio of the microcracks with the stress build-up (and subsequent release). The tectonic event likely to responsible for this is the Vatnajökull eruption that started on September 30, 1996, the fourth largest eruption in Iceland this century. The volcano is over 160 km away, so the effect is also expected to be visible on other stations during this period.

The only other station with sufficient data during this time period is BJA. BJA is near the centre of the SISZ (Figure 20) and is in a much more complicated tectonic area than SAU. The data does not show the same trend as SAU over the period May to October 1996, but there is an average increase in delays when a shorter time period is taken (mid-July to October 1996). For this time period, there is an increase in the delay measurements in both bands of data, suggesting there was also some increase in crack density. This trend may be related to the changing stress state prior to the eruption. However, there was also a magnitude 4.2 event, only 7 km from the BJA on October 14, 1996. It is possible that this increase of delay times over the shorter period is related to this more local event, rather than the eruption (200 km from BJA).

Data from station KRI is also shown in Figure 21. The measurements at this station

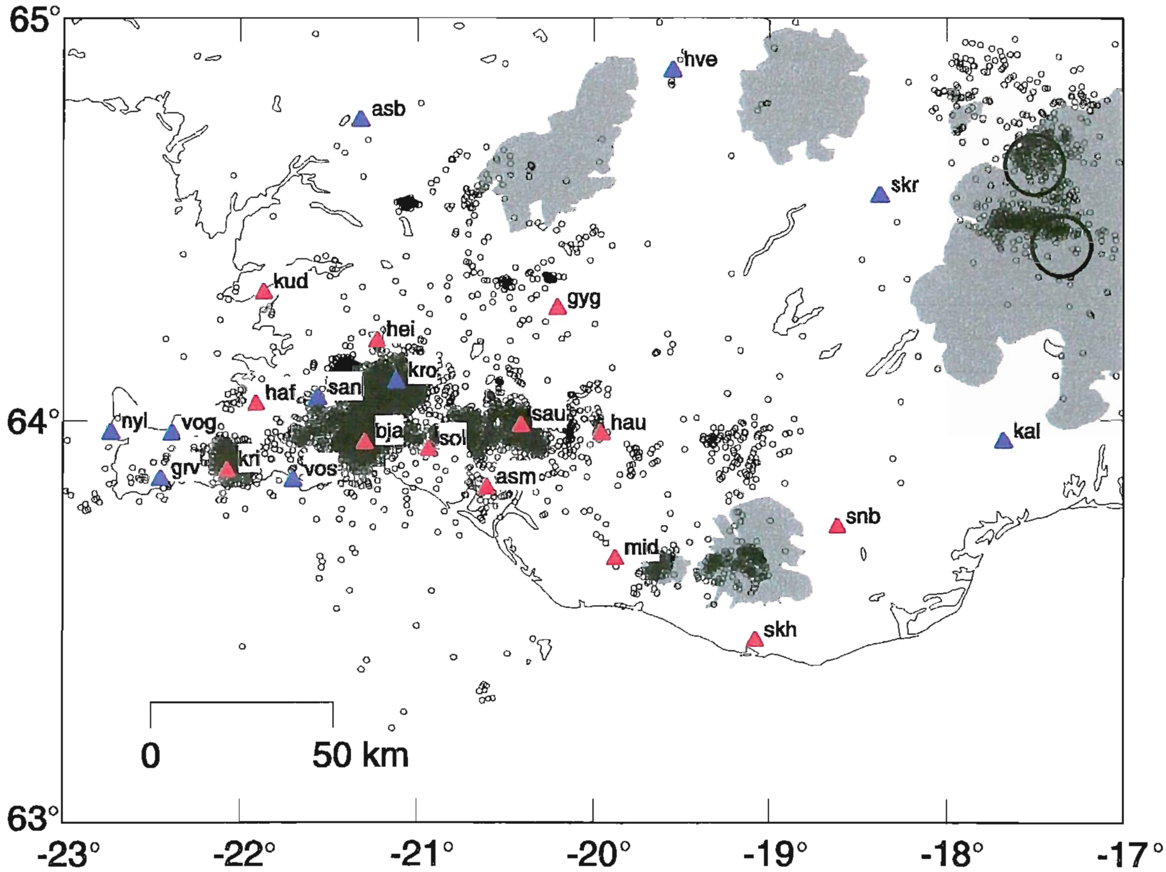

Figure 20: *Map of SW-Iceland showing all seismicity recorded during the period January 1996 - May 1997 (inclusive). Red triangles are SIL stations that were deployed for the whole period, and blue triangles are stations added to the network during this period. The large black circles show the locations of the Bárdarbunga and Grímsvötn volcanoes beneath the Vatnajökull ice sheet.*

have polarizations N51°E± 28°. In February 1997 there was an increase in activity just north of the station which culminated in a magnitude 3.9 event on February 23, 1997, 7 km from KRI. This is the largest event in this area for at least two years. There is some evidence from the time-delay data in Figure 21 that there is an increase in delays prior to this larger event. As can be seen from the projection, the events all have similar locations, hence similar ray paths that make the changes in delays all the more significant, as they are less subject to variations caused by different ray paths.

3.3.3 Task 3: Developing routine techniques

Start: March 1997 (month 13)
End: February 1998 (month 24)
Responsible partner: UEDIN.DGG

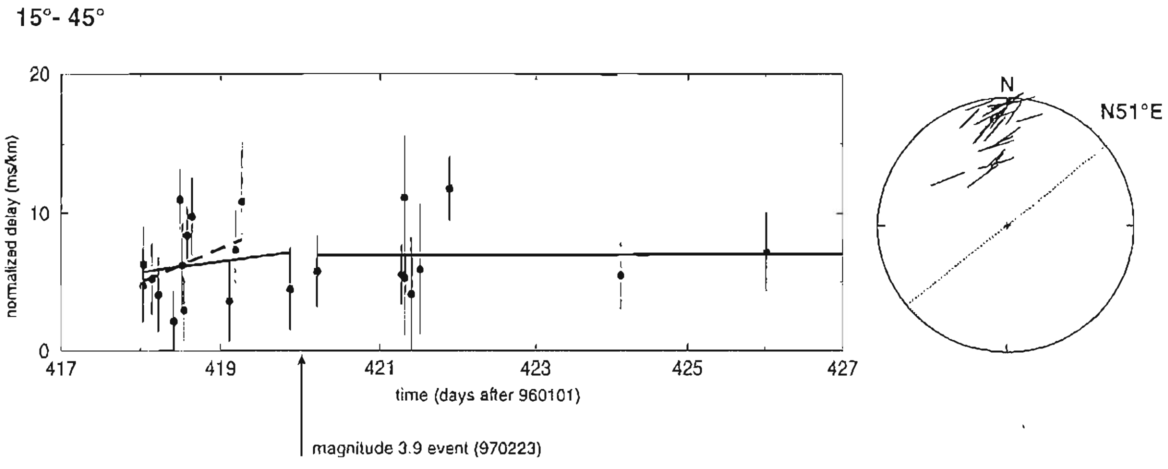

Figure 21: *Normalized time-delays at KRI from February 15, 1996 to March 15, 1997, as for Figure 18. Lines are linear least-square fits before and after the magnitude 3.9 event, 7 km from KRI (no data recorded in the 0°–15° band).*

Effort has gone into developing routines for data manipulation for shear-wave splitting analysis, including programs to select and download the relevant data from the database at IMOR.DG. The actual measurements are still done manually. Fully automated, real-time measurement will require significant further work.

3.3.4 Task 4: Identify optimum areas

Start: September 1997 (month 19)
End: February 1998 (month 24)
Responsible partner: UEDIN.DGG

Optimum areas for further stations, permanent or temporary, have been identified on the basis of recent seismicity patterns. One suggestion is for more stations around SAU, where the particularly good alignment of polarizations suggests time-delay patterns will be the most informative. If the same events can be recorded at more than one station this will give much greater constraints on the anisotropy. In NE-Iceland, a station on Flatey Island, or on the coast further south from LEI will also record events suitable for shear-wave splitting analysis near the Húsavík transform fault and Grímsey zone.

3.3.5 Meetings and conferences

Stuart Crampin attended the XXV ESC General Assembly in Reykjavík, September 9–14, 1996. Stuart Crampin and Helen J. Rowlands attended the ninth biennial EUG meeting in Strasbourg, March 23–27, 1997. Stuart Crampin attended a two day workshop in Paris, October 24–25, 1997.

Stuart Crampin attended the symposium Earthquake Research in Ankara, September 30 – October 5, 1996. Stuart Crampin attended the symposium Assessment of Schemes for Earthquake Prediction, Geological Society, London, November 7–8, 1996. Stuart Crampin and Helen J. Rowlands attended the ninth biennial EUG meeting in Strasbourg, March. 23–27, 1997.

3.4 Subproject 4: Borehole monitoring of fluid-rock interaction

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3.4.1 Subpart 4A: Geophysical loggings

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Frank Roth

Subcontractor:

Valgardur Stefánsson

In the framework of the EC project, *Earthquake Prediction Research in a Natural Laboratory*, a pilot study has started to obtain a time series of logs in the South Iceland seismic zone (SISZ). An 1100 m deep borehole (LL-03, Nefsholt) inside the zone (63.92°N, 20.41°W, 7 km south of the seismic station SAU) is used and provides the unique opportunity to perform measurements much nearer to earthquake sources than usual – the hypocenter depths at that location range between 6 and 9 km. Moreover, data can be obtained for a depth interval of more than 1000 m, uninfluenced by the sedimentary cover and less disturbed by surface noise.

In the preparational phase of an earthquake, stress accumulation is expected to be connected with the creation of borehole breakouts, changes in the number and size of cracks, a possible variation of the stress direction, etc. Therefore, the following set of geoparameters is monitored:

- P-wave travel time.
- Electrical conductivity.
- Water content and porosity.
- Stress information from borehole breakouts (orientation and size).
- Crack density, crack opening.

This is achieved by repeated logging with tools as:

- Sonic log (BCS).
- Dual induction/latero log (DIL).
- Neutron log.
- Four-arm-dipmeter (FED).
- Borehole televiewer (BHTV).

The neutron log is run with the logging equipment of OS, the rest with the Halliburton logging truck of GFZ.DR.DBL.

Temporal changes visible in these logs will be correlated with data obtained by other methods used in the whole project, as there are: seismicity, anisotropy observed in S-waves, crustal deformation, gravity, etc.

3.4.1.1 Task 1: Logging activities

Start: July 1996 (month 5)
End: December 1997 (month 22)
Responsible partner: GFZ.DR.DBL

As described in the previous reports, three logging campaigns took place in 1996. During these campaigns, repeated measurements were performed in well LL-03 (Nefsholt). In co-operation with Orkustofnun, logging was done in 5 other boreholes, of which at least the borehole-televiewer measurements in well LJ-08 are relevant for this project.

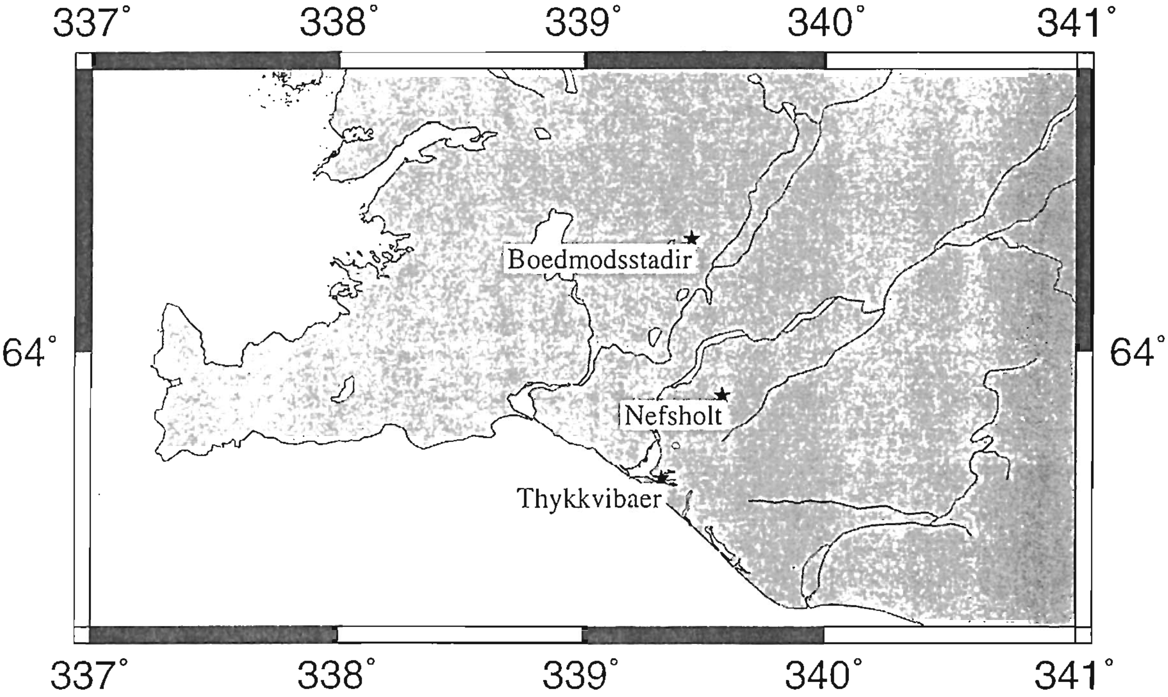

Figure 22: *Map of the south-western part of Iceland showing the location of the site of repeated logging (Nefsholt) and of the other two boreholes where borehole-televiewer measurements have been performed during 1997.*

The recent activities within this subproject comprise two logging campaigns in 1997, one in September, the second in December. The first was exclusively concerned with repeated logging in borehole LL–03 (Nefsholt) inside the SISZ. During the second campaign, additional logs were run with the borehole-televiewer in Bödmódsstadir (located at the northern edge of the SISZ, close to Laugarvatn) and in Thykkvibær (slightly south of the SISZ, near the south coast). The latter borehole was drilled very recently. The locations are shown in Figure 22. Table 1 shows the logs performed during the first and second year of this project.

These five campaigns have thus attributed to the two aims of this subproject:

- Observation of changes in physical parameters of the rock and of changes in degree of fracturing and orientation of principal stresses with respect to seismic activity.
- Indirect measurement of tectonic stress orientation to evaluate the tectonic stress field in the area of the SISZ.

3.4.1.2 Task 2: Check for changes – results from repeated logging

Start: July 1996 (month 5)
End: February 1998 (month 24)
(following each logging campaign)
Responsible partner: GFZ.DR.DBL

Name:	Location:	Max. depth:	Logged interval:	Tools used:	Date:
NG-01	Ólafsvellir (inside SISZ)	1070 m	180–1070 m	FED, GR, SP, 3-arm-caliper, 16"- and 64"-resistivity	July 1996
HS-36	Reykjavík	980 m	330–980 m	BHTV, BCS-GR	July 1996
LPN-10	Laugaland near Akureyri, North Iceland	890 m	80–880 m	BHTV, BCS-DIL-GR	July 1996
LJ-08	Sydra Laugaland near Akureyri	2740 m	120–1890 m 120–1330 m	FED, BHTV, BCS-DIL-GR	July 1996
TN-02	Ytri-Tjarnir near Akureyri	1370 m	260–1370 m	BCS, GR	July 1996
LL-03	Nefsholt (inside SISZ, site of repeated logging)	1309 m	80–1100 m	BHTV, BCS-DIL-GR, neutron-neutron, X-Y-caliper, 16"- and 64"-resistivity, SP	July 1996 October 1996 September 1997 December 1997
THB-13	Thykkvibær south-west of Hella near the south coast	1254 m	466–1225 m	BHTV	December 1997
BS-11	Bödmódsstadir near Laugarvatn	1193 m	703–1090 m	BHTV	December 1997

Table 1: *As borehole NG-01 partly collapsed between log runs, the hole was abandoned and well LL-03 was chosen for repeated logging. GR indicates Gamma-Ray-log, SP stands for Spontaneous Potential. FED means Four-Arm-Dipmeter which includes an oriented four-arm-caliper. BHTV means ultrasonic Borehole-Televiewer. BCS is Borehole-Compensated-Sonic; DIL is Dual-Induction/Latero log. For technical reasons, no FED run was possible in LL-03, no BHTV run was possible in LJ-08 below 1330 m depth, no BHTV run was possible in BS-11 above 703 m depth. Due to the limited availability of a crane, no BHTV or FED run were possible in TN-02. The deepest parts of wells LJ-08, LL-03, THB-13 and BS-11 were not accessible anymore.*

Repeated measurements in Nefsholt showed good repeatability, especially of the sonic log. The standard deviation is in average between 2.5% and 3.5% of the average travel time measured.

A good interpretation can be made in depth intervals with high sonic amplitude. In these intervals the standard deviation usually is lower than 2.5%. Depth intervals where the amplitude of the registrated signal is very low show significant variation in the (automatically) picked travel-times and thus cannot be considered for an analysis of changes. Small differences between repeated logs in the high amplitude intervals seem to be caused by inaccurate depth matching due to slightly different curve shapes (Figure 23). Thus, no changes in the sonic velocity have been observed so far. The same is true for the resistivity measurements, as can be seen from Figure 24.

On the other hand, no relevant seismic activity has been observed in the surrounding of

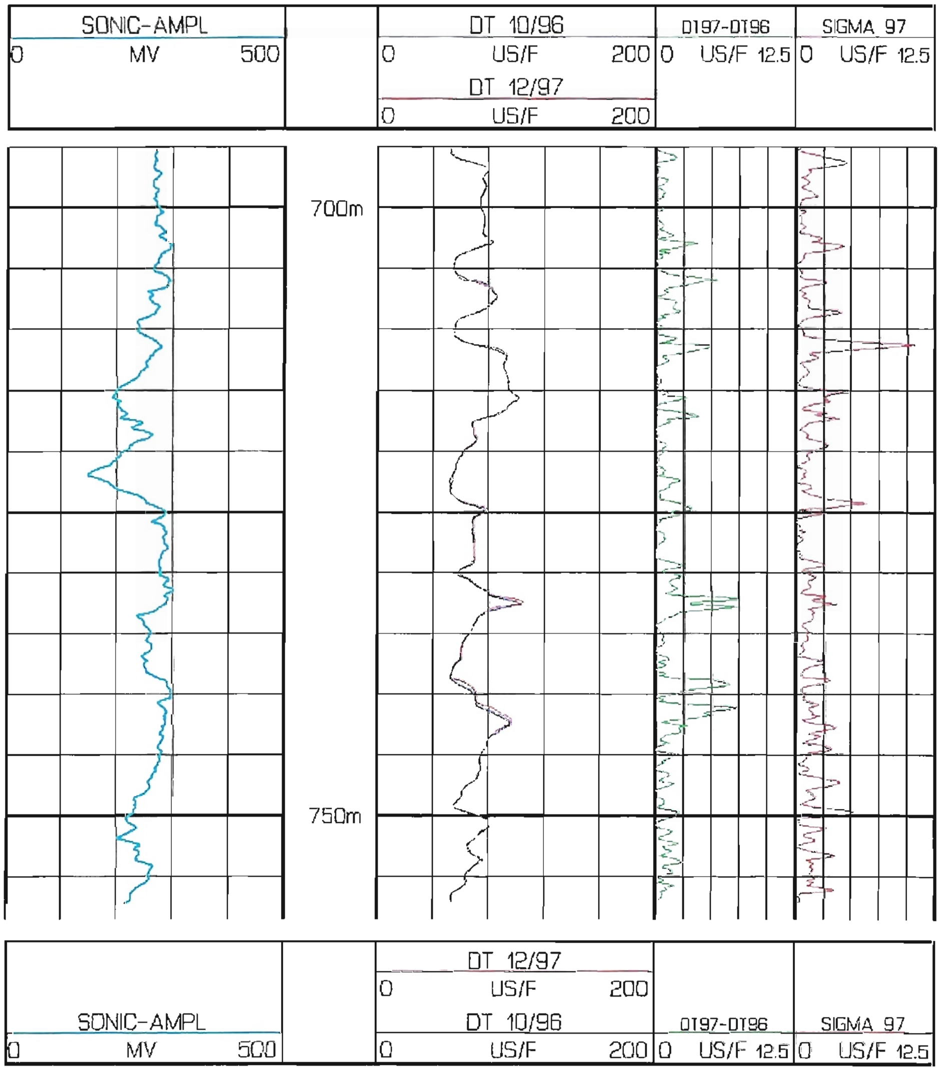

Figure 23: *Data example showing from left to right panel: an average curve of sonic amplitude, a superposition of the average compensated travel times measured in October 1996 and in December 1997 (each averaged over four runs performed immediately one after the other), the difference between these two average travel time curves (absolute value, green curve) and the standard deviation (absolute value) derived from the four runs performed in December 1997. Compensated travel times are given in microseconds per foot. The difference between the average travel times exceeds the standard deviation only in low amplitude intervals (not shown here) or at depths with inaccurate depth-matching (for example around 740 m).*

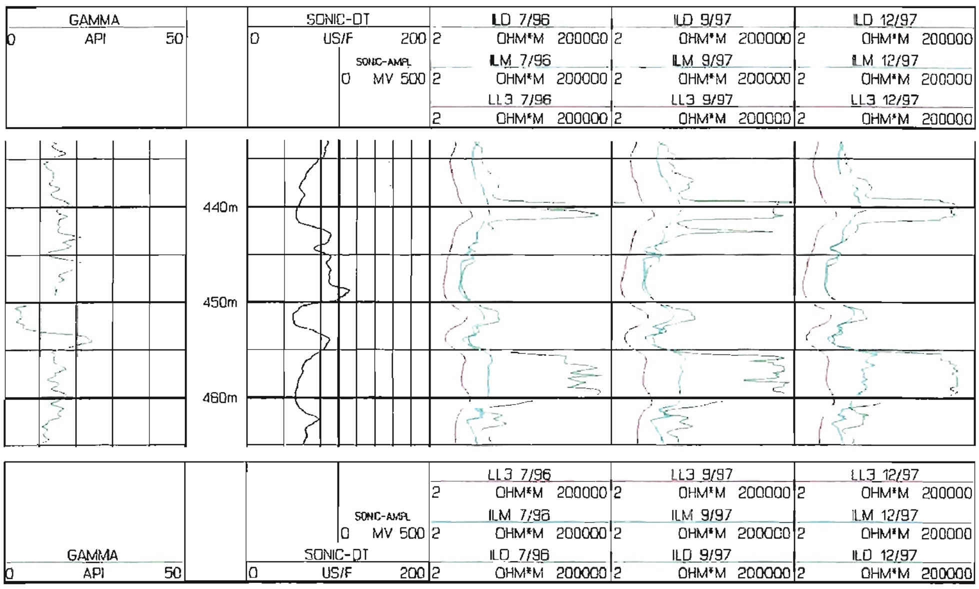

Figure 24: *Data example showing from left to right panel: gamma-ray log in API, compensated travel time in microseconds per foot and the sonic amplitude, and three repeated measurements of latero log (LL3), medium induction log (ILM) and deep induction log (ILD). Month an year of campaign are given.*

this borehole since the beginning of the measurements.

We are thankful that Orkustofnun provided a lithology log of the well at Nefsholt. This log shows a nearly continuous sequence of altered basalt, interrupted only by a few thin sedimentary layers and some thin layers of dolorite, hyaloclastites and fresh basalt. Corresponding to a porosity change within each basaltic layer, the sections of altered basalt show very different characteristics in sonic velocity and resistivity as well as in the neutron log. These differences allow to distinguish between the lava-flows (Figure 25).

3.4.1.3 Tasks 3 and 4: Evaluation of measuring results

Start: July 1996 (month 5)
End: February 1998 (month 24)
Responsible partner: GFZ.DR.DBL

Borehole-televiewer measurements
The televiewer-data collected in the well at Nefsholt have been presented in the previous reports. **These previous presentations have to be corrected for an error in orientation!** Attempts were made in 1996 to correct for instrumental problems with the orientation of the data. Unfortunately, these efforts now turned out to have failed. To give the data the right orientation, it is necessary to change the coordinate system from clockwise to counterclockwise rotation. General breakout-orientations and fracture statistics from the measurements in Nefsholt with the correct orientation are presented in words below.

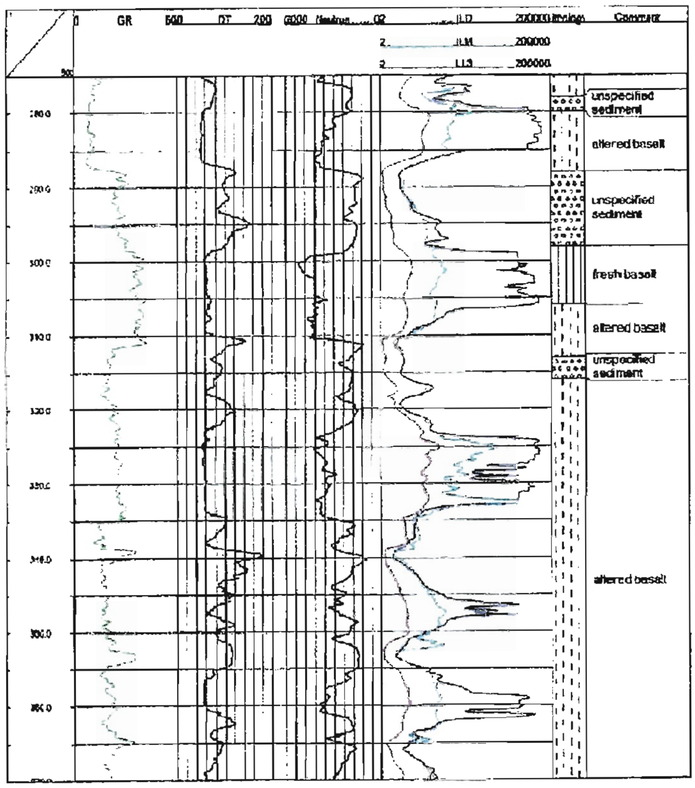

Figure 25: *Data example showing the correlation between the performed logs and the lithology log provided by Orkustofnun. GR = gamma-ray in API, DT = compensated travel time in microseconds per foot, neutron = neutron log in API, ILD and ILM = induction log deep and medium in Ohmm, LL3 = laterolog in Ohmm.*

Also are discussed breakouts in the borehole BS–11 (Bödmódsstadir), which was logged down to 1090 m, and the borehole THB–13 (Thykkvibær), down to 1245 m.
Nefsholt: The previously found orientation of the borehole breakouts of about N35°E have to be corrected in 120.5° to 126°, giving a direction of the maximum horizontal principal stress of N30.5°E to N36°E. The circular standard deviation (1σ) is of the order of 10°. The stress direction is in agreement with the expected stress direction from large scale tectonics (left-lateral strike slip). The length of picked breakouts sums up to approximately 5.5 m.

308 fractures have been picked in the depth interval between 300 m and 1090 m. Determination of dip-angle and -direction are presented in Figure 26. They show that most of the steep dipping fractures (dip angle greater than 60°) are dipping ESE, a slightly smaller set of steep fractures dipping WNW. Considering all fractures, this trend is much less pronounced, but there is still a preferred dip-direction of W to WNW with a smaller dataset of dip-angles ESE. The averaged strike of these fractures is thus NNE, like the strike of the fractures observable at the surface.
Thykkvibær: Borehole breakouts have been found in the depth intervals 925 m to 927 m and 937 m to 941 m. The breakouts in these two depth intervals sum up to approximately

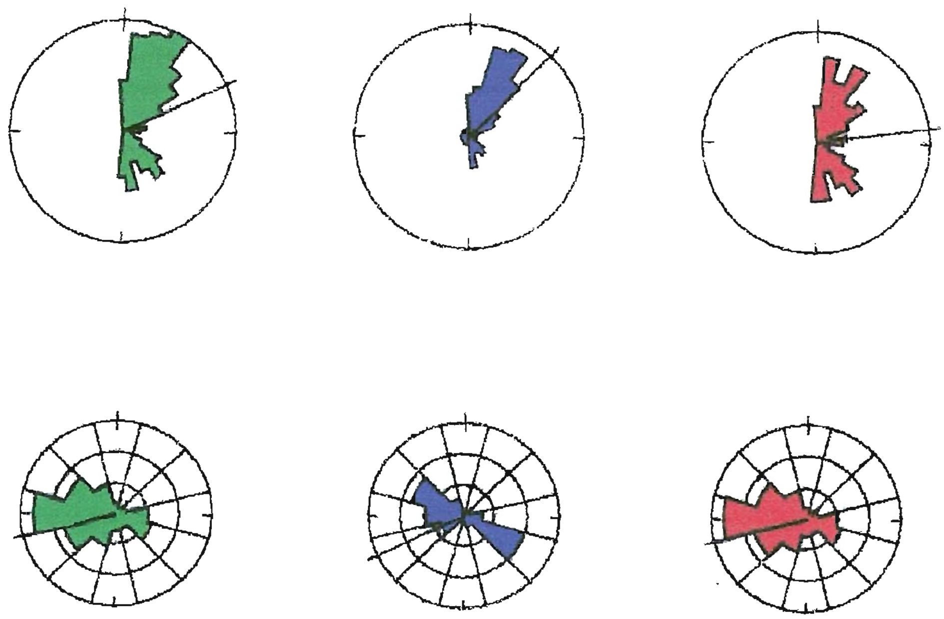

Figure 26: *Strike (upper row) and dip (lower row) of fractures observed in Nefsholt. Blue diagrams: dip-angles greater 60°; red diagrams: dip angles less than 60°; green diagrams: all fractures.*

3.5 m. Data quality is rather poor due to weak reflection amplitudes. Figure 27 shows a data example. The average breakout azimuth is between N105°E (upper depth-interval) and N121°E (lower depth-interval). Statistic analysis over the whole depth range gives a breakout-orientation of N111°E with a circular standard deviation (1σ) of about 10°. This would mean that the larger principal horizontal stress is in average orientated N21°E. This is in agreement with the stress directions expected from the overall tectonics as well as with the results from Nefsholt.

Bödmódsstadir: No breakouts have been observed in this borehole, but there are vertical fractures visible between 713 m and 934 m depth. The length of the vertical fractures sums up to 45 m. Vertical fractures are expected to occur in the direction of the maximum horizontal principal stress because of tensile failure of the borehole wall. They are supposed to be drilling induced and not of natural origin. These fractures occur at an azimuth of N45°E to N90°E. One data example is presented in Figure 28.

Additional to the drilling induced fractures, 52 natural fractures have been picked in the depth interval between 820 m and 1060 m. The steep dipping fractures (dip angles greater 60°) show a dominant strike ENE. Regarding all natural vertical fractures, there are two datasets: One striking nearly N and the other striking ENE to E.

The results can be summarized as follows:

- The repeated measurements of sonic P-wave velocity, resistivity and gamma-ray show good repeatability. Neither changes in logs nor changes in seismic activity have been observed yet.

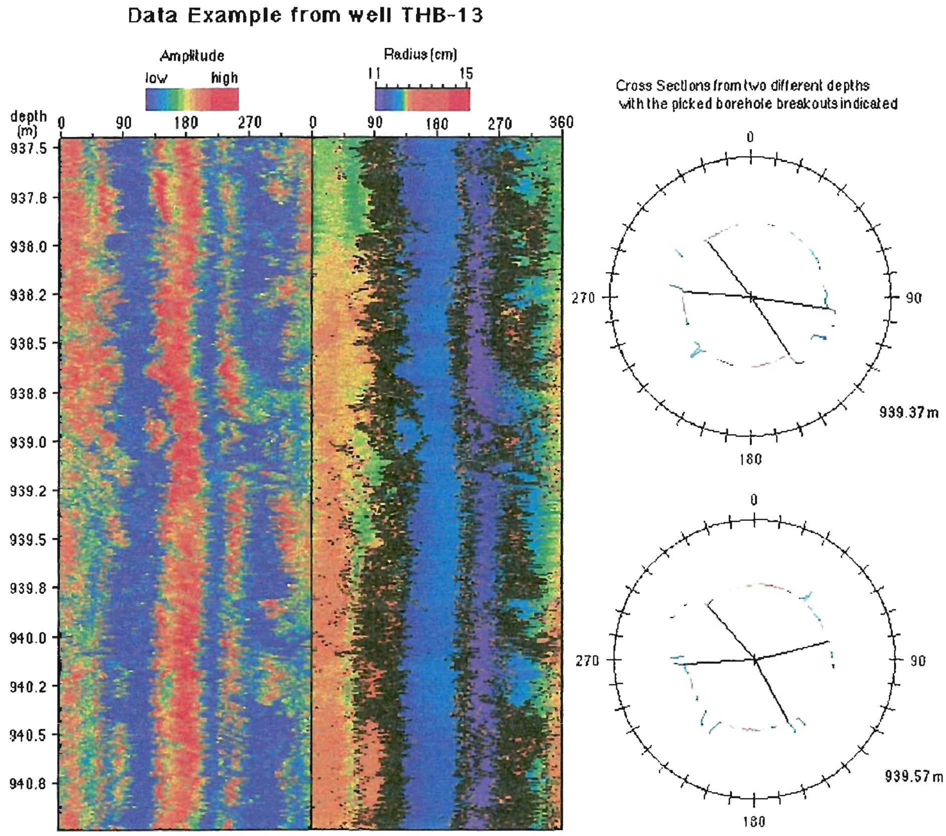

Figure 27: *Example for the borehole breakouts found in Thykkvibær with two cross sections. The two panels show the amplitude of the reflected signal (left) and the radius calculated from the travel time (right) unwrapped from North over East, South, West to North. Vertical axis: depth in meters. Breakouts appear as vertical bands of low reflection amplitudes. Due to low reflection amplitude, the values for the radius are missing in these parts, resulting in black bands. In the two cross sections, the black lines indicate the picked breakouts.*

- Borehole breakouts observed in Nefsholt and Thykkvibær correlate with the expected large-scale stress direction in the SISZ: they show the maximum horizontal principle stress at an azimuth of approximately NNE (N21°E to N36°E). The data obtained in Bödmódsstadir show an average direction of maximum principle horizontal stress ENE. Thus, the direction of maximum principal horizontal stress as found by the televiewer data varies from NNE (north of the SISZ, BS–11) to ENE (south of the SISZ, THB–13). This variation is of the same order as the standard deviation.
- Fractures found down to nearly 1100 m depth show the same dominant strike as those observed at the surface. A dependency of fracture orientation with depth or with geographical latitude could not be found so far. Fracture picking in the data collected in Thykkvibær is not finished yet.

Outlook

It is planned to continue the logging activities in 1998, depending on seismic activity. After

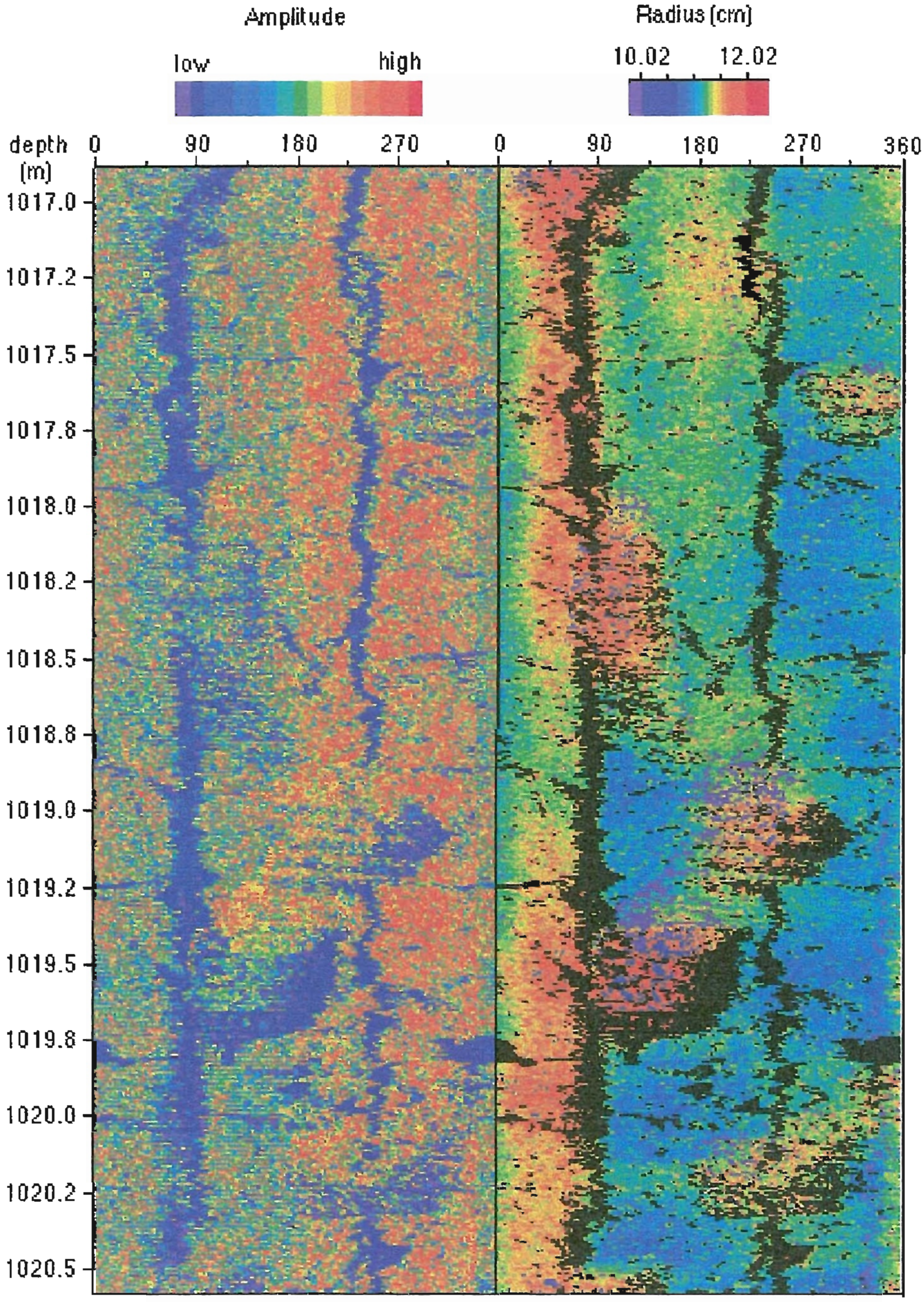

Figure 28: *Example for drilling induced vertical fractures observed in the borehole at Bödmódsstadir. Same principle of displaying the data as described in Figure 26. The fractures appear as vertical stripes of low reflection amplitude. Values for the radius calculated from travel time are missing for these stripes due to low amplitudes.*

that, the work will be focussed on theoretical investigations.

Besides K. Henneberg, the proposer and the subcontractor, the following scientists and technicians have worked in the subproject, especially the field campaigns: G. Axelsson (OS), H. Bäßler (Karlsruhe), C. Carnein (GFZ), E.T. Elíasson (OS), H.-J. Fischer (GFZ), S.T. Gudlaugsson (OS), G. Hermannsson (OS), M. Hönig (GFZ), S. Mielitz (GFZ), J. Palmer (GFZ), H. Sigvaldason (OS), Ó. Sigurdsson (OS), B. Steingrímsson (OS), V. Stefánsson and M. Thoms (GFZ).

3.4.1.4 Acknowledgements

We thank Orkustofnun for excellent preparation and support of the logging campaigns. We like to thank the owners of the boreholes for their permission to work in the wells. We are very grateful to the Geophysical Institute of Karlsruhe University for lending us a BHTV for the logging campaign in December 1997.

3.4.2 Subpart 4B: Radon related to seismicity in the South Iceland seismic zone

Associated contractor:
Páll Einarsson

Subcontractor:
Páll Theodórsson

3.4.2.1 Task 1: Build an improved LSC apparatus to measure the radon content of water and gas samples

Start: September 1997 (month 19)
End: April 1998
Responsible partner: UICE.DG

This task is at a final stage. The beginning of the project was delayed, first because expected funds showed not to be available for the completion of the project (Task 2), and then it was delayed due to some bureaucratic difficulties in transferring funds and resulting problems in scheduling the work.

The design and construction of a new system for automatic monitoring of radon in ground water for earthquake prediction is now in its final phase. The work was delayed seriously because of the late transfer of the grant, more than half a year later than expected. The main designer and constructor of the system left for graduate study in Copenhagen in the middle of the work, but he could continue part time on the project in Copenhagen and work on it during two short periods when he returned to Iceland. Despite this, the progress of the work is satisfactory and the system will hopefully be finished in the middle of April 1998. In order to optimize the radon monitoring work we have emphasized:

- Simple sampling, as this is done by a group of inexperienced people.
- Small size of water samples in order to facilitate the sending of samples.

- High sensitivity so that the radon content of a small water sample can be measured.
- Simple transfer of radon from water to scintillation cocktail.
- Automatic sample changing to minimize the work of measuring the samples.

The key to the present solution is a novel way of suppressing interfering background pulses, a method which seems not to have been put into routine use before. This is based on delayed counting, i.e. to count only pulses if a pulse has arrived in the preceding millisecond period. Only pulses from Po-214, a radioisotope in the radon decay chain, fulfil this requirement. This secures both low background and strict control over the proper functioning of the system. 200 ml water samples will be collected at the sampling stations and sent to Selfoss, where the radon system will be operated. The radon will be transferred to a toluene scintillation cocktail by bubbling 0.3 liter of air through the water sample and then through the scintillator in a conventional 20 ml liquid scintillation vial. The automatic sample changer is of the carousel type: 8 vials sit on the carousel, which is driven by a step motor. The scintillations are short light bursts that occur each time (1) a radioactive isotope emits an alpha- or a beta particle, (2) when a cosmic ray particle traverses the scintillator or (3) when an external gamma ray is absorbed. The scintillations are detected by a photomultiplier tube, which nearly touches the side of the sample vial. The tube gives an electric pulse each time a light burst arrives. The electronic system consists of a PC-computer and a dedicated interface unit, which is inside the sample changer chassis. This unit contains a power supply, the stepping motor driving circuit, regulated high voltage supply, pulse amplifier and a pulse size threshold detector. The PC-computer reads continuously the threshold detector and records delayed pulses. A major part of the work, the production of the carousel sample changer, is now finished. The electronic system has been designed, printed circuit boards have been made and electronic components are now being soldered to the boards. According to our plan the system will be fully assembled in the middle of April and then tested in our laboratory.

The new LSC apparatus will be set up at Selfoss, in the South Iceland seismic zone, in summer of 1998, where the routine radon measurements will be made. Sampling will be organized at some of the tested sampling sites of our 1977-1993 program, Flúdir, Hlemmiskeid, Kaldárholt, Laugaland, Thorleifskot and Bakki, possibly also at Öxnalækur and Ormsstadir. Tests for consistency and diurnal variations will be run in the beginning, and then regular sampling will begin, at least twice a week. See next section.

3.4.2.2 Task 2: Revive the radon sampling program in South Iceland

Start: March 1996 (month 1)
End: April 1998
Responsible partner: UICE.DG

This part of the project is funded by the SEISMIS project in Iceland. The start of the reviving of the radon sampling program has been delayed due to delays in building the necessary instruments (Task 1). Regular sampling of radon and analysis using the new instrument will start during the summer, funded by the SEISMIS project in Iceland.

In spite of the delays in finalizing the construction of the LSC instrument for the radon analysis and resulting delays in starting the regular radon monitoring, significant work has been carried out, cost by the contractor, which is a good preparation for the new regular radon sampling program. This work was concentrated in two areas:

- Analysis of radon time series collected in South Iceland 1977-1993. These represent some of the longest time series available. The results have been reported in several publications [45, 46, 47, 48] and a manuscript will be submitted to a refereed journal within the next month [49].

- Development and testing of some of the physical concepts behind the improved LSC apparatus. This work was funded by other projects. This work has been documented by Theodórsson [84] and in a recent book on weak radioactivity [85].

The work on analyzing the 1977-1993 radon time series can be shortly summarized as follows:

During the period 1977–1993 radon was monitored in water samples from several geothermal drill holes in the South Iceland seismic zone. The 3–16 years long time series are generally smooth functions with sharp anomalies or excursions superimposed on them. The anomalies show a distinct relationship with earthquake activity in the region. About 35% of all measured anomalies are related in time to earthquakes. More than 30% of all seismic events satisfying certain magnitude-distance criteria (M $\geq$2.0 and M $\geq 2.4 \log D - 0.43$) are accompanied by anomalous excursions in the radon time series. Seven events were preceded by anomalies detected at more than one station. One event was accompanied by anomalies at 5 stations. Majority of the anomalies are positive and occur before the respective seismic events. There is a 38% probability that a measured, positive anomaly is immediately followed by an earthquake. The efficiency of the sampling stations at detecting earthquake-related anomalies is found to be positively correlated with the average radon activity of the water, which is related with the radioactivity of the host rock. The success rate of a monitoring network of radon for the purpose of earthquake forecasting can most likely be improved from these figures by increasing the sampling rate, refining the definitions of what constitutes a radon anomaly at each sampling station, and a careful selection of sampling sites. Several anomalies were found that are related to the eruptions of the nearby volcano Hekla in 1980 and 1981.

3.5 Subproject 5: Active deformation determined from GPS and SAR

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Sigurjón Jónsson did work 50% in the project from March 1, 1996 to May 1, 1997. Funded by EC.

Subproject 5 is divided into two subparts, A and B.

3.5.1 Subpart 5A: SAR interferometry

3.5.1.1 Task 1: Analysis of SAR images from the ERS–1 and ERS–2 satellites

Start: March 1996 (month 1)
End: September 1997 (month 19)
Responsible partner: CNRS.DTP
Cooperative partners: NVI, UICE.DG

Kurt L. Feigl, Freysteinn Sigmundsson, Helene Vadon and Didier Massonnet

The objective of this work (according to the revised work description) was to calculate and interpret Synthetic Aperture Radar (SAR) interferograms to capture interseismic deformation, spanning at least one year.

This goal has been reached and even exceeded. We have studied two areas in Iceland using radar interferometry, the Reykjanes Peninsula oblique plate boundary in SW-Iceland and the Krafla volcanic system in Iceland. In both areas we have captured interseismic deformation spanning up to three years, thereby validating the use of radar interferometry for the monitoring of crustal deformation in the seismic and volcanic zones in Iceland. The results help to understand the mechanism of oblique rifting, the behaviour of volcanic zones in post-eruptive periods, and the generation of earthquakes. The work was conducted in collaboration with Didier Massonnet and Helene Vadon at CNES, Toulouse. Initially a number of interferograms were calculated at CNES for each of the two study areas. These interferograms have then been successfully modelled, interpreted, and published in reviewed scientific journals of international repute.

In the first study area, the Reykjanes Peninsula in SW-Iceland, we have used satellite radar interferometry to map the satellite-view component of a plate-boundary velocity field, as well as volcano deformation. The area is the direct onland structural continuation of the submarine Mid-Atlantic Ridge. Oblique spreading between the North American and Eurasian plates of 1.9 cm/year occurs there, causing both shearing and extension across the plate boundary. Using ERS-1 images from the 1992–1995 period we have formed interferograms, spanning up to 3.12 years. The fringes in these interference patterns are clear, indicating that the dielectric properties of the ground surface in this area remain unchanged. Moreover, these fringes measure crustal deformation. The most obvious deformation is secular deflation of the Reykjanes central volcano, averaging to 15 mm/year, probàbly caused by compaction of a geothermal reservoir in response to its utilization by a power plant. The deflation we infer is in good agreement with levelling data. This gives confidence in the interpretation of more subtle deformation signal in the interferograms, fringes aligned in the direction of the plate boundary caused by plate boundary deformation. Relying partly on geologic evidence, we assume the shape of the horizontal and vertical crustal velocity field. We estimate best-fit model parameters by maximizing the global coherence of the residual interferograms, the difference between observed and model interferograms. The data constrain the locking depth of the plate boundary to be about 5 km. Below that level the plate movements are accommodated by continuous ductile deformation, not fully balanced by inflow of magma from depth, causing about 6.5 mm/year subsidence of the plate boundary. Previous regional geodetic data agrees with this interpretation.

For the other study area, the Krafla spreading segment in North Iceland, we have used radar interferometry to map deformation in the 1992–1995 period, related to readjustement of the spreading segment to crustal rifting. Three images acquired by the ERS satellites were used to produce 3 interferograms. Time-average deformation in the 1992–1995 period amounts to 24 mm/year subsidence above a shallow magma chamber at Krafla, superimposed on 7 mm/year along-axis subsidence of the spreading segment. The rate of subsidence decays with time, it appears two times lower in 1993–1995 than in 1992–1993. Several process may contribute to the subsidence, all which relate to ongoing post-rifting adjustment of the spreading segment after a rifting episode in 1975–1984. Subsidence above the magma chamber may relate to magma solidification and cooling; solidification of $10^6 - 10^7$ m^3/year of magma is required to fully explain it. Processes likely to contribute to subsidence along the Krafla rift are ductile flow of material from the rift axis and cooling. Cooling by 0.5°C per year, the measured cooling of groundwater at the rift, of 1.5 km wide and 3 km high zone along the rift axis could explain the subsidence. The time decaying subsidence may also reflect time decaying ductile flow of material from the rift axis. The relative contributions of cooling and ductile flow to the subsidence is difficult to assess, but both processes indicate the readjustment of the spreading segment to crustal rifting. The current low rates of deformation at Krafla suggest the readjustment is in a final stage, a decade after the end of the 1975–1984 rifting episode.

3.5.2 Subpart 5B: GPS geodesy

3.5.2.1 Task 1: Installation

Start: March 1996 (month 1)
End: June 1997 (month 16)
Responsible partner: NVI
Cooperative partners: UUPP.DGEO, IMOR.DG

Freysteinn Sigmundsson, Sigurjón Jónsson, Páll Einarsson and Reynir Bödvarsson

The initial objective was to initiate continuous GPS measurements in South Iceland to determine temporal variations in deformation rates.

In 1996, we reoriented our priorities to focus on interesting results uncovered since the beginning of the study in 1994:

i) the SAR-interferometry study was given higher priority than GPS, ii) we studied elevated seismic activity in the Hengill area, at the the western end of the South Iceland seismic zone (SISZ), relying on conventional GPS and levelling. New results on temporal variations in deformation rates in this part of the seismic zone have been interpreted and published.

Nonetheless, we have made some progress with continuous GPS measurements. One GPS instrument (Trimble 4000 SST) has been installed and operated in a semi-continuous mode near the center of the SISZ (station Saurbær), since March 1997. Automatic transmission of the data through the SIL system has not yet been accomplished, rather the data is transported through the Internet.

3.5.2.2 Task 2: Deformation rates

Start: August 1996 (month 6)
End: February 1998 (month 24)
Responsible partne: NVI
Cooperative partners: UICE.DG, IMOR.DG

Freysteinn Sigmundsson and Páll Einarsson

The data from the semi-continuous GPS station in the SISZ has been analyzed and the movement of the station is already significant. Relative to a station in Reykjavík (on the North-American plate), the velocity of the Saurbær station is estimated 11.5 mm/year in direction N87°E. For the first year of observation the relative velocity appears steady in time, about 1 mm/month during the last year. There is no suggestion of temporal variation in the deformation rate in this part of the seismic zone. Also, the inferred velocity is close to expected, about half the 2 cm/year full spreading vector in South Iceland. If the GPS-station were located to the south of the seismic zone (on the Eurasian plate), we would expect to observe the full spreading vector. The semi-continuous data collected sofar will serve as a reference, against which we can compare future measurements.

Based on conventional GPS and levelling, we have information on temporal variation in deformation rates in the Hengill area, at the western end of the seismic zone. There an unusually persistent swarm of earthquakes (M<4.0) has been in progress since 1994. Activity is clustered around the center of the Hrómundartindur volcanic system, in the Hengill area. Geodetic measurements indicate a few centimeters uplift and expansion of the area, consistent with a pressure source at 6.5 ± 3 km depth beneath the center of the volcanic system. The system is within the stress field of the South Iceland transform zone, and majority of the recorded earthquakes represent strike–slip faulting on subvertical planes. We show that the secondary effects of a pressure source, modelled as a point source in an elastic halfspace, include horizontal shear that perturbs the regional stress. Near the surface, shear stress is enhanced in quadrants around the direction of maximum regional horizontal stress, and diminished in quadrants around the direction of minimum regional stress. The recorded earthquakes show spatial correlation with areas of enhanced shear. The maximum amount of shear near the surface caused by the expanding pressure source exceeds 1 microstrain, sufficient to trigger earthquakes if the crust in the area was previously close to failure. This study has improved the understanding of triggering of earthquakes in volcanic areas.

3.6 Subproject 6: Formation and development of seismogenic faults and fault populations

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Gudmundsson hired a scientific assistant to work for 2 years 50% on this project (50% on volcanic risk). This assistant did work on all aspects of the project: aerial photographs, maps, manuscripts, illustrations, etc. Helgi Torfason was hired to carry out specific tasks, mainly very detailed maps of specific seismogenic faults in the South Iceland seismic zone (SISZ). Gudmundsson has also been starting a collaboration with Philip Meredith (University College, London, who is also in PRENLAB-2); that collaboration has involved some travel cost for Meredith.

Francoise Bergerat and Jacques Angelier had a student, Segolene Verrier, working on the paleostress fields of the SISZ, but that student has not been paid from the project.

Thierry Villemin also had a student working on the project, but no salary from the project was paid to that student. Sigurdur Th. Rögnvaldsson also worked on the project.

3.6.1 Subpart 6A: Paleostresses

3.6.1.1 Task 1: Determine the paleostress tensor

Start: July 1996 (month 5)
End: January 1998 (month 23)
Responsible partner: CNRS.TT
Cooperative partners: NVI, IMOR.DG

Francoise Bergerat and Jacques Angelier

The paleostress tensors for many localities in the SISZ have been made, using fault-slip datasets. Preliminary work on Tjörnes fracture zone (TFZ) was carried out last summer, and some paleostress tensors for this zone have already been calculated. This task was in collaboration with Ágúst Gudmundsson.

3.6.1.1.1 *Detailed analysis of focal mechanisms of earthquakes and recent faulting in the central part of the SISZ (work carried out with Gudmundsson and Rögnvaldsson)*

First, a seismotectonic analysis was carried out in the Vördufell mountain considered as a test area (64.05°–64.12°N and 20.5°–20.6°W). Good outcrops permit geological study of the recent faults which affect the quaternary lava pile, and focal mechanisms of shallow earthquakes are available. Among the earthquakes recorded in southern Iceland by the SIL network with determinations of earthquakes mechanisms, a dataset of 68 earthquakes, occurring in this area from 1991 to 1995, was used. 18 data corresponding to quarry blasts were rejected, and 50 focal mechanisms of natural earthquakes were selected.

The variety of these focal mechanisms of shallow earthquakes shows that the whole set cannot be accounted for by a single tectonic stress state. Numerous mechanical analyses were done, based either on geometrical considerations or on stress-slip consistency. Within the range of acceptable misfits (defined as a function of both the assumptions about stress-slip relationships and the uncertainties of data), a separation of two main groups of data (and related stress regimes) accounts for the whole dataset. First, using the P- and T-dihedra method, the general consistency within each group is highlighted. The largest subset includes 30 strike-slip, 4 reverse and 4 normal mechanisms. It is consistent with NW-SE compression and NE-SW extension, in agreement with left-lateral shear along E-W trends and right lateral strike-slip on N-S trending faults. The smallest subset includes 8 strike-slip, 1 reverse and 3 normal mechanisms. Its indicates NE-SW extension and NW-SE compression, with more dispersion than for the main group. Second, numerical inverse methods were used in order to compute the average stress tensors which best fit the observed fault plane solutions. Two main methods were used: the 4-D search (R4DT-R4DS), and the direct inversion method (INVD). Contrary to the P- and T-dihedra method, these methods require a choice among nodal planes. Because of its arbitrary character in geological terms, the choice of the nodal plane which best fits an average stress tensor was not adopted as an unique criterion. The geological study in the field and from aerial photographs allowed identification of the orientations of faults, fractures and other zones of weakness at both the scale of outcrops and that of the Vördufell mountain. A comparison between fault plane solutions of earthquakes and fault slip data observed in outcrops was carried out. Combining these three criteria resulted in the final selection. In terms of numerical estimators considered alone, one may simply choose the best fitting fault plane solution for each earthquake. This was not done because, dealing with shallow earthquakes, reasonable choices between nodal planes imply consideration of the geological structure.

For each subset, the orientation of stress axes, the ratios of principal stress differences and the misfit estimators depend relatively little on the method adopted. The results are quite significant for the main subset. For the secondary subset, the misfits are larger despite its smaller size, which indicates inhomogeneity. Weighting data according to the quality of individual determinations did not result in significant improvement which suggests that mechanisms with small weights are quite acceptable. The main difference between the subsets mainly results from a kind of permutation between extreme stress axes. The direction of the maximum stress average N60°E for the main subset and N120°E for the subsidiary one, while the directions of the minimum stress average average N150°E and N40°E, respectively. The main subset reflects regional tectonic mechanisms, whereas the secondary subset, mechanically less consistent, principally reflects fault rebound and local accommodation.

Before examining earthquake data, a surprising result of geological studies of fault slip data in the field was the identification of two opposite tectonic regimes, respectively characterized by a NW-SE extension (the major one, principally including strike-slip and normal faults) and a NW-SE compression (the minor one, principally including strike-slip and few reverse faults). We point out first that for most of geological and geophysical data independently collected, similar tectonic regimes dominated by NW-SE maximum stress and NE-SW minimum stress were identified, and second that both these studies revealed permutation of extreme stress axes for the remaining data.

We conclude that the Vördufell area is dominated by NW-SE extension, principally accommodated by strike-slip and normal faulting, in agreement with the general behaviour of the SISZ. Local stress permutations, however, play a major role, resulting in subsets of conflicting mechanisms for both the present-day shallow earthquakes and the quaternary fault movements.

3.6.1.1.2 *Seismi-tectonic studies in the whole SISZ (work carried out with Gudmundsson and Rögnvaldsson)*

After the first study on Vördufell, the field studies have been carried out in September 1996 in the whole SISZ in order to collect fault slip data measurements and reconstruct paleostress tensor. The collection has been made in some selected sites in late Tertiary and Pleistocene lavas and hyaloclastites and in postglacial lavas. The areas investigated were the Skardsfjall, Hestfjall and Búrfell mountains, the Grímsnes area and the canyons of Stóra Laxá and Stóra Mástunga. This study has been completed by analysis of focal mechanisms of earthquakes in the same areas. We collected about 700 brittle tectonic data at 25 sites in Upper Pliocene to Holocene basalts and hyaloclastites. At each site the whole dataset reveals two opposite stress regimes, each including normal and strike-slip faulting. The analysis of the strike-slip faults in the major data subset indicates paleostress tensor with subhorizontal σ_1 and σ_3 axes, the trend of σ_3 being N270°E to N340°E (main trend: N315°E). The normal faults in the major subset characterize vertical σ_1 and horizontal σ_3, also trending N270°E to N340°E. In the minor data subsets, the direction of σ_3, for the strike-slip faults as well as for the normal ones, ranges from N20°E to N80°E (N45°E on average). The major stress regime includes 70% of the total population of faults. Of a total of 718 fault slip data, 55% indicate primarily normal-slip and 45% primarily strike-slip. The ratio normal/strike-slip faults is lower than in other areas of Iceland. Moreover, many normal faults were generated in the western rift zone segment, then drifted out of it. The above results indicate that the dominating stress field in the SISZ favours strike-slip faulting, with an horizontal σ_3 axis trending approximately WNW-ESE to NW-SE. We point out, however, that in addition, there is a contrasting minor stress field, characterized by approximately NNE-SSW to NE-SW extension. These results were compared to the stress regimes determined from earthquakes mechanisms. The determination of the stress regimes is done through calculation of stress tensors, involving the use of inverse methods. Preliminary analyses of focal mechanisms recorded by the SIL network revealed the presence of two contrasting stress regimes. The crucial problem of the choice between nodal planes of double couple focal mechanisms is solved in two ways. First, some methods do not require the choice between the nodal planes, such as for the right dihedra (P- and T- dihedra) method. Second, for those inversions requiring choices between nodal planes, and because the earthquakes studied are very shallow, the rich geological information on the fractured medium deserves attention. We use an integrated approach including four criteria; geophysical and geological: consideration of nodal plane attitudes as compared with geological discontinuities, comparison with recent fault mechanisms observed in the field, consideration of mechanical likelihood for each fault solution, and best fit criterion relative to the stress tensors calculated. The systematic use of these criteria for nodal plane selection within a weighted approach (reliability, magnitude, depth, etc.) allowed better determination of the stress regimes in the SISZ. As for faults collected in the field, major NW-SE extension is in agreement with the left-lateral behaviour of the E-W seismic zone. A minor NE-SW extension is attributed to rebound phenomena, local block accommodation and magmatic effects. For both these regimes, strike-slip mechanisms prevail, many normal and few reverse mechanisms being also present. Permutations between stress axes, σ_2/σ_3 and σ_1/σ_2, are common.

3.6.1.1.3 *Stress tensor determination from focal mechanisms: development of new methodology, especially aiming at solving the problem of the choice between the nodal planes*

The reduced stress tensor includes the orientations of the three principal stress axes σ_1, σ_2, σ_3

and the ratio of principal stress differences, $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$. For a homogeneous subset of double couple mechanisms, this tensor can be determined through inversion of data, under the classical assumptions of mechanical consistency. This is a classical problem for geologists in brittle tectonics. In the case of focal mechanisms, however, there is an additional problem, that of the choice between nodal planes of double couple focal mechanisms. Classically, the answer either consists of avoiding the choice by using the right dihedra (P- and T- dihedra) method, or aims at performing this choice in various ways prior to numerical inversion of data. It is demonstrated that there is a third possibility, which allows one to carry out the mathematical inversion of data and to obtain the complete reduced stress tensor, without doing any choice between the nodal planes of each earthquake. Furthermore, the formulation is such that it is possible to carry out the inversion by pure analytical means, based on cancelling partial derivatives relative to the unknowns of the reduced stress tensor. The solution of the problem is thus straightforward and numerical problems are avoided. Using a simple direct inversion of double-couple mechanisms of earthquakes enables one to focus on a more important problem, that of the inhomogeneity of datasets in terms of stress states. Separation into subsets is made easier because in the new method calculation is extremely brief despite the complexity of algebraic derivations.

3.6.1.2 Task 2: Participate in a cooperative effort in the overall project to reconstruct the stress field in these seismic zones

Start: July 1996 (month 5)
End: February 1998 (month 24)
Responsible partner: CNRS.TT
Cooperative partners: NVI, IMOR.DG

Francoise Bergerat and Jacques Angelier

This task has involved collaboration with Thierry Villemin and Olivier Dauteuil. It focussed on deformation pattern, morphology and tension-shear deformation in the Krafla fissure swarm.

3.6.1.2.1 *Deformation pattern and morphology in the Krafla fissure swarm: the Mófell area (work carried out with Dauteuil and Villemin)*

In the northern part of the rift, the deformation affects an area 60 km wide. In this area most of the active extensional deformation is localized into fissure swarms, 1 to 5 km wide. Major volcanic centers are present along swarm axes. We analyzed the partitioning of extension into a major fissure swarm: the Krafla fissure swarm. The studied area was a 4.5 km^2, near the Mófell mountain, north of the Krafla volcano and composed of basaltic lava flows younger than 10,000 years.

We used two information sources to estimate the spatial distribution of strain in this area. The first dataset was obtained from detailed mapping structures combining field measurements, SPOT satellite images and aerial photographs. Most faults and fissures trend N010°–030°. The fissures width ranges from 10 to 200 cm. The faults have a maximum vertical throw of 20 m. The second dataset used is a network of more than 450 geodetic points providing an accurate record of topography within the fissure swarm. This allows us to determine exactly the amount of tilt blocks (less than 2 ees), in an area with a weak extensive rate since 10,000 years. This network was used to define blocks with planar upper surface. The plunge and the trend of each plane were estimated and analyzed in compared to the fault network. The plunge values vary from 0.2° to 3°, with trend comprised between N030° and N100°. The tilt of the blocks was used to estimate the stretching accommodated by the block rotations.

A balance of the extension accommodated by block tilting and fissure dilation is discussed along E-W profiles and on maps. Assuming that the whole area is affected by the same stretching amount, important variations are thus highlighted inside the system.

3.6.1.2.2 ***Tension-shear deformation in the Krafla fissure swarm: the Leirhnjúkur area (work carried out with Dauteuil and Villemin)***

The geometry of the fracture pattern of a small graben (studied area: 280 m long and 150 m wide) in the Krafla fissure swarm was analyzed in detail. Based on geodetic analysis of the present-day topography at the top of Holocene basaltic lava flows which fill the axial rift zone, the deformation of this initially horizontal surface can be reconstructed. Extensional deformation is localized at all scales and block tilting, albeit present, remains minor.

Using simple models of the surface expression of normal faults, the geometrical characteristics of the topographic features related to active deformation during tectonic-volcanic events are quantitatively analyzed. At crustal depths of about one kilometer, normal faults are present and have an average 70° dip. Comparison with the dip distribution of older normal faults observed in the uplifted and eroded shoulders of the rift zone, at paleodepths of 1-2 km, indicates that this dip determination is valid. Comparisons between the local case study and structural analyses of active fissure swarms on a larger scale suggest that normal faulting plays a major role in the middle section of the thin, newly formed brittle crust of the rift zone. In the axial oceanic rift zone of NE-Iceland, the extensional deformation in the upper crust is dominated by horizontal tension and normal shear, their relative importance depending on depth. Absolute tension dominates in the uppermost several hundred meters of the crust, resulting in the development of fissure swarms. Effective tension plays an important role at a deeper level (2-5 km), because of the presence of magmatic fluid pressure from magma chambers which feed dyke injections. At crustal depths of about 1 km, normal shear prevails along fault planes which dip 60°–75°. This importance of normal shear at moderate depth, between upper and lower crustal levels where tension prevails, is pointed out. Within the extensional context of rifting, these variations of tectonic behaviour with depth are controlled by both the lithostatic pressure and the effective tension induced by the presence of magmatic fluid pressure.

3.6.2 Subpart 6B: Field and theoretical studies of fault populations

3.6.2.1 Task 1: Make a detailed study of the faults in the TFZ and the SISZ

Start: July 1996 (month 5)
End: February 1998 (month 24)
Responsible partner: NVI

Cooperative partners: IMOR.DG, UUPP.DGEO

Field inspection of the faults in the SISZ was made in the summer of 1996. Detailed mapping of individual seismogenic faults in the Holocene lavas of the SISZ has already resulted in detailed maps of the Leirubakki-Svínhagi fault and many other faults were studied. This work, which now includes considerations of fluid pressure effects and the relation of seismogenic faults to geothermal systems, is made in collaboration with Helgi Torfason, Icelandic Energy Authority (OS).

A map of the TFZ has been been made in collaboration with Thierry Villemin (see Task 5), who, with his students, is now primarily responsible for this map.

3.6.2.1.1 *The SISZ*

The work has focussed on aerial inspection of the main fault systems. Some of the faults have been selected for a detailed areal study for comparison with on-land field studies. The principal questions addressed are: Why are the fault systems in the Holocene lava flows so complex? How do these systems compare with the nearby faults in the Pleistocene rocks.

With the view of answering these questions partly, a detailed aerial inspection and mapping of the Leirubakki-Svínhagi seismogenic fault has been made. This fault is just over 7 km long strikes N12°. The fault consists of many segments within a zone that is 100-250 m wide. In the northern part of the zone, individual fractures strike around N12°, around N15° in the middle part, and around N25° in the southernmost part. The fractures thus become more easterly striking towards the south. The fractures consist of en echelon segments, with small push-ups or hillocks as well as pull-apart structures between the nearby ends of the segments. These structures are associated with areas of transpression and transtension, respectively, along the main strike-slip fault.

The Leirubakki-Svínhagi fracture is location in the 9000 years old Thjórsárhraun lava flow. The age of the fracture itself is, however, not known. It is obviously less than 9000 years old, but may be only several hundred years old. At the southern end of the fracture, near the farm Svínhagi, hot water (15-20°C) emits from the fracture. The presence of warm water in the fracture indicates that it is not very old as otherwise it would have been sealed up with silica.

There are at least three main trends of fractures associated with the Leirubakki-Svínhagi fault: NNE, ENE and WNW. Most of these cracks are presumably strike-slip faults. In addition, there are NE trending tension fractures. All these trends are also found in the fault populations in the nearby Pleistocene rocks. Nevertheless, the WNW trend of segments associated with the Leirubakki-Svínhagi fault is unusually clear and conspicuous and must be explained by any model that attempts to account for the fracture pattern associated with the SISZ.

Many other faults in the Holocene lava flows have been studied, on land, by aerial inspection, and from aerial photographs. These results have been compared with those obtained by field studies of faults in the nearby Pleistocene areas of the SISZ. As was to be expected, the same populations of faults occur in the Holocene lava flows as in the Pleistocene rocks; these populations are discussed in more detail in the section on fault populations below.

Work on the SISZ as regards the field studies and paleostresses is in close collaboration with Jacques Angelier, Francoise Bergerat, Sigurdur Th. Rögnvaldsson and Helgi Torfason. Concerning analytical studies on fault development, a close collaboration is with Maurizio Bonafede and Maria Elina Belardinelli. A manuscript on the stress fields and fracture pattern in the central part of the SISZ has already been submitted, and another manucript, combining field and theoretical studies on faults in the eastern part of this zone, is in preparation.

3.6.2.1.2 *The TFZ*

This work has focussed on two aspects of seismotectonics: (1) to combine field and numerical studies with seismic studies from the extension of the SIL network in this area, (2) to study the effects of faulting on all scales on the migration of crustal fluids in a major fault zone like the TFZ. As regards the first aspect, a manuscript has already been submitted to JGR [67]. The purpose of this paper is to combine a detailed seismic analysis by Sigurdur Th. Rögnvaldsson and Ragnar Slunga with on-land field studies of the faults in the TFZ. Our conclusion is that many of the strike-slip faults in the Grímsey fault, as well as those associated with the Dalvík "lineament" are northerly trending sinistral faults rather than westerly trending dextral faults. We are working on numerical (boundary element) models with a view of explaining the current stress field in this area. As regards the second aspect an abstract entitled: *Development of permeability in fault zones*, was presented at the XXIII EGS General Assembly in Nice, April 1998. This work is discussed further in the next section. Work on the TFZ is in collaboration with Jacques Angelier, Francoise Bergerat, Sigurdur Th. Rögnvaldsson, Ragnar Slunga and Thierry Villemin.

3.6.2.1.3 *Effects of fluid pressure on fault development*

Pore-fluid pressure greatly affects the probability of failure and reactivation of the faults, both in the SISZ and in the TFZ. A detailed study has been made of the mineral veins (old channels of geothermal water) on the fault planes in the Pleistocene rocks of the SISZ and in the Pleistocene-Tertiary rocks in the TFZ. One of the principal questions addressed in this study is: how rapidly do seismogenic faults in these zone heal and how do changes in fluid pressure in one region (e.g. in association with major earthquakes or volcanic eruptions) affect slip on faults in other regions. It is likely that changes in fluid pressure can be transmitted over considerable distances and thus trigger earthquakes in areas relatively far away from the source of the initial pressure change. Fluid pressure also affects friction on fault planes, hence the probability of fault slip.

This work has now been extended to the Fennoscandian area, where the detailed data on seismicity and postglacial uplift make a comparative study with the seismic zone in Iceland important. The stress field controlling the seismic zones in Iceland is primarily related to the horizontal divergent plate movements, and the crustal structure of Iceland is essentially oceanic. By contrast, the stress field controlling faulting, fluid flow and current seismicity in Fennoscandia appears to be largely generated by the postglacial uplift in this region, and the crustal structure of Fennoscandia is entirely continental. A manuscript entitled: *Postglacial crustal doming, stresses and fracture formation with application to Norway*, has been submitted to Tectonophysics [30].

This research is particularly important in view of the major geothermal activity associated with earthquake fractures in South Iceland and elsewhere. The work on earthquake fracture healing is partly in collaboration with Philip Meredith, University College, London.

3.6.2.2 Task 2: Boundary-element models of the faults

Start: March 1996 (month 1)
End: September 1997 (month 19)
Responsible partner: NVI
Cooperative partner: UBLG.DF

This work was carried out in collaboration with Maurizio Bonafede and Maria Elina Belardinelli, who use analytical methods and has focussed on the well-defined faults in the Holocene part of the SISZ. A manuscript, entitled: *Secondary earthquake fractures generated by a strike-slip fault in the SISZ* [15], has been submitted to JGR.

3.6.2.2.1 ***Analytical and numerical studies on fault populations***
Fault populations develop in space and time. Both analytical and numerical studies are important in order to be able to predict the evolution of fault populations, in particular those in the SISZ and in the TFZ. This work is made in collaboration with Maurizio Bonafede and Maria Elina Belardinelli. Fault populations generally show power-law (or fractal) frequency distributions as regards fracture length and displacement, that is either fracture length and width (for tension fractures) or fracture length and vertical or horizontal displacement (for faults). In addition, there is commonly a linear relationship between the lengths and widths of tension fractures, and between the length and displacements (vertical or horizontal) on faults. For many fracture populations studied in the Holocene lava flows in Iceland there is, however, a very large scatter in the data, so that two fractures of the same length in the same population may have widely different displacements. A model has been developed where this large scatter is partly attributable to the fracture displacements being related to different controlling dimensions. For some fractures the displacement is controlled by the strike dimension, for others by the dip dimension. A manuscript has been submitted on these results.

3.6.2.3 Task 3: Boundary-element studies of the TFZ and the SISZ

Start: March 1996 (month 1)
End: September 1997 (month 19)
Responsible partner: NVI
Cooperative partners: CNRS.TT, IMOR.DG

General models have already been made and give some of the most interesting results obtained in Subpart 6B. The models indicate that stress migration is indicated schematically be the wave-like migration of the countours of constant shear stress as the loading of the fault zone (because of plate movements) is increased. The first contours to appear are those in the areas of highest shear stress concentration. As the loading (or displacement) is increased, however, these contours migrate over wider parts of the seismic zone, while the stress concentration in the initial high-stress "source"areas increases. The actual shear stress in the source areas does not become greater than the frictional equilibrium on faults in these areas allows; the stress is kept within these limits by repeated slip on many small faults. Because of increased loading, however, the regions where the shear-stress magnitude makes slip on faults possible gradually increases in size and depth, until the whole volume associated with the largest rupture area that the seismic zone is capable of generating is stressed to failure. These results offer the possibility of forecasting the largest earthquakes by detailed monitoring of the evolution of the seismicity in that zone.

Many of the results from Subpart 6B, including some of those indicated above, will be included not only in the scientific papers listed below, but also in the book: *The Geology of Iceland and Mid-Ocean Ridges*, that Gudmundsson is writing [31].

3.6.2.4 Task 4: Make analog models of the SISZ and the TFZ

Start: March 1996 (month 1)
End: February 1998 (month 24)
Responsible partner: NVI
Cooperative partner: CNRS.TT

Olivier Dauteuil has already made analog models of transform faults in general and published recently in JGR. Dauteuil is now applying these models to the SISZ and the TFZ. This work also includes a continuing study of large-scale Holocene crustal deformation in the area south of the TFZ, using glacio-morphological data. The purpose of this work is partly to attempt to detect the Holocene crustal deformation in the area that could be related to the controlling stress field of the TFZ.

3.6.2.5 Task 5: Detailed tectonic map of the TFZ

Start: July 1996 (month 5)
End: December 1997 (month 22)
Responsible partner: NVI
Cooperative partners: IMOR.DG, CNRS.TT

Detailed tectonic map of TFZ. This work is on schedule. The main part was made in the summer of 1997 to be continued in the summer of 1998 in collaboration with Ágúst Gudmundsson and Freysteinn Sigmundsson.

3.6.2.5.1 *The TFZ*

Part of the work on the TFZ is made in collaboration with Thierry Villemin, particularly on the on-land parts of the Húsavík-Flatey fault. A detailed GPS network, set up by the NVI in 1994, was expanded in collaboration with Villemin in 1995 and again in 1997. Altogether, there are now 44 GPS points in this area. In 1997, 32 points were remeasured, as well as the 12 new points. The results from 1997, compared with those from 1995, are not yet available but should be so later in 1998. One objective of this work is to correlate the seismicity on the Húsavík-Flatey fault with the on-land slip of the fault, as measured by the GPS network. A paper was presented at the ninth biennial EUG meeting in Strasbourg on some of the results of this work.

Mapping of the whole Krafla fissure swarm has also been made and a detailed map of the junction between the Húsavík fault and the rift zone is under the way. A SAR study is planned of the TFZ and its junction with the rift zone.

3.7 Subproject 7: Theoretical analysis of faulting and earthquake processes

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3.7.1 Subpart 7A: Crust-mantle rheology in Iceland and Mid-Atlantic Ridge from studies of post-seismic rebound

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Andrea Antonioli was supported with a fellowship from October 1, 1996, to September 30, 1997. He did work 100% of his time on the project.

Maria Elina Belardinelli did work 30% of her time on the project from March 1, 1996.

Maurizio Bonafede did work 20% of his time on the project from March 1, 1996.

Antonio Piersanti did work 30% of his time on the project from March 1, 1996.

Giorgio Spada did work 30% of his time on the project from March 1, 1996.

Eleonora Rivalta did work 50% of her time on the project from April 1, 1997.

The subproject is mainly focussed on modelling the stress and the displacement fields due to earthquakes and to rifting episodes in Iceland. Emphasis is posed on the interaction between the two processes following stress relaxation in the asthenosphere. From these studies we may obtain a significantly improved understanding of the space and time relationships between earthquakes and other geophysical phenomena governing the state of stress in the crust.

Global studies of post-seismic and post-rifting rebound in Iceland were performed employing spherical, radially stratified earth models [59, 2, 56]. Earthquakes and rifting episodes are modelled in terms of suitable distributions of equivalent body forces. The method of solution is based on a spectral approach to the equations which govern the deformations of a spherical earth due to seismic sources located within the crust. The method, has the advantage of including a realistic mantle layering and a self-consistent description of the gravitational effects. Post-seismic and post-rifting deformation are proved to be significant transient components of plate motion. Studies on a local scale are performed employing the theory of elastic dislocations in layered media. Comparison is constantly made with observations obtained in the framework of structural geology [13, 19, 15, 21]. Near-field studies on the stress field induced by ridge activity are performed employing original methods of theoretical fracture mechanics in plane-strain configuration. The singular integral equations governing fault and ridge dynamics are solved by means of suitable polynomial expansions, yielding a linear inverse problem which is solved by standard numerical methods [19, 20].

3.7.1.1 Task 1: Inferences on the regional stress field from the study of secondary earthquake fractures

Start: March 1996 (month 1)
End: June 1997 (month 16)
Responsible partner: UBLG.DF
Cooperative partner: NVI

Maurizio Bonafede, Maria Elina Belardinelli and Ágúst Gudmundsson

Most earthquakes in the South Iceland seismic zone (SISZ) occur on NNE-trending dextral and ENE-trending sinistral strike-slip faults. Many of the earthquake fractures rupture the surface in basaltic (pahoehoe) lava flows of Holocene age. The resulting rupture zones display complex en-echelon patterns of secondary structures including arrays of (mostly) NE-trending fractures and hillocks (push-ups). The field data indicate that the arrays consist of both mixed-mode cracks and pure mode-I cracks, concentrated in a narrow belt trending in the direction of the strike-slip faults in the Pleistocene bedrock buried by the Holocene lava flows. For the dextral faults, the angle between the strike of the fault array and the strike of individual secondary fractures ranges over several tens of degrees, but is commonly $10-30°$ (Figure 29). Modeling indicates that if the arrays consist of pure tension (mode-I) fractures, the angle between the strike of the hidden fault and each tension fracture must be between $22.5°$ (if the prestress dominates with respect to the seismic stress) and $45°$ (if the prestress is negligible), assuming that faulting occurs according to the Coulomb-Navier

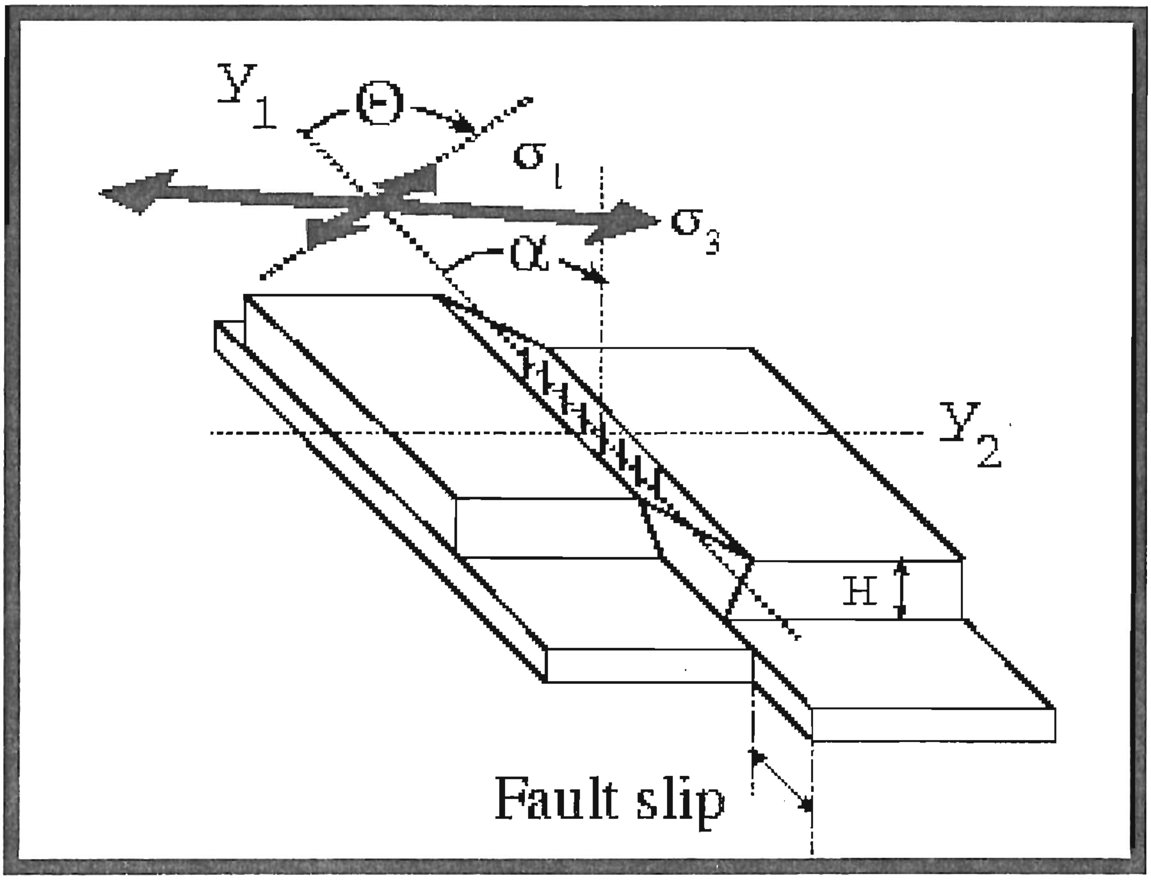

Figure 29: *See text for discussion.*

failure criterion and the prestress is purely deviatoric. If the arrays consist of mixed-mode cracks, the angle between the fault strike and individual cracks is lower than 22.5°, this value being attained if the seismic stress dominates.

Modelling suggests that all fractures, being narrowly concentrated near the fault strike, form as a consequence of slip-induced local stresses during major earthquakes, small angle fractures being predominantly mixed-mode cracks, while higher angle fractures may be pure mode-I cracks. The role played by the regional prestress field is found to be significantly dependent on the rigidity contrast between the shallow layer and the basement rock. Useful inferences on the regional stress field can be extracted from such modelling. Results have been submitted for publication [15], and were discussed in several meetings and workshops [10, 11, 12, 16, 14]. Further results, on the role of rheological properties in triggering large aftershocks have been published [13].

3.7.1.2 Task 2: Global post-seismic rebound following strike-slip and normal faulting earthquakes

Start: March 1996 (month 1)
End: February 1997 (month 12)
Responsible partner: UBLG.DF

Maurizio Bonafede, Antonio Piersanti and Giorgio Spada

In order to study the post-seismic rebound following large lithospheric earthquakes we have built a spherical, self-gravitating earth model with viscoelastic rheology [59]. This model, which allows to compute coseismic and postseismic displacements associated to lithosperic earthquakes, has been originally employed to predict horizontal and vertical rates of deformations in Alaska [1]. The results were compared with geodetic data in order to better constrain the rheological structure of the upper mantle beneath Alaska. Although motions associated with rift dynamics and postglacial adjustment are expected to contribute in a dominant way to present-day velocities in this area, new insights are expected from the application of our postseismic rebound model to Iceland. Accordingly the model has been further developed to account for strike-slip earthquakes characteristic of the SISZ and for rifting activity along the middle Atlantic Ridge, described in terms of a distribution of tensile dislocations.

A simple earth model was preliminarly employed, which includes a 100 km thick elastic lithosphere, a uniform mantle with Maxwell rheology, and a fluid inviscid core. The source of deformation consists of a 200 km long tensile fault buried at a depth of 50 km. Figure 30 portrays the coseismic surface displacement u (in centimeters) observed at a given distance from the fault along different azimuths α (namely, $0°$, $45°$ and $90°$ from top to bottom). The surface displacement is decomposed along the spherical unit vectors r, θ, and ϕ (dash-dotted, solid, and dotted curves, respectively). Figure 31 shows the long term relaxation of the displacement field. The time-scales governing the transition from coseismic to postseismic displacements depends essentially on the viscosity stratification of the mantle. For an upper mantle characterized by a relatively low viscosity (such as the mantle beneath Iceland) these time-scales amount to a few years. Large amounts of relaxation may affect all of the components of the displacement field. In particular, we observe amplifications by a factor of 2 for the θ and r components of displacements. Another interesting feature of Figure 31 is the large spatial scale of the region experiencing horizontal motions in the postseismic regime. The solutions and algorithms developed under Task 2 were employed as working tools for addressing Tasks 3 and 5. Results have been discussed at a PRENLAB workshop [4], a paper is in preparation.

3.7.1.3 Task 3: Comparison between global earth models, including sphericity and self-gravitation, and plane models

Start: March 1996 (month 1)
End: October 1997 (month 20)
Responsible partner: UBLG.DF

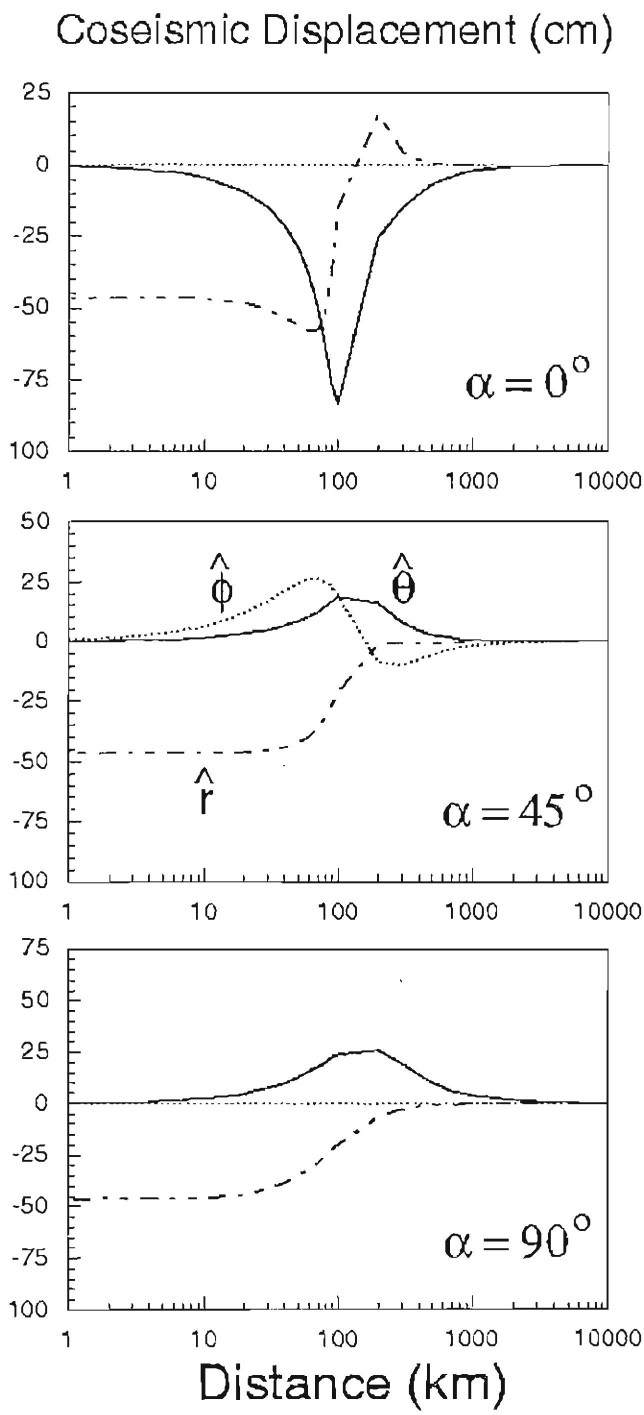

Figure 30: *See text for discussion.*

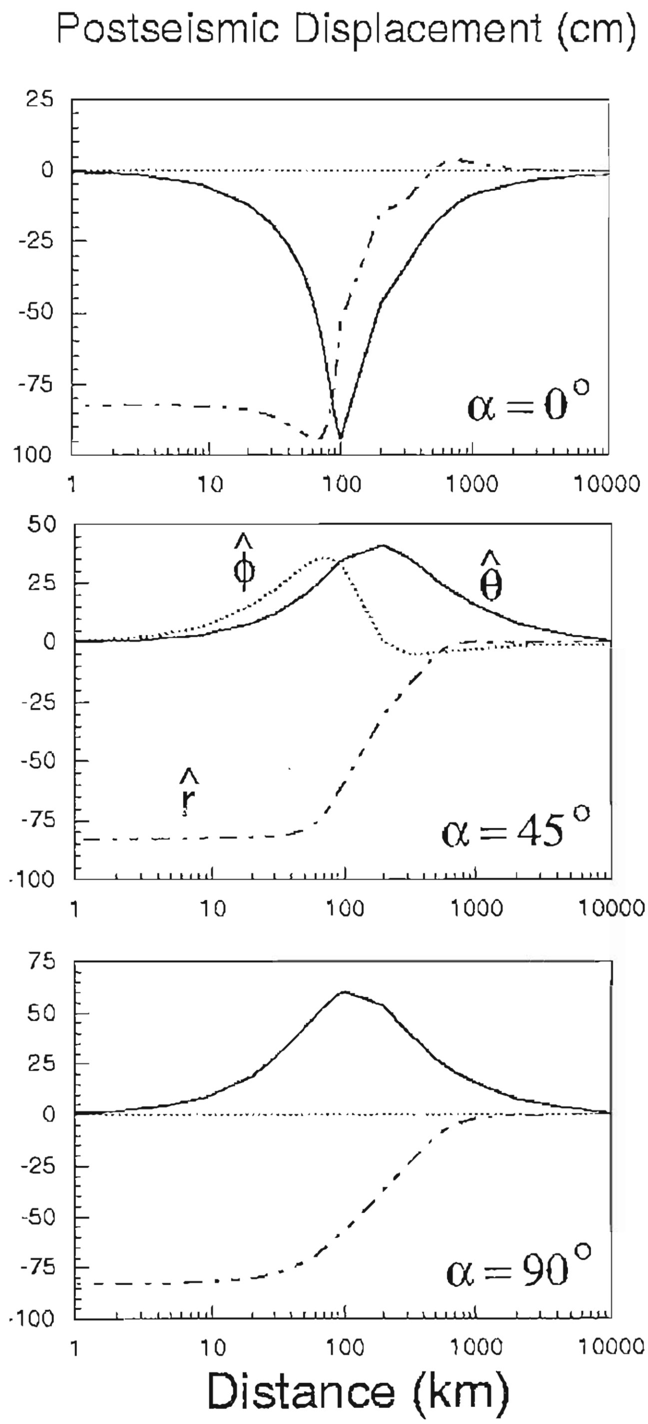

Figure 31: *See text for discussion.*

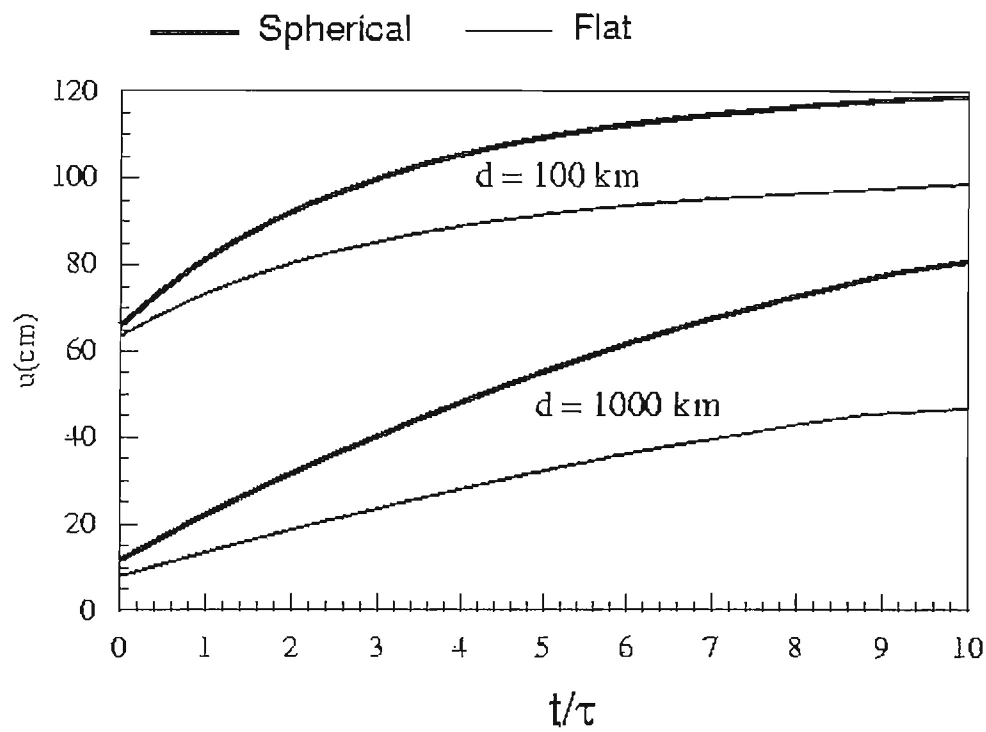

Figure 32: *See text for discussion.*

Andrea Antonioli, Maurizio Bonafede, Antonio Piersanti and Giorgio Spada

Major results on this topic have been presented in a paper entitled: *Post-seismic deformations: a comparison between spherical and flat earth models and stress diffusion following large earthquakes*, in press on Geophysical Journal International [2]. In this work we have compared the co- and postseismic deformations of a spherical and of a flat model perturbed by strike-slip earthquakes. A new manuscript is being submitted, *Spherical vs. flat models of postseismic deformation* [56], where a more detailed study is performed for general shear dislocations. The purpose of these investigations is to provide a clear account of the effects of sphericity on postseismic motions, and to define the range of validity of flat models currently employed in the literature. An excerpt of the results obtained are shown in Figure 32.

In this case, we show the displacement in the near field (d=100 km) and in the far field (d=1000 km) induced by a vertical strike-slip fault with width of 50 km buried in the lithosphere at a depth of 25 km. The displacement u along the strike of the fault is evaluated as a function of time for two models: a spherical and a flat one. The former has been first proposed by Piersanti et al. [57], whereas the latter has been introduced by Bonafede et al. [18]. In both cases we account for the delayed response of the asthenosphere. At any time t (given in units of Maxwell times of the asthenosphere), the displacement predicted by the spherical model is sensibly larger than the one provided by the flat one. The discrepancies increase with increasing time, up to a factor of 2 in the case of far-field deformations. These results reveal that a precise determination of postseismic motions must be based on spherical models even when relatively short source-observer distances are involved. We have verified that this also holds for the residual time-dependent stress field following both strike-slip and dip-slip earthquakes. This could have implications on the interpretation of the process of stress diffusion and particularly on the interaction between postseismic stress field and the evolution of the Mid-Atlantic Ridge in the Iceland region.

The results of this study have been presented in two papers [2, 56].

3.7.1.4 Task 4: Modelling of a spreading ridge

Start: October 1996 (month 8)
End: March 1997 (month 13)
Responsible partner: UBLG.DF

Andrea Antonioli, Maurizio Bonafede, Antonio Piersanti and Giorgio Spada

The dynamics of a spreading ridge has been studied by means of an approach based on a spherical earth model. The main goal of this study is to enlighten the impact of episodic uprises of magma along the Iceland rift on intermediate and large-scale ground deformations. The method employed, based on a spherical model with radially varying rheology, is particularly suitable for this purpose, since a realistic time-evolution for the opening of the rift can be easily introduced. In addition, it possible to appreciate the time-dependent effects associated with the delayed response of the ductile properties of the soft asthenosphere beneath Iceland. This method employed is more appropriate than previous ones, based on flat half-spaces with purely elastic properties, in that it also allows for a self-consistent description of the effects associated with the gravity field. The interesting possibility that the episodic uprise of magma along the Iceland rift may induce time-dependent stress accumulation in the surrounding regions, with triggering effects on the seismic activity along transform faults of Iceland is under study. A manuscript is in preparation on this topic: *Time-dependent deformations driven by spreading ridges in a spherical earth* [3].

In Figure 33, we show the time-dependent displacement field associated with the opening of a ridge. The time-history employed, shown in the bottom frame, is characterized by a transient of length of 5 years during which the ridge is subject to a constant rate of spreading. The displacement is computed at the eartht's surface perpendicularly to the axis of the fault. The opening ridge is modelled by a 200 km long planar distributions of elementary tensile faults located in the middle of the elastic crust. Due to the delayed response of the asthenosphere to the imposed forces, the displacement u attains an asymptotic regime only after a considerable amount of time is elapsed since the end of the transient opening. In the vicinity of the ridge, up to a distance of $X \sim 30$ km, the displacement is negative, to indicate that motions are towards the source. Maximum positive displacements, associated with motions away from the source, are found at a distance of about one half the source length ($X \sim 100$ km). The surface horizontal stress field, proportional to the derivative of u with respect to X, is characterized by a quite complex spatial and temporal evolution. A fully 3-dimensional descriptions of the deformation and stresses in the regions surrounding the fault is under way.

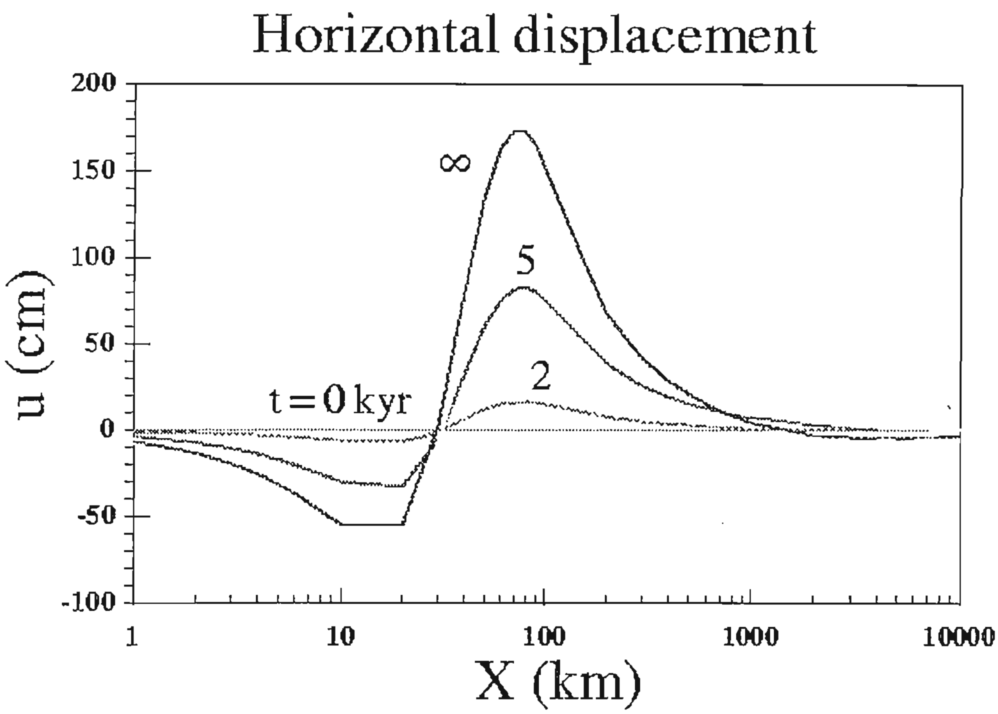

Figure 33: *See text for discussion.*

Preliminary results on this topic have been discussed in meetings and workshops [1, 58, 3]. A paper is in preparation.

3.7.1.5 Task 5: Modelling of accelerated plate tectonics on a ridge following a major earthquake in a transform shear zone: inferences on the rheological structure below Iceland

Start: March 1997 (month 13)
End: February 1998 (month 24)
Responsible partner: UBLG.DF

Andrea Antonioli, Maurizio Bonafede, Antonio Piersanti, Eleonora Rivalta and Giorgio Spada

Magma ascent through a mid-oceanic ridge can be modelled as a tensile crack within which the overpressure is determined by magma buoyancy. Explicit analytic solutions are given for the elementary dislocation problem in the most simple layered medium, made up of two welded half spaces characterized by different elastic parameters. Particularly interesting appears to be the case of a crack cutting across the boundary between the two media. In this case a further singularity appears in the kernel of the integral equation, which is connected

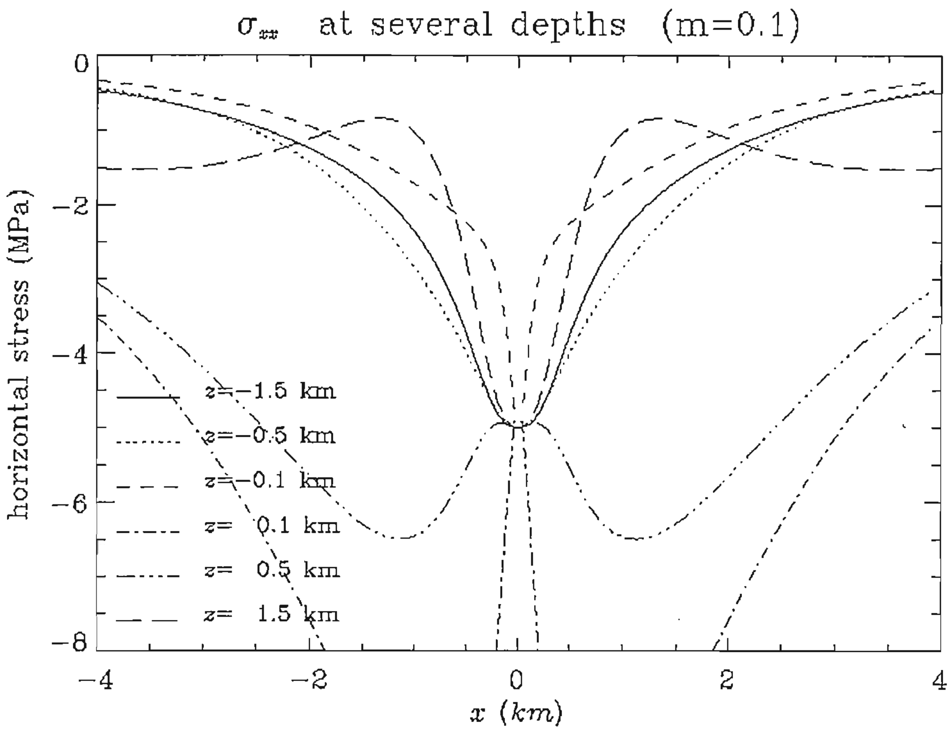

Figure 34: *See text for discussion.*

with the presence of the boundary surface. The problem can be solved by splitting the crack into two interacting open cracks. The application of a constant overpressure within the crack is found to produce drastically different stress regimes in neighbouring regions located on opposite sides of the interface; this feature may provide a straightforward explanation for the episodic reversal (from sinistral to dextral) of strike-slip mechanisms observed in the SISZ. If the rheological discontinuity between the lithosphere and the asthenosphere is considered, model results predict a much larger horizontal flow in the asthenosphere than is accomplished by motion of lithospheric plates. Furthermore, the stress field near the transition depth is strongly controlled by differential shear flow in the asthenosphere, thus yielding a simple explanation for the different stress regimes prevailing in the seismogenic zones of Iceland.

Figure 34 shows graphically a result of great interest in interpreting Iceland seismicity: if a vertical dyke 4 km long cuts across the interface between the half-space z>0, with rigidity 10 times greater than the half-space z<0, the horizontal compression in the stiffer medium may be much higher than magma overpressure (5 MPa) in the dyke. This component of stress is dominant in generating a significant deviatoric stress. Figure 35 shows the deviatoric component of the stress field generated in a layered medium, compared with results pertinent to a homogeneous medium. Since the asthenosphere has much lower long-term rigidity than the brittle crust above it, these results explain in a straightforward way the compressive stress transients inferred from shear wave splitting in connection with magma injection episodes along the rift zone.

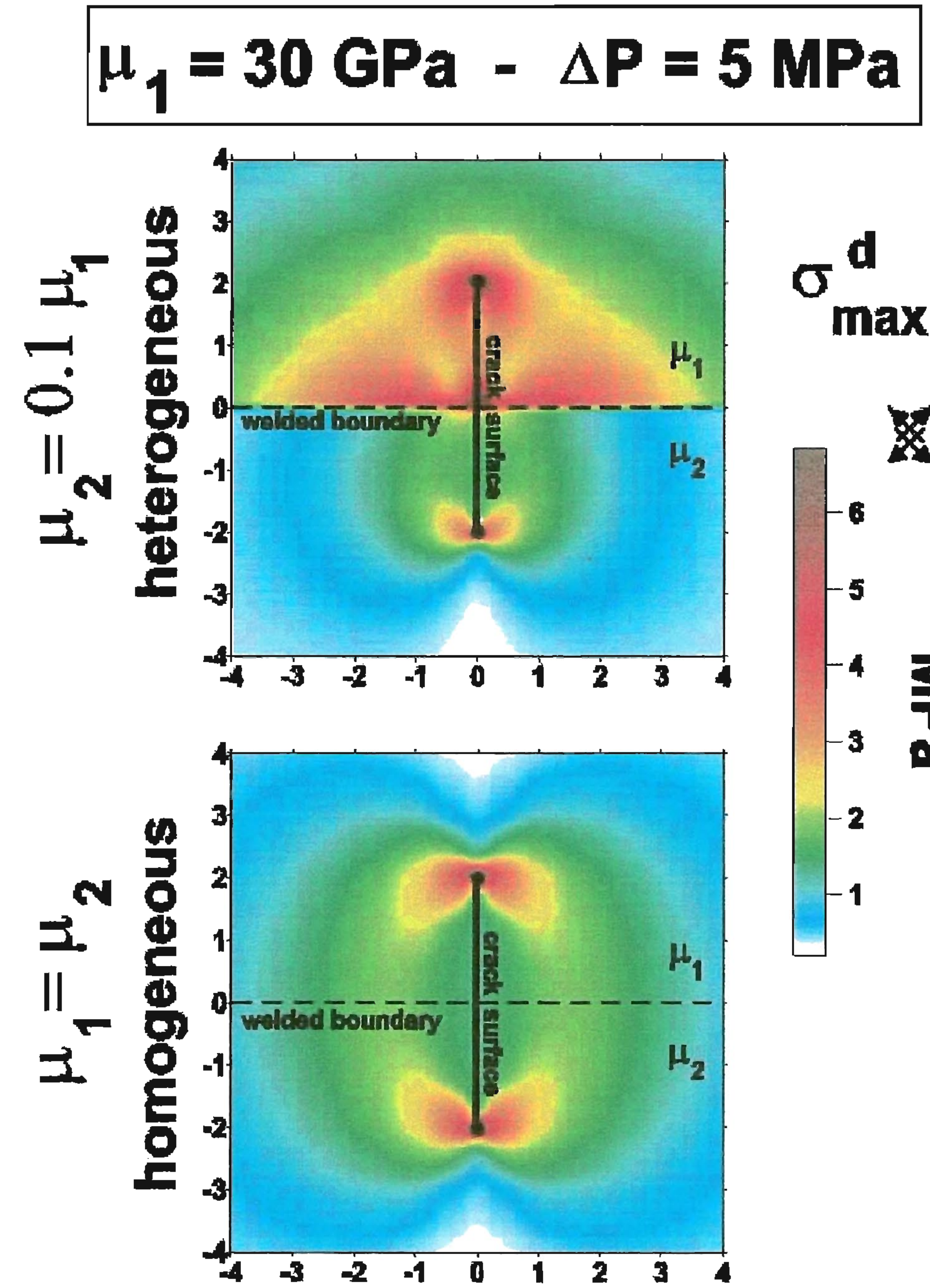

Figure 35: *See text for discussion.*

Results are presented in two papers [19, 21]. A further paper, devoted to the study of stress induced by dyke injection over rheological discontinuities, is to be submitted soon. Preliminary results on this topic were shown at the PRENLAB workshop in Paris [20].

3.7.1.6 PRENLAB workshops and coordination meetings

XXI EGS General Assembly, The Hague, May 6–10, 1996.

XXV ESC General Assembly, Reykjavík, September 9–14, 1996.

Institut de Physique du Globe, Paris, September 30, 1996 (meeting of Maurizio Bonafede, Ágúst Gudmundsson, Jacques Angelier and Francoise Bergerat).

PRENLAB workshop, Paris, October 24–25, 1997.

3.7.2 Subpart 7B: Modelling of the earthquake related space–time behaviour of the stress field in the fault system of southern Iceland

Associated contractor:
Frank Roth

In the framework of PRENLAB, a model study was begun to obtain forward models of the stress field and stress changes in the South Iceland seismic zone (SISZ).

This proposal has the target to model the space-time development of the stress field using data on strain and stress changes from the other experiments and from databases. In detail, this aims at the modelling of:

- the changes in crustal strain and stress due to earthquakes and aseismic movement in the fault system of the SISZ.
- the formation and growth of faults and their interaction.
- the mutual influence between volcanic and earthquake activity, e.g. magmatic upwelling and shearing at fault zones.

With the funding available, the following models are addressed:

3.7.2.1 Task 1: Calculation of the stress field due to motions on the main faults

Start: March 1996 (month 1)
End: October 1997 (month 20)
Responsible partner: GFZ.DR.DBL
Cooperative partner: IMOR.DG

3.7.2.2 Task 2: Comparison with the seismic moment release

Start: March 1996 (month 1)
End: October 1997 (month 20)
Responsible partner: GFZ.DR.DBL
Cooperative partner: IMOR.DG

3.7.2.3 Task 3: Stress build-up by these motions and stress release by the major earthquakes

Start: March 1996 (month 1)
End: October 1997 (month 20)
Responsible partner: GFZ.DR.DBL

3.7.2.4 Task 4: Forward modelling of the rheological parameters of the lithosphere/asthenosphere in southern Iceland using data of postseismic deformations

Start: May 1997 (month 15)
End: February 1998 (month 24)
Responsible partner: GFZ.DR.DBL

Results of carrying out the tasks above are demonstrated in Section 3.7.2.7.

3.7.2.5 Methods

The database for the modelling are the seismicity, deformation, strain and stress data existing already and being gathered in future in the measuring efforts of the proposers to this research project. A long historical record of earthquakes larger than 6 is available for events since 1700 and instrumental data are available from 1926 on. Starting 1990, data from the SIL seismic network complete down to magnitude 0 within the test site can be used. Furthermore, the model calculations will make use of data on crustal deformation, especially on distance changes measured by geodimeters and GPS techniques. Moreover strain changes are recorded by volumetric borehole strainmeters. In general, it is based on the current state of knowledge of seismotectonics of Iceland and the interpretations of crustal strain and movements in the region.

The objectives of these investigations are:

- A better understanding of the distribution of seismicity in space and time, its clustering and migration in Iceland.
- To seek a detailed explanation for the relation between the left-lateral strike direction of the SISZ and the fact that after historical earthquakes new cracks were often created following the complementary N-S right-lateral strike direction.
- To make a contribution to the intermediate-term earthquake prediction in this populated and economically important region of Iceland.
- To provide models for the joint interpretation of the data gathered in the common research programme proposed here.
- To compare models of stress fields at SIL to those for stress fields in other regions, e.g. the North Anatolian fault zone.

On a wider scope, more insight in the relation of seismic and volcanic activity is envisaged as well as into the possibilities of earthquake prediction. The situation on Iceland is very favourable for both, as there are volcanos and longer faults. Concerning scale, the SIL area fills a gap between small experiments in the laboratory and investigations in mines on one hand and the research on large areas as the North Anatolian fault or the San Andreas fault, on the other. Thus, the transfer of results from one scale to another might get easier.

The forward modelling of stress fields will be done by applying static dislocation theory to geodetic data and data obtained through seismic moments from seismograms. It allows to calculate displacements, strain and stresses due to double-couple and extensional sources in layered elastic and inelastic earth structures. Besides the change in displacement during the event, the changes caused by the movement of plates can be included.

3.7.2.6 Modelling tools

GFZ provides computer programs to calculate:

- Displacement, strain and stress in a homogeneous (in-)elastic half-space due to point sources and extended sources of double-couple type, of explosion and crack opening type.
- Surface and subsurface displacement, strain and stress due to a point source of variable type in a layered half-space, including one inelastic layer.
- The superposition of stress fields from fault segments with offset and/or different strike direction.
- Displacement and stress due to loads of various shapes on a spherical shell.

With the experience and tools given, the goals set above are achieved.

3.7.2.7 Report

For three months, Dipl. Geophys. Gerhard Kurz could be hired as a graduate student to help on programming and changing the plotting routines to run with the MATLAB software. As a first step in carrying out the tasks the existing software was checked and transferred into the new Fortran-90 standard. Then the programs were tuned for faster performance and extended to allow calculation of six instead of five layers to account for detailed knowledge of velocity depth profiles.

In the following, a preparational study was made on the influence of several layers, i.e. their elastic constants and thickness, on surface deformation. Doing so, special attention was paid to the effects of the physical properties of the source layer on amplification or diminishing displacement at the surface. Results were reported at the 1996 EGS and ESC General Assemblies.

Information was gathered on strong (historical) earthquakes on Iceland and its surroundings, especially from IMOR.DG.

Two models were prepared: (1) a model of the SISZ and the adjacent part of the eastern volcanic zone and (2) a scheme comprising the main ridge parts on Iceland and the North Atlantic Ridge to the north and to the south of the island, including both faults and the load due to Katla and Hekla volcanos.

3.7.2.7.1 *The model on stress changes in the SISZ*

Introduction

Movements on faults occur in earthquakes, aseismic slip or inelastic creep. There are sequences of seismic quiescence followed by seismicity and so on. Stresses are accumulated by plate motion and released in earthquakes and/or the mentioned processes. In the following. a model is described that accounts for plate motions and earthquakes on Iceland.

The SISZ is situated between two sections of the Mid-Atlantic Ridge, the Reykjanes Ridge (RR) and the eastern volcanic zone (EVZ). Even though the angle between the SISZ and the neighbouring ridges is far from 90°, it is considered as a transform fault (for the geological structures, see Figure 2). Following the transform fault hypothesis, left-lateral shear stress is expected along the E-W striking zone. This is equivalent to right-lateral shear stress with N-S orientation. In fact, earthquakes seem to occur on N-S trending faults ([25, 35]. They are located side by side between the Hengill triple junction, where the RR meets the low activity western volcanic zone (WVZ), and Hekla volcano, a part of the EVZ [25].

The questions to be solved are:

- Do these events, placed on parallel faults, release all the energy stored in the 3-D volume of the SISZ?
- Do the earthquakes always take place in areas of high stress?
- What is the critical stress level? How large is its variability?
- Where are the highest stresses nowadays?

The method

The elasticity theory of dislocations is used to calculate the stress changes induced by earthquakes with a double-couple strike-slip mechanism on an extended rupture plane [61].

The area investigated extends from 18 to 24°W and from 63 to 65°N. The origin of the coordinate system is set to 24°W, 64°N (Figure 36) it includes the SISZ, north and south of 64°N, the SW edge of the EVZ (extending NE from about 18.7°E, 64°N), and the north eastern most part of RR (approximated by a straight line trending from about 23°W, 64°N at the SISZ in SW direction). This latter assumption is a strong simplification as the RR changes strike direction all along Reykjanes Peninsula up to Hengill triple junction where it finally mainly strikes E-W as the transform fault itself.

The initial stress field is determined as follows: a tensional stress acting N103°E (nearly parallel to the SISZ [23] is assumed, due to ridge push or basal drag of the adjacent plates. The stress magnitude, which is unknown, is set to a value that produces left-lateral shear stresses in E-W direction as large as the stress drop determined for the largest event (M=7.1) in the studied earthquake sequence. Insofar, this stress is the minimum stress to be expected. The amount of this minimum shear stress is 2.7 MPa (consistent with Gudmundsson [32], who determined maximum values of 12 MPa from maximum displacement of superficial fault traces found in the field). This shear stress corresponds to an uniaxial tensional stress of -13.1 MPa. Tensional stresses at both ridges are modelled as constantly being released to have zero values at the rifts. These are the major disturbance of the unknown background stresses.

On this initial field, the stress changes due to earthquakes are iteratively superposed as well as the stress changes due to further spreading at the ridge segments based on an opening of 2 cm/year. This value is taken from [23]. The stress field before every event is thus the sum of the initial field, the stress drop of all preceding events, and the plate tectonic stress build-up since the starting time of the model, which is set to 1706, as discussed below.

Results were calculated for 56 x 44 test points covering 280 km in E-W direction and 220 km in N-S direction; i.e. the spacing is 5 km in both coordinates. Stresses were computed for

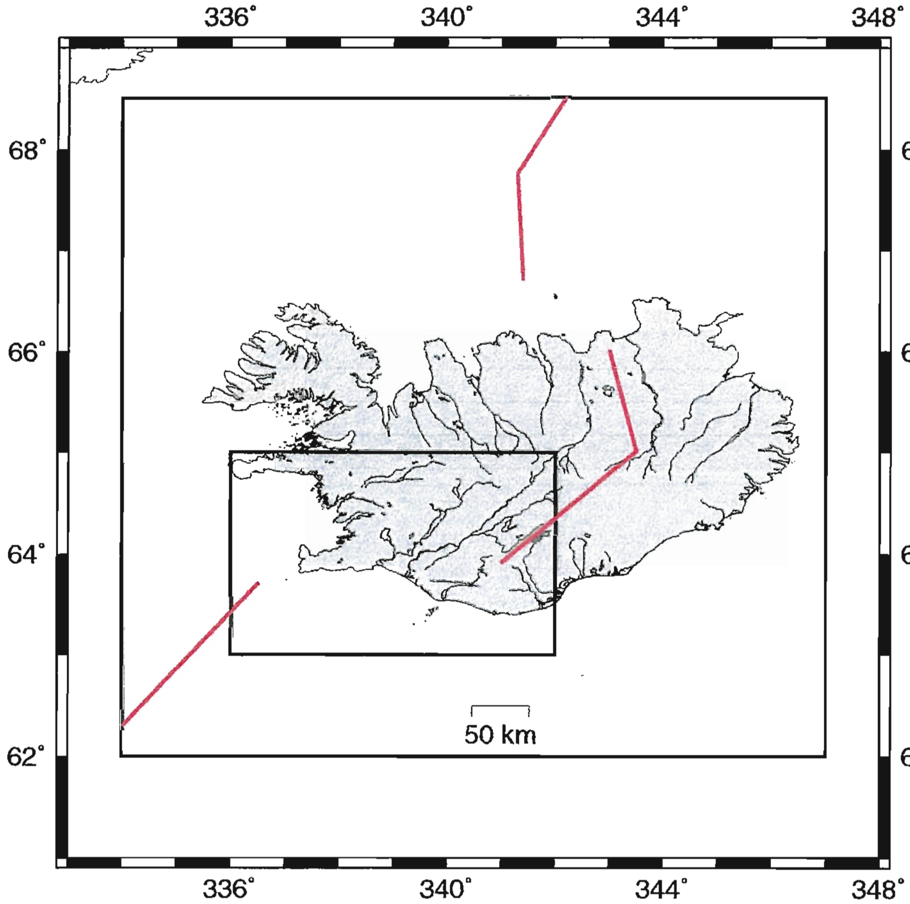

Figure 36: *Map of Iceland and surrounding area. Thick red lines indicate Mid-Atlantic Ridge segments, as used in the modelling. The smaller box shows the region of the model on the SISZ. The SISZ extends approximately between (125, 0) to (200, 0). The large box gives the region for the Iceland rift model.*

a homogeneous half-space (as a starting model) with both Lamé's constants being 39 GPa. Although surface stress changes are calculated, these should be representative for crustal stresses using these values for the moduli, that are typical for oceanic crust [24] and not for sedimentary layers at the surface.

Figures 37 and 38 give an example to illustrate the modelled effects: the background stress level is about 2.7 MPa as explained above. The shear stress is reduced to very low up to negative values in the ridge segments (lower left and upper right) where the tensile stresses, oriented N103°E, have been reduced to zero by rifting. At the tips of the ridge segments and on the line connecting them high shear stresses are induced. In the framework of an initial stress field as in Figure 40 an earthquake happened at (164, 0) releasing the stresses there to values around zero (see especially Figure 38 where the area around the epicenter has been enlarged). Please note that the yellow isolines in the figures correspond to different values:

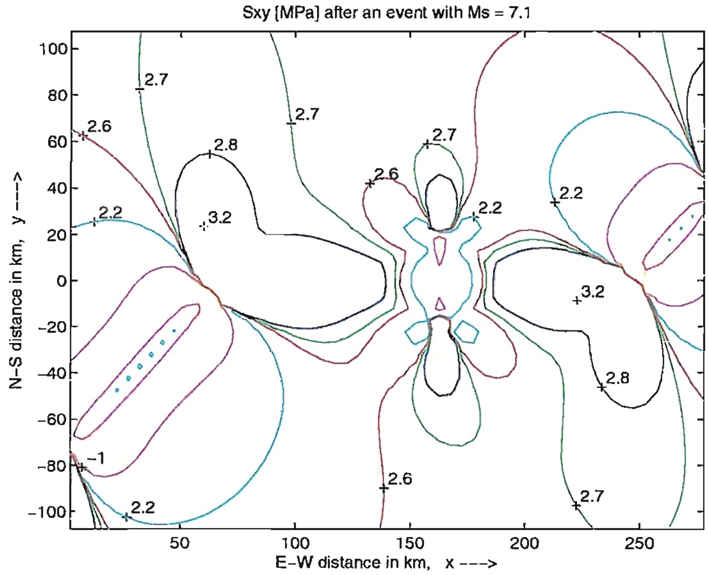

Figure 37: *Demonstration of the effect on the shear stress field by a sample earthquake at position (164 km, 0 km) with magnitude 7.1, a rupture plane of 35 km length and 14 km vertical extend, as well as an average co-seismic displacement of 1.9 m. The initial stress field is shown in Figure 40. Values at the isolines of stress are in MPa.*

those near the ridge and earthquake rupture planes show stresses of -1MPa (Figure 40), those

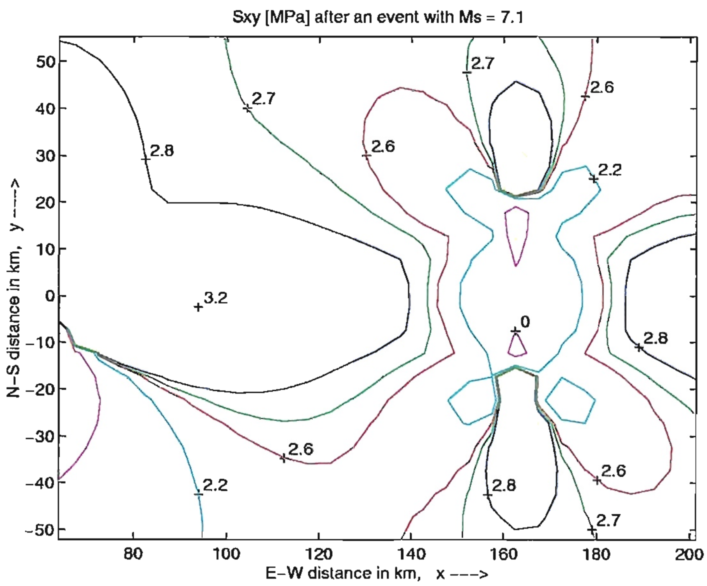

Figure 38: *Same as Figure 37. The area around (130, 0) is enlarged.*

off the rupture plane tips give values of 3.2 MPa. Besides the reduction of stress at the fault plane, there is an increase off its tips and at intermediate distances along the strike of the rupture.

The earthquake data
All events in the SISZ with M $\geq$ 6 since 1706 were used (Table 2), following [38, 76, 77]. Even though the time of first 3 events is not exactly known, their occurrence seems to be secured (in contrast to other events [25]) and the catalogue is supposed to be complete from 1706 for earthquakes with M $\geq$ 6 [77].

Date[1]	Magnitude[1]	Epicenter[1]		South end of rupture[2]		Co-seismic slip[3]	Rupture length[4]
		Lat. °N	Lon. °W	x [km]	y [km]	U_0 [m]	L [km]
20.04.1706	6.0	64.0	21.2	131	-5	0.30	10
07.09.1732	6.7	64.0	20.1	183	-11	0.77	22
22.03.1734	6.8	63.9	20.8	150	-23	0.96	25
14.08.1784	7.1	64.0	20.5	164	-18	1.9	35
16.08.1784	6.7	63.9	20.9	145	-22	0.77	22
26.08.1896	6.9	64.0	20.2	178	-14	1.2	28
27.08.1896	6.7	64.0	20.1	183	-11	0.77	22
05.09.1896	6.0	63.9	21.0	140	-16	0.30	10
05.09.1896	6.5	64.0	20.6	159	-9	0.48	18
06.09.1896	6.0	63.9	21.2	131	-16	0.30	10
06.05.1912	7.0	63.9	20.0	187	-27	1.5	32

Table 2: *1) Data taken from [77]. 2) Position in the model coordinate system with origin at* 64°*N,* 24°*W. 3) Calculated via the magnitude moment relationship* $\log M_0$ *[dyne cm]* $= 1.5M_S - (11.8 - \log(\sigma_a/\mu))$ *with the apparent stress* $\sigma_a = 150$ *MPa and the shear modulus* $\mu = 0.39 \cdot 10^{11}$ *Pa after [50], followed by using the values of* μ *above, the rupture length as given in the table as well as a vertical fault width of 14 km east of* 21° *W and 7 km between* 21° *W and* 21.2° *W. Finally, the values were reduced by a factor of 2, following the discussion in [35]. 4) Calculated using* $\log L$ *[km]* $= 0.5M - 2$ *(after [60]) which results in slightly lower values compared to e.g. [70].*

The shape of their damage distribution and the strike of surface breaks (Figure 39) further confirms strike-slip events on N-S trending rupture planes [25]. Nevertheless, all but one event are not recorded instrumentally. The damage areas from historical records are not gathered by scientists and are as usually biased by uneven population density. So the magnitudes and locations are not very accurate. Due to the unknown initial stress field, the model results (especially the pre-seismic stress level) can only be checked at places where more than one event occurred in the sequence. Therefore, a long time span should be and was used.

Determination of seismic moment, size of the fault plane, and average co-seismic slip from the magnitudes, was done as indicated in Table 2. As also discussed in [35], there is the problem that fault lengths observed (e.g. 1912) are rather short compared to the magnitude

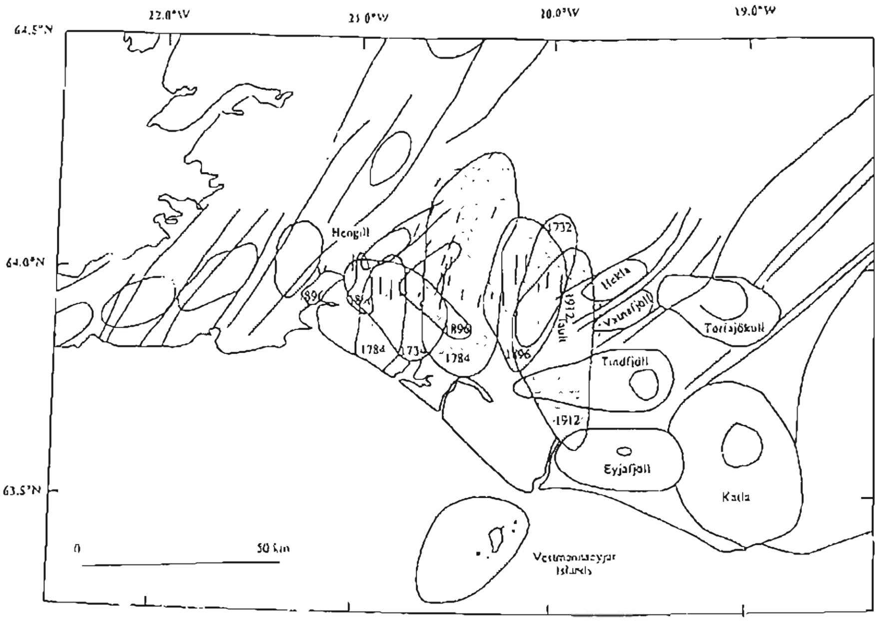

Figure 39: *The SISZ showing mapped surface breaks and regions in which over half of the buildings were destroyed in historic seismic events [25]. The N-S dashed line near Vatnafjöll indicates the estimated location of the fault on which the May 25, 1987, earthquake occurred [17]. The structural features and coastline are from [26].*

of the events. Therefore a formula of Qian [60] was used here to calculate the rupture length. Additionally, the vertical fault width is limited by a brittle crustal thickness of about 15 km (cf. also the hypocenter vs. longitude plot of Stefánsson et al. [77], their Figure 8) — even though the effective short term crustal thickness reacting in brittle manner might be thicker for high frequency events as earthquakes compared to slow geological processes. For this first model, however, the co-seismic slip values were estimated to be lower (by a factor of 2) than from the global relation [50] combined with the fault lengths used here. Hackman et al., had a reduction by a factor of 1.4 [35]. The reduction in slip values is equivalent to slightly reducing the magnitudes.

Earthquake fault planes near the Hengill triple junction were assumed to extend vertically to 7 km depth, for events further east 14 km were used (cf. the above mentioned hypocenter depth distribution). All ruptures were set to be oriented N-S.

The results

The stress fields at 18 dates were calculated: the pre- and post-seismic situation for all 11 events and the stresses in 1998. The time before 5 events was too short to accumulate appreciable plate tectonic stresses since the preceding event. In these cases, the post-seismic stress field of the preceding event was set equal to the pre-seismic stress field of these earthquakes.

Figure 40 gives the initial stress field in 1706. The rift segments, lower left and upper right, with about zero tensile stresses also show low shear stresses. The area between the

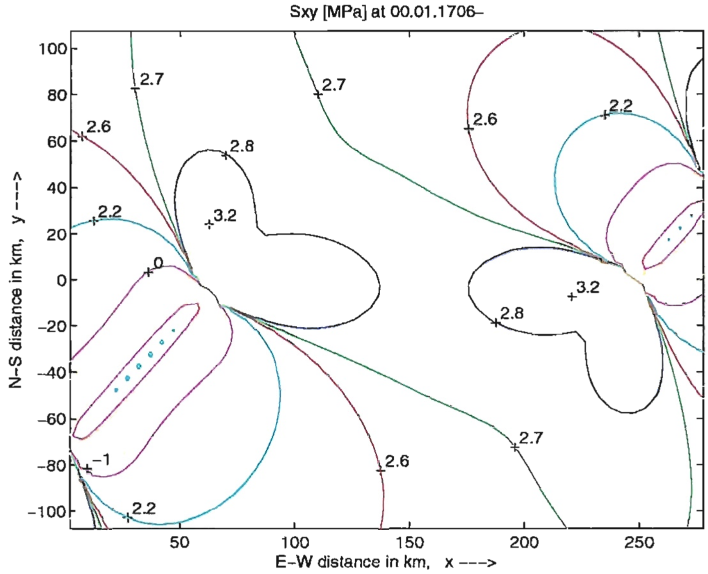

Figure 40: *Shear stress field in the SISZ and its surroundings as assumed in 1706 — the starting field for the model calculations. The background stress is 2.7 MPa. It is increased between the rift tips which are at (60,-10) and (250, 0). — Note that yellow isolines have two meanings: 3.2 and -1.0 MPa.*

tips of the rifts shows increased left-lateral E-W shear stresses (equivalent to right-lateral N-S shear stresses). The SISZ as a strike-slip fault zone extends from 23°W, 64°N or (125, 0) to 20.5°W, 64°N or (200, 0). Concerning the yellow isolines, please note the remarks on Figures 37 and 38. Figure 41 gives the stress field after the 1706, M=6, earthquake took place at (131, 0) reducing stresses there to values below 2.2 MPa.

26 years later, at the break of the next large event, the stresses had slightly increased, see e.g. between (160, 0) and (175, 0) in comparing Figures 41 and 42. The 1732, M=6.7 event then hit at (183, 0) in an area of high stress. After this, the 1734, M=6.8 earthquake hit the high stress area at (150,-12), just aside the 1706 event (Figure 43). Then the largest shock, the August 14, 1784 earthquake, occurred in the high stress segment between the 1734 and 1732 deformation regions ((164, 0) (Figures 44 and 45).

The two August 26 and 27, 1896, M=6.9 and M=6.7 events occurred at the same position as the 1732, although the stresses at (178–183, 0) had not yet recovered beyond the background value of 2.7 MPa, besides two very small areas at (183,±17). Figures 46, 47 and 48 show the pre- and post-seismic situation. The September 1896 events occurred further west, but did not hit small high stress spots at about (150, 15) and (105,±20).

The stress field 16 years later, before the 1912 earthquake (M=7, at (187, -11)) had not changed much compared to 1896, but the stresses in the south part of the epicentral area were rather high. Figure 49 shows the stress field after the 1912 event.

Figure 50 summarizes the mean shear stress level before each of the earthquakes at the area of the impending event. The stress level for the 1706, 1732, 1734, the first 1784, the first

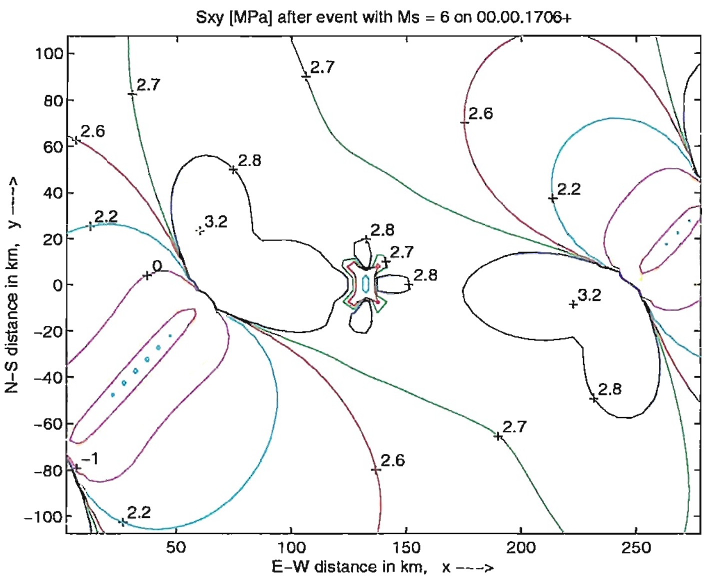

Figure 41: *The stress field after the 1706, M=6, earthquake occurred at (131, 0).*

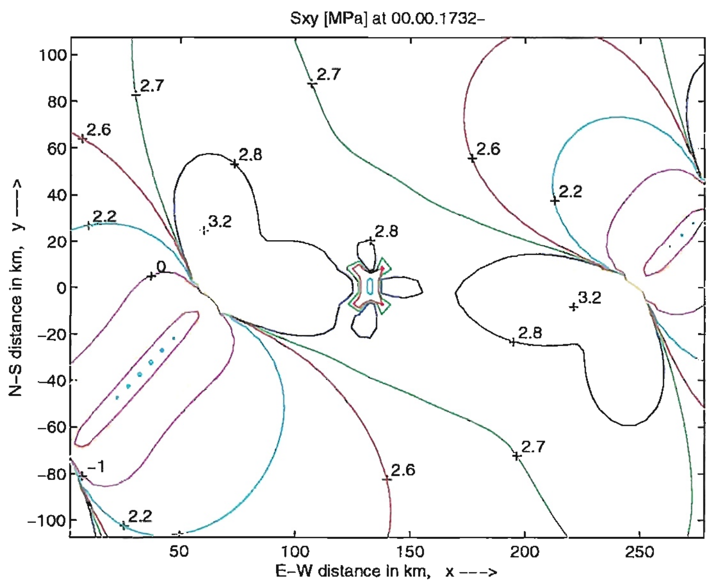

Figure 42: *The stress field before the 1732 event.*

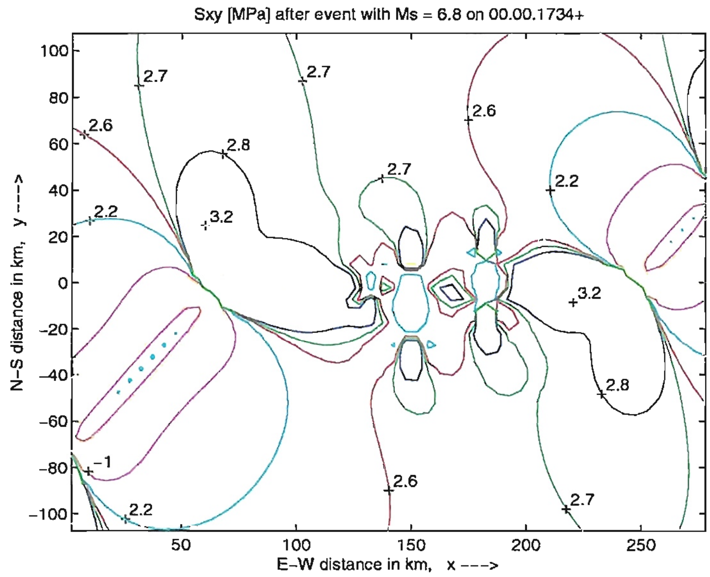

Figure 43: *The stress field after the 1734, M=6.8 earthquake occurred at point (150,-12).*

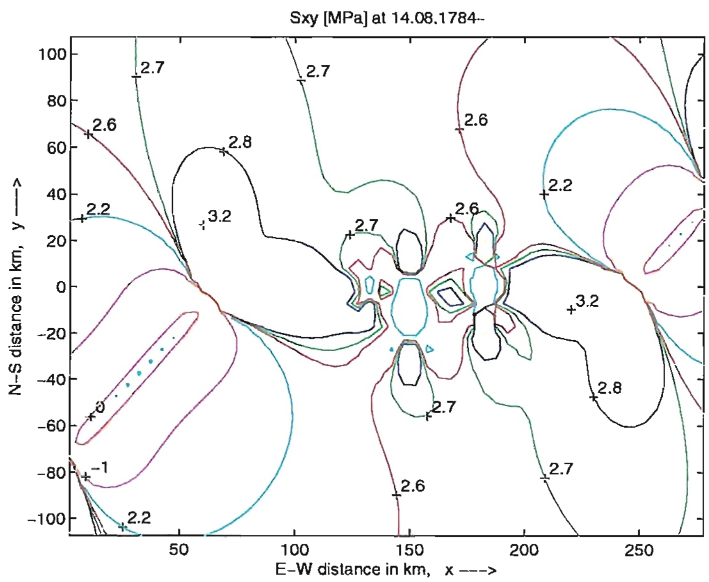

Figure 44: *The stress field before the August 14, 1784 event.*

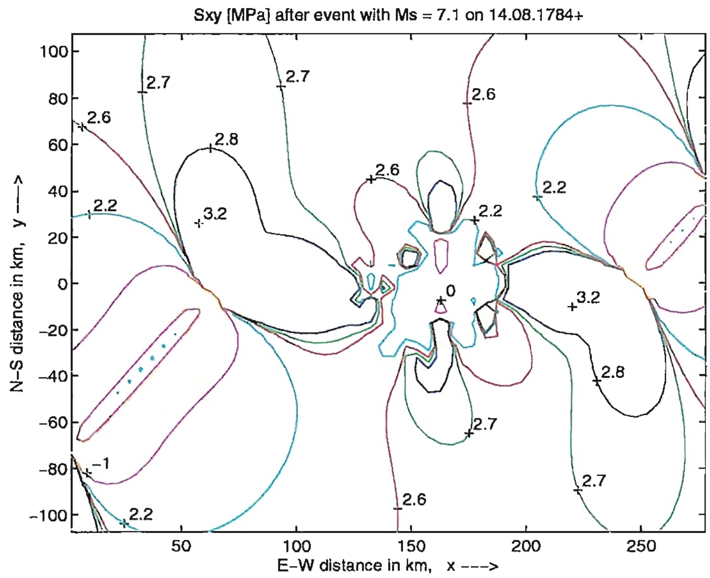

Figure 45: *The stress field after the August 14, 1784, M=7.1 earthquake occurred at (164, 0).*

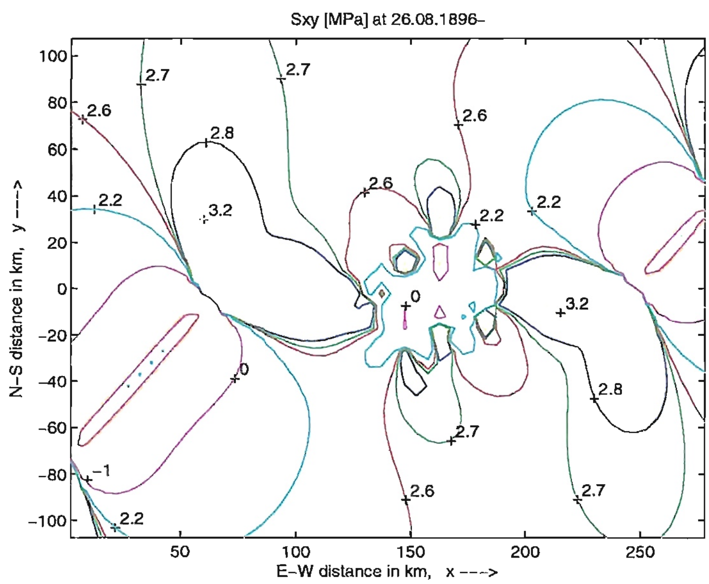

Figure 46: *The stress field before the August/September 1896 event series.*

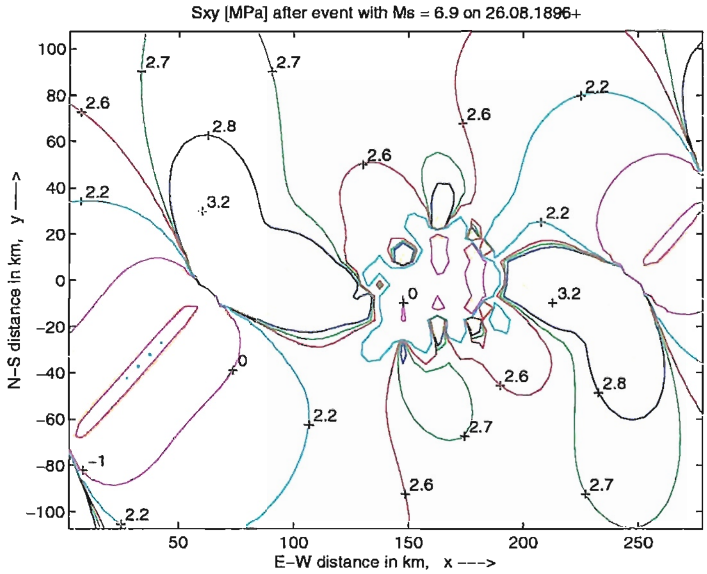

Figure 47: *The stress field after the August 26, 1896, M=6.9 earthquake occurred at (178, 0).*

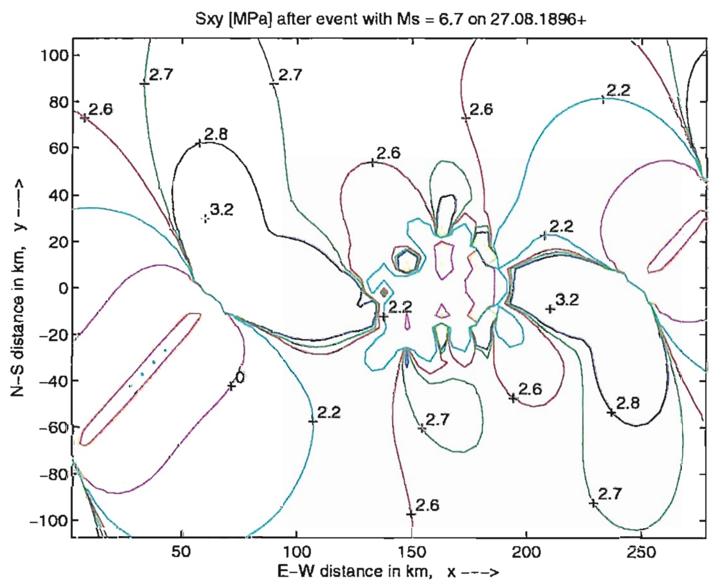

Figure 48: *The stress field after the August 27, 1896, M=6.7 earthquake occurred at (183, 0).*

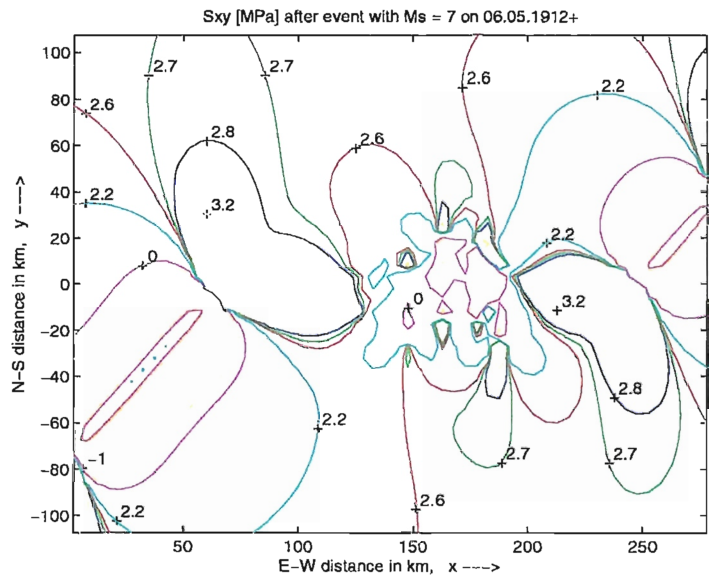

Figure 49: *The stress field after the May 6, 1912, M=7.0 earthquake occurred at (187, -11).*

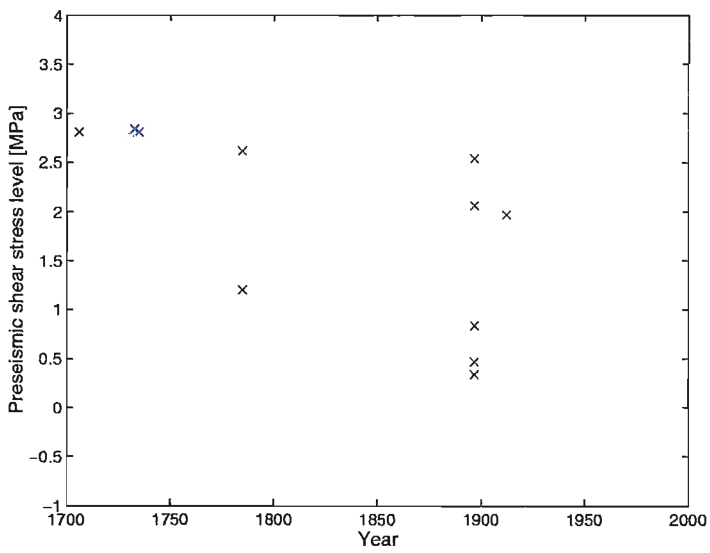

Figure 50: *Cross plot of the pre-seismic shear stress level at the site of the impending earthquakes vs. occurrence time. The stress values at 2 to 14 test points near the surface trace of the rupture plane were averaged.*

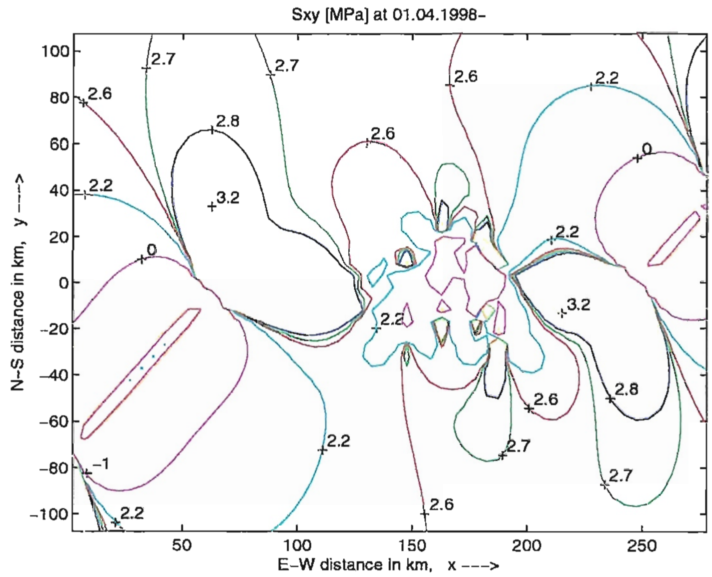

Figure 51: *Extrapolation of the shear stress distribution from 1912 to 1998.*

and last 1896, and the 1912 events are rather high (≥2.0 MPa). The second 1784 earthquake (two days later, 0.4 in magnitude smaller, 19 km away) might be an aftershock and therefore situated in a lower stress area (1.2 MPa). The same might apply to the second, third and fourth of the 1896 events, whereas the last 1896 shock hit a high stress area (2.5 MPa) — the place of the 1706 earthquake, where the stress had recovered since then.

Finally, the stress field was extrapolated to spring 1998, with the additional stresses due to plate motion since 1912. Figures 51 and 52 show the shear stress distributions. The shear stress inside the SISZ (Figure 52) are only high at (150, 10) and at some places at the northern and southern margins of the seismically active zone. West and east of the zone there are high stresses where the SISZ meets the ridge segments and where stresses may be release by earthquakes or by aseismic creep due to high temperature near the surface at changing places and variable in time (this is not yet included in the model). Interestingly, in 1987, there was a strong earthquake, M_S=5.8, at 63.91°N 19.78°W (198,-9) near Vatnafjöll (Figure 39). This event was not included in the modelling as its magnitude was below M=6. Nevertheless, it occurred in a region of high stress as shown in Figures 51 and 52.

Discussion

The pre-seismic stress for most main shocks is high, 2.0–2.8 MPa. It is fairly stable. As the initial stress field is unknown, the stress level at a site where the earthquakes recur in the sequences provides a good test for the right assumptions concerning the stress build-up due to plate movements: 1706 compared to September 6, 1896 and 1912; 1732 compared to August 1896. The tendency with time towards slightly lower values, is an indication that the stress increase due to rifting might have been assumed too low, i.e. the spreading rate between 1706 and 1912 might be higher than 2 cm/year.

Even though the earthquake rupture planes strike N-S, the stress changes calculated here

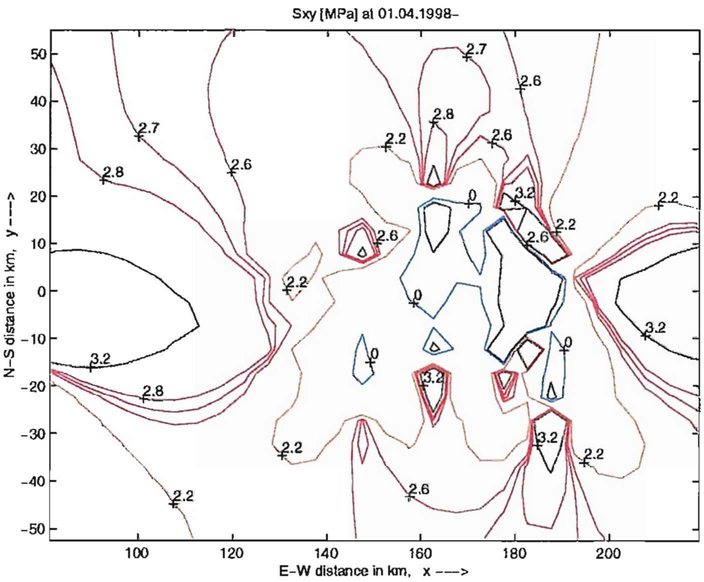

Figure 52: *Same as Figure 51. The area around (150, 0) is enlarged. The SISZ extends approximately between (125, 0) to (200, 0).*

affect the whole area of the SISZ. The areas west and east of the SISZ show constant stress increase in most parts. Here, the model should be improved to account for an extension of the spreading movements into these regions. Moreover, the initial stress field of 1706 could be reduced in the eastern part and the central part, where the first events did not occur before 1732 and 1734, respectively.

Smaller, instrumentally recorded events (as e.g. the above named Vatnafjöll event) will be included in a model with a denser test point distribution, based on the stress field determined here for 1912.

The known layering of the crust and upper mantle below Iceland is now introduced into the model, especially to account for inelastic layers, i.e. to include post-seismic relaxation processes. This will be compared to continuous GPS crustal deformation data as soon as these are available. A new code is prepared for this much faster, more accurate, and capable of including even more layers than the existing one.

Conclusions

The fact that almost all events occur in high stress areas indicates that this first and simplified model can already explain the main features of the behaviour of the SISZ. This is especially astonishing, when the fact is kept in mind, that most (all but one) events used are not instrumentally recorded.

The model goes beyond the standard earthquake moment release analysis as it includes the spatial location and extension of the events and provides an extrapolation to the present situation.

3.7.2.7.2 ***Model on the influence of volcanic loads***

The second modelling part tries to check end member models for the influence of volcanic loads, e.g. from Vatnajökull volcano, on the stress field in SISZ as produced by rifting. The calculations above are uninfluenced by such forces, i.e. the very large volcano (diameter 100 km) near the seismic zone (volcano centre to SISZ centre is about 160 km) is assumed to be totally in equilibrium due to isostasy and/or dynamic support by the up-welling magma in EVZ. Here, we supply a simulation of the load above sea level being not compensated (by buoyancy forces of a root or by other forces) and being compensated to 75%.

The method

The method used here is the analysis of a load on a thin shell (lithosphere) above a substratum. As a first approach the substratum is assumed to be an elastic fluid. This will be changed to an inelastic solid material (asthenosphere) in later models. The work is based on [74].

The thickness of the elastic plate is assumed to be 10 km, its Young's modulus is 71.4 GPa, its Poisson ratio is set to 0.25 (these parameters are chosen equal to those used by [40], for a model for the northern EVZ). The density of the fluid is set to 3.1 kg/dm^3. The volcano is approximated as having a radius of 50 km, an average height above sea level of 1.5 km, and a density of 2.8 kg/dm^3 (in the fully uncompensated case) or 0.70 kg/dm^3 (in the 75 % compensated case).

The results

The stress field was calculated for the region which corresponds to the larger box in Figure 36, i.e. for Iceland and its surrounding area. The spacing of the test points is 20 km in both directions. This means that 30 x 36 points cover 600 x 720 km^2. Figure 36 also gives the ridge segments as entered into the model via calculations of the type of the former model for the SISZ. Only the region has been enlarged now. The SISZ is situated at (x = 200 km — 280 km, y = -185 km) in this reference frame.

Figure 53 gives the orientations of the principal horizontal stress axes for the fully compensated model, i.e. the one uninfluenced by loads. As the emphasis is lead here on stress orientations, the scaling of the stress components is logarithmic. Therefore the sign (shown by arrow tips) is clearly visible at the cost of the relative size of the components being misleadingly similar. The SISZ shows a homogeneous stress field from east to west.

Figure 54 gives the orientations of the principal horizontal stress axes for the uncompensated model, i.e. the full visible load of Vatnajökull creates stresses below the volcano and the adjacent area. The stress orientations in the SISZ are disturbed, at least as far west as (220, -185).

Finally, Figure 55 gives the orientations of the principal horizontal stress axes for the 75% compensated model, i.e. only 25% of the visible load of Vatnajökull creates stress in addition to the ridge segments. Here, the stress orientations inside the SISZ are hardly influenced.

Preliminary conclusions

We assume that the last model is more realistic than the fully uncompensated one. Thus the influence of the loading effect on stress orientation inside the SISZ seems to be small and may-be negligible.

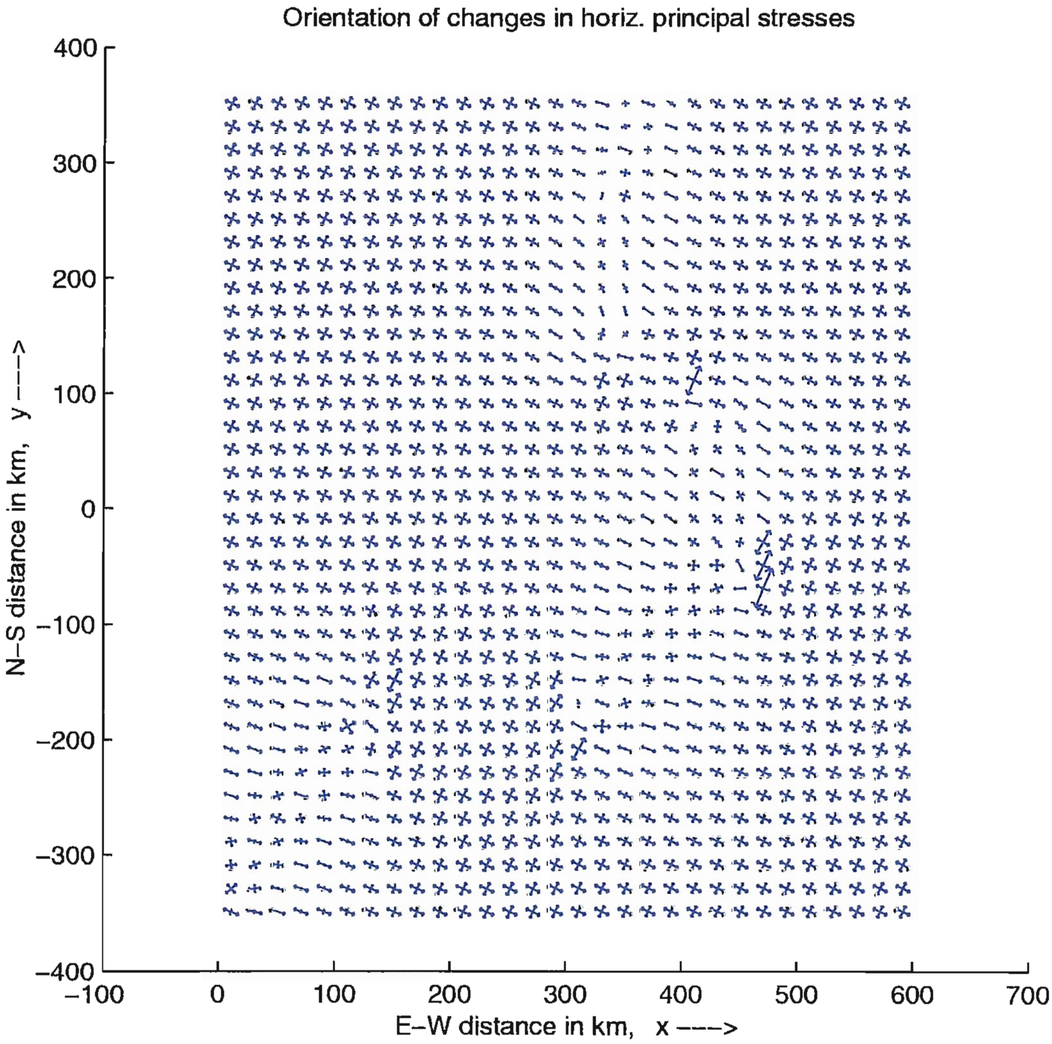

Figure 53: *The orientations of the principal horizontal stress axes for the fully compensated model – without volcanic loads. The area covers the region of the larger box in Figure 36, i.e. Iceland and its surroundings, and includes the five ridge segments shown there. The scaling of the stress components is logarithmic, the sign is displayed by arrows (tension is shown by arrows in outward direction). The relative size of the components tend to look similar in this scaling, even if they differ by two orders of magnitude.*

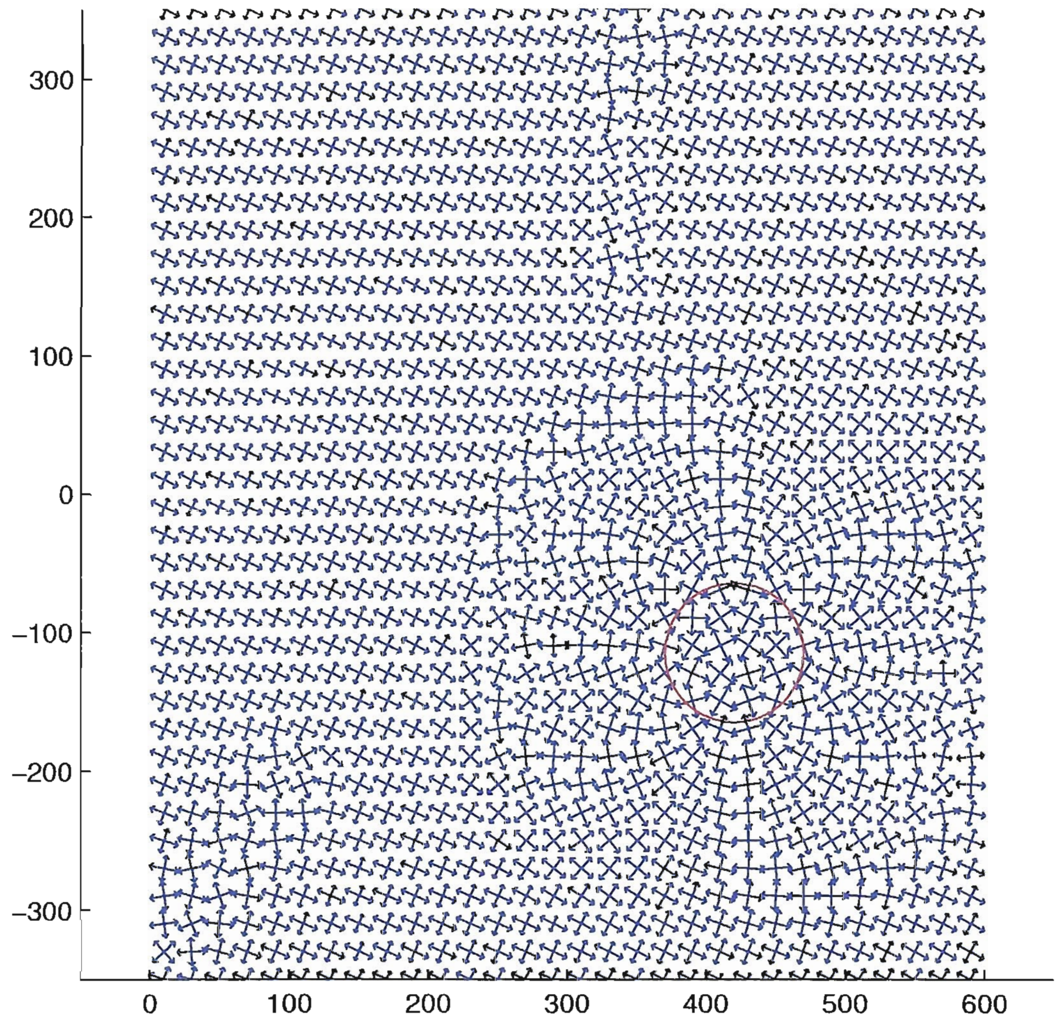

Figure 54: *The orientations of the principal horizontal stress axes for the uncompensated model – with the full volcanic load. The area and the scaling are as in Figure 53.*

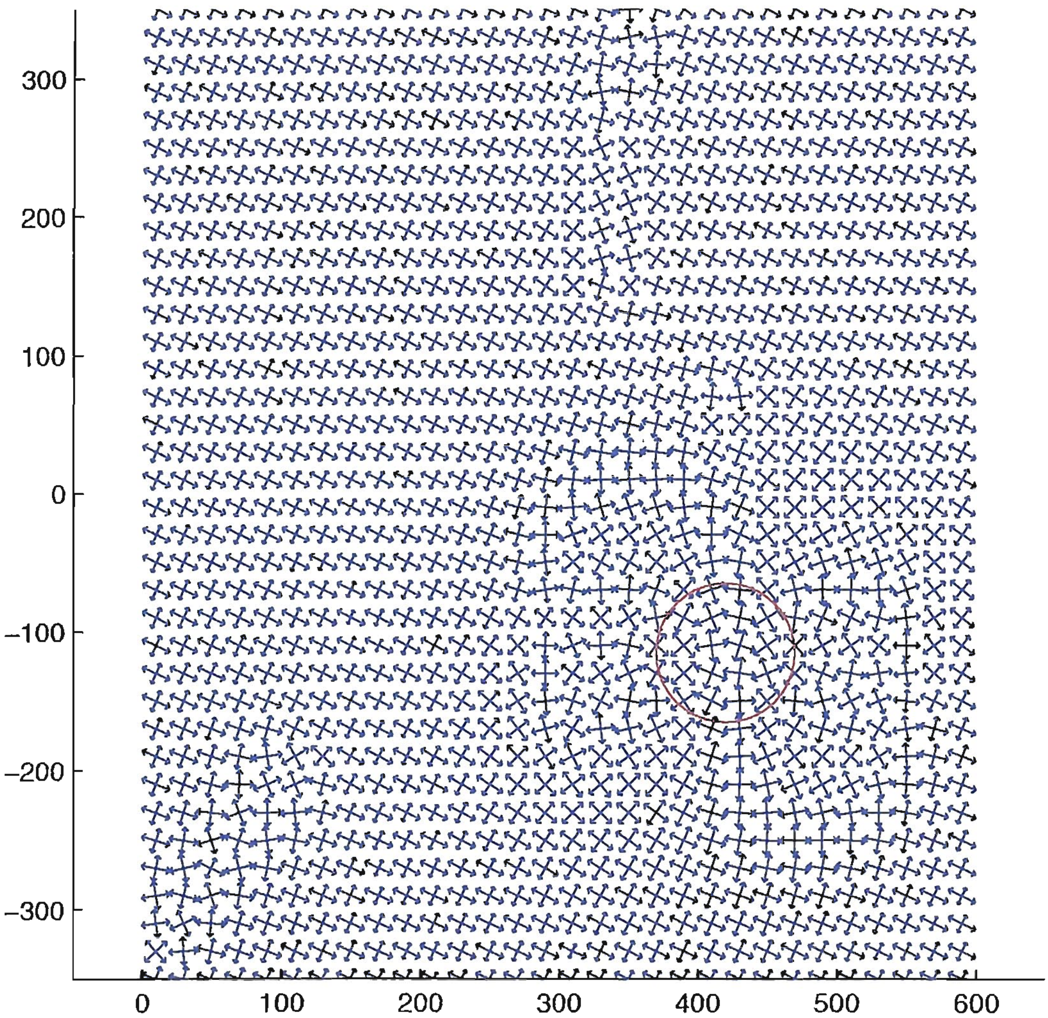

Figure 55: *The orientations of the principal horizontal stress axes for the 75% compensated model - with 25% of the volcanic load. The area and the scaling are as in Figure 53.*

3.7.2.8 Meetings and conferences

Meetings between Maurizio Bonafede and co-workers with Frank Roth took place in May in The Hague and in September in Reykjavík. Report on first results were given in papers presented at the XXI EGS General Assembly, The Hague, May 6–10, 1996, the XXV ESC General Assembly, Reykjavík, September 9–14, 1996, and on a PRENLAB workshop in Paris, October 24–25, 1997.

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