VEÐURSTOFA ÍSLANDS

Report
01001

Ragnar Stefánsson, Françoise Bergerat, Maurizio Bonafede, Reynir Böðvarsson, Stuart Crampin, Kurt L. Feigl, Frank Roth, Freysteinn Sigmundsson, Ragnar Slunga

PRENLAB-TWO - final report

April 1, 1998 - June 30, 2000

VÍ-JA01
Reykjavík
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Earthquake–prediction research in a natural laboratory –

THE PRENLAB–2 PROJECT

April 1, 1998 – June 30, 2000

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4 methods and algorithms for warnings

Shear–wave splitting, stress changes
Strike of horizontal compressions
Slunga warnings – seismicity and source radius
SAG – spectral amplitude grouping

New base for studying crustal processes

Microearthquake technology
Paleoseismology
Modelling – multidisciplinary
Continuous GPS and SAR
Role of fluids
Visualization
Real–time research

Warnings during the project period

M=5 earthquake, November 1998
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Two M=6.6 SISZ earthquakes, June 2000

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Building an early warning system (Icelandic project)
Developing stress monitoing sites SMSITES (EU project)
Continuation of PRENLAB–2

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Chapter 1

Summary

The PRENLAB-2 project started on April 1, 1998, and ended on June 30, 2000. It was a continuation of the PRENLAB project lasting from March 1, 1996, to February 28, 1998.

1.1 Activity overview

The project has successfully been carried out in accordance with the workprogramme. The individual subprojects have been carried out successfully in accordance with the general outlines in the workprogramme, as confirmed in reports on individual subprojects. Earth activity, seismic and volcanic, has been extremely high in Iceland during the time of the project. Therefore it was necessary to put much emphasis in enhancing the monitoring system and collection of data. Consequently, it was possible to study crustal processes related to earthquakes to an extent far beyond what was originally expected. The increased earth activity as well as scientific progress, not least of the PRENLAB projects, led to an increased interest and thus increased support of the government of Iceland for monitoring earthquake- and volcano-related crustal processes.

Successes in providing useful warnings have led to increased confidence of the public as well as of authorities of Iceland in the possibilities of seismology and related sciences in mitigating risks, as well as in the significance of the PRENLAB projects. The earth activity in Iceland led to slight shifts in the emphasis within individual tasks of the workprogramme in order to grasp the opportunities nature provided to carry forward the main objectives of the project, which are to understand better where, when and how earthquakes occur.

An earthquake sequence in the Hengill-Ölfus area in SW-Iceland (Figure 1) and associated deformation lead to concentration of the PRENLAB-2 activity in this area which, because of these events, became the most significant part of the natural laboratory during the first part of PRENLAB-2.

Two eruptions occurred in southern part of Iceland during the period of the project.

Two large earthquakes which occurred in the South Iceland seismic zone (SISZ), both magnitude 6.6 (Ms), near the end of the project period, were a test for the state of risk mitigation and earthquake prediction research in Iceland at present, and reveal new possibilities for the progress of such a research. These two earthquakes and related observed earth activity are of enormous significance for the progress of many parts of the PRENLAB-2 project far beyond its objectives.

1.2 Significant achievements as concerns short-term warnings, hazard assessments and understanding crustal processes related to earthquakes

1.2.1 New methods and algorithms have been developed and are applied - a basis for earthquake warnings

Iceland is divided into 34 basic alert regions. When number or size, etc., of small earthquakes in these regions changes beyond predefined levels scientists are alerted to take a closer look at the ongoing activity, to try to see if it might be premonitory for hazards.

Within PRENLAB-2 several algorithms have been developed to add to the alert functions and to base short-term warnings on. The limited understanding of earthquake processes as well as of their variability, requests many methods, based on our understanding of the physics of earthquake sources, or experience.

Following four methods are presently applied at IMOR.DG, for testing and as a basis for warnings.

1.2.1.1 Changes of shear-wave splitting time to observe changes of stress

By observing changes in shear-wave splitting time of local earthquakes, changes of stress can be observed in the ray path of waves radiated from the sources. Near source regions of frequent local earthquakes it is possible to observe stress changes, possibly in the build-up period of large earthquakes or eruptions. The method has already been applied in a successful stress forecast before an earthquake, and changes seen in hindsight before other events are promising for the usefulness of the method. The method has been developed within Subproject 3 at UEDIN.DGG. The method is applied for observing stress changes in seismic data from Iceland at UEDIN.DGG in close co-operation with IMOR.DG, for possibly preparing stress forecasts of earthquakes or volcanic eruptions, and for testing, as further described in Subproject 3.

1.2.1.2 Short-term warnings based on continuous observation of the strike of horizontal compressions from fault plane solutions of microearthquakes

A short-term warning algorithm has been developed which is based on completely automatic evaluations of automatically located small earthquakes and automatic fault plane solutions. This algorithm is already in continuous operation at IMOR.DG for some areas of Iceland, for short-term warning and for testing. It shows stable strike directions during a long period of time, changing however when there is a change in the mode of microearthquake activity. There are examples of precursory changes of this parameter before large earthquakes. A description of the method and results is found under Subproject 1. The method has been developed at IMOR.DG on basis of methods for fault plane solutions based on spectral amplitudes by Ragnar Slunga at UUPP.DGEO.

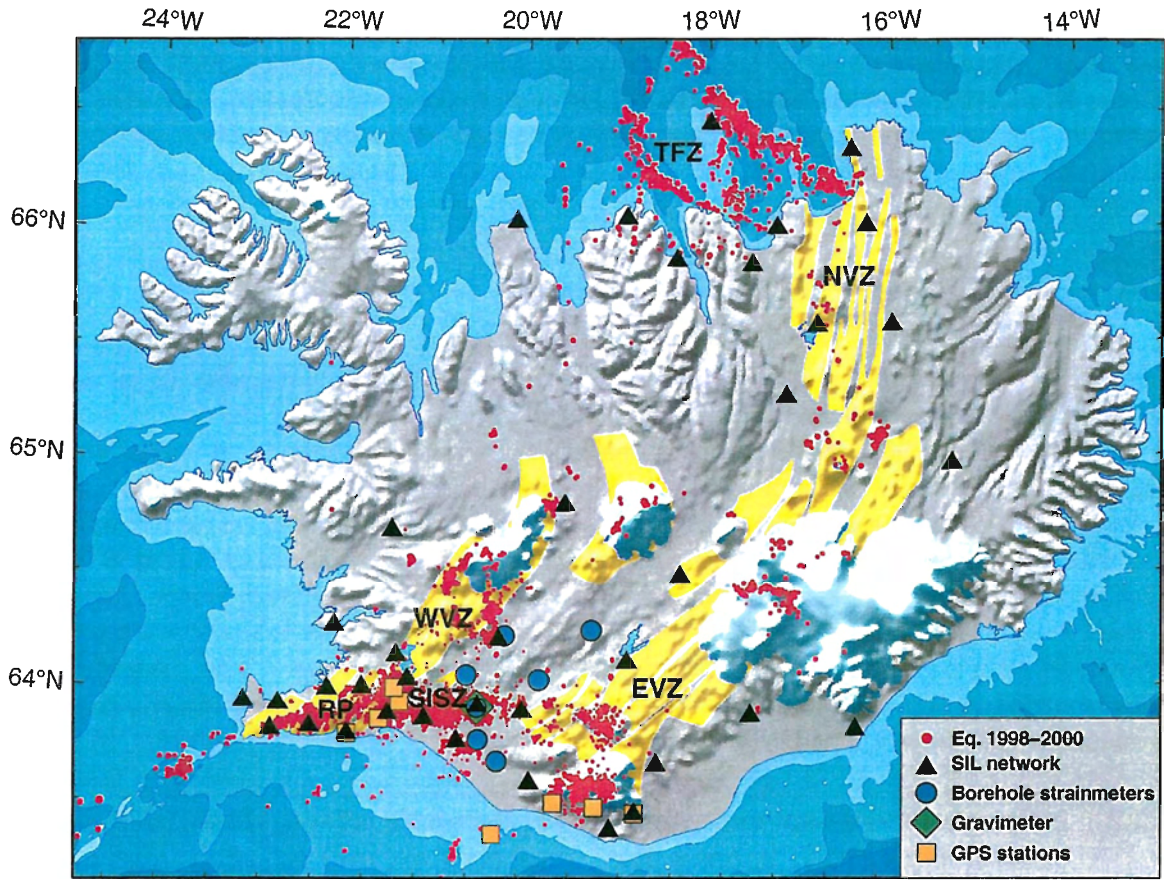

Figure 1. *Iceland, with its rift zones and volcanic zones, which delineate the mostly NS elongated mid-Atlantic ridge through Iceland. The EW plate divergency across the mid-Atlantic ridge and upwelling mantle plume below Iceland (Hotspot) are responsible for the seismicity and the volcanism. The observational network for continuous monitoring, used in the project, is shown. Volcanic zones are shown in yellow, i.e. the very active eastern volcanic zone (EVZ), the less active western volcanic zone (WVZ), and Reykjanes peninsula (RP). Large earthquakes occur along the EW elongated South Iceland seismic zone (SISZ) and in the Tjörnes fracture zone (TFZ) off the north coast. Glaciers are shown in bluish-white. The Hengill-Ölfus area, frequently mentioned in this report, is at the triple junction between SISZ, RP and WVZ.*

1.2.1.3 Slungawarning, an algorithm for alerting about time and site of impending earthquakes

The Slungawarning algorithm is based on watching seismicity of small earthquakes as well as of their source dimensions. The idea behind this is that the minimum size of source radius of earthquakes (microearthquakes) varies in time and space in the faulting area. A special case is the preparatory period of large earthquakes. Observations in hindsight of earthquake activity since 1991, after the start of the SIL system, by this algorithm provide short-term alarms for the larger events with few false alarms. This algorithm is now applied routinely for testing and gradually for short-term warnings at IMOR.DG. The method has been developed at UUPP.DGEO (see Subproject 2).

1.2.1.4 SAG, spectral amplitude grouping, a method for monitoring general stress increase in an area

It is often observed that increased stresses or closeness to fracture criticality in an area is reflected in an increase in the frequency of small earthquakes. Much of the seismic activity is, however, independent of the general stress changes, i.e. they have local energy sources and are not necessarily signs of general stress increase. By SAG spectral amplitudes of various phases of microearthquakes are used to group together earthquakes which are close to identical, and leave them out when seismicity is observed versus time. It is a better measure of closeness to fracture criticality to observe only singular events versus time than to observe all registered earthquakes. The method is a promising tool to observe the general stress level on a regional basis over a longer period of time, i.e. useful for medium-term assessments of the state of stress. It can be applied on a routine basis at IMOR.DG. It is developed in Subproject 2 at UUPP.DGEO.

1.2.2 New observations and new understanding of earthquake related crustal processes, a basis for long-term as well as real-time interpretations

The basic objective of the PRENLAB-2 project is to provide knowledge about earthquakes and related earth processes which can be basis for reducing seismic risk. The approach is physical and multidisciplinary. New measurements have been introduced and new understanding has been created to help in carrying forward these objectives.

1.2.2.1 The build-up of continuous GPS measurements in Iceland and observations of active deformation preceding earthquakes

Most significant extension of the observational network is that continuous monitoring of deformation has been initiated in Iceland by the installation of continuous GPS for observation at 8 sites in an area of high seismic and possibly volcanic activity in SW-Iceland.

These 8 stations are linked to observations of two former continuous GPS stations, which create a reference base for the local deformation monitoring. The cost of the equipment has been paid by Icelandic authorities, but the development of the observations and of the observational technology has to a large extent been a part of the PRENLAB-2 project. The continuous GPS measurements which have only been carried out for one to two years, have already recorded significant land deformations, either preceding or coinciding with earthquake occurrence, as further described below. The significant results of these observations are gradually creating a basis for funding more stations for continuous monitoring. The continuous GPS measurements provide new constraints in using the activity in this area as a basis for modelling earthquake processes. This work has basically been carried out in cooperation between Subproject 1 and Subproject 5 and is further described under Subproject 1.

1.2.2.2 Seismic and interseismic deformation observed by interferometric analysis of Synthetic Aperture Radar (InSAR) images

Satellite radar interferometry has been used to conduct extensive investigations of crustal deformation in SW-Iceland. The Hengill volcanic area has been the main target area, and there a series of interferograms show clearly a concentric fringe pattern, indicative of uplift of 19 mm/year from 1993 to 1998. The uplift is due to an expanding pressure source located at 7 km depth, and is interpreted to be result of magma accumulation. The inflation causes stresses that exceed the Couloumb failure critertion, and the results indicate that inflow of magma into the crust can furnish the primary driving force to actually break rocks on a fault in an earthquake. Furthermore, a new technique has been developed to combine GPS and satellite radar interferometry results in order to produce three-dimensional motion maps, that give an unprecedented view of plate motions. Significant results in applying SAR technique are described under Subprojects 5 and 6.

1.2.2.3 The significance of paleoseismology for catching the variability of seismicity in time and space

Geological studies of exposed parts of the fracture and fault zones in Iceland in conjunction with microearthquakes studies have revealed significant new understanding of the variability of fault zones and faulting in time and space. Established fault zones reveal significant perturbations in stress field.

Both the South Iceland seismic zone (SISZ) and the Tjörnes fracture zone (TFZ) show large variations in mechanical decoupling during short time spans. Comparable variability is also observed on a much shorter time scale. Repeated GPS measurements as well as observations by SAR have during repeated measurements since 1995 revealed variability in time and space as well as the interaction of areas, with different mode of tectonics, in governing the crustal processes. During the 5 years of observations it has been revealed that the dangerous Húsavík-Flatey fault is at present locked above the ductile brittle boundary, below which it has enormously variable creep velocity. It has been modelled how magmatic activity in adjacent volcanic zones can influence the probability of earthquakes in the fault zones. This variability in time highlights the necessity of continuous GPS measurements for risk mitigation in these areas in addition to the seismic methods. The results are described in Subproject 6.

In the SISZ borehole measurements to obtain the horizontal stress directions indicate stability in these since in the 1970s as described under Subproject 4.

1.2.2.4 Laboratory studies of rock samples and fluid activity in the fault zones

Experimental studies on Icelandic rocks demonstrate that due to the high temperature gradient and low lithostatic stress, thermal cracking may be an important process in controlling fracture in the Icelandic crust. This leads to fast increasing permeability. Field observations of mineral-filled veins in exposed deep parts within the TFZ indicate that fluid pressures due to faulting there may be as high as 20 MPa above the least compressive stress. By implication this is thought to be similar in the SISZ. This means that the driving shear stress needed to trigger fault slip is low, only 4-6 MPa. However, for triggering an earthquake the stress conditions along the entire fault plane must be homogenized, for example by fluid flow. This can be of significance for forecasting large earthquakes, if the homogenization process can be monitored. The results are described in Subproject 6.

1.2.2.5 Modelling of processes in earth realistic heteorogenic crust

Geological and geophysical techniques aim to reveal crustal processes by observing various derived changes. This would be relatively simple if the earth could be assumed to be rheologically homogeneous in all cases. However, simplifying such conditions may be very misleading. Within the PRENLAB projects there has been significant success in applying analytic crack theory to explain the response to applied stresses in proximity of rheological discontinuities. Models which have been developed help to interprete induced seismicity in rift zones in response to stress changes. Other models help to interprete faulting and deformation at depth based on surface observations. Such results are described in Subproject 7, Subpart 7A.

A model was created of the space-time development of stress field in the SISZ on basis of historical earthquakes and expected tectonic loading. Modelling of stress field due to plate motion and the sequence of strong earthquakes since 1706 showed that the events released stress in the whole volume of the E-W trending SISZ despite that they take place on N-S faults. The earthquakes in most cases occurred in areas where the model shows relatively high stress at the time of the events. This was also partly true for the two large earthquakes of June 2000 as described under Subproject 7, Subpart 7B.

1.2.3 Significant warnings and other risk mitigating information during the project period

The PRENLAB projects have in many ways increased understanding of crustal processes, as well as the awareness that it is possible to mitigate risks by warnings preferably ahead of a hazardous event. Three examples will be described in the following.

1.2.3.1 Stress forecast before the magnitude 5 earthquake on November 13, 1998

On basis of experience in studying shear-wave splitting time patterns in the very active Hengill-Ölfus area in SW-Iceland a successful stress forecast was issued by Stuart Crampin at UEDIN.DGG, on November 10, 1998, to IMOR.DG. This forecast said that an earthquake of magnitude 5-6 could occur anytime between the issuing of the forecast (M=5) and the end of February 1999 (M=6) if stress kept increasing. An earthquake of magnitude 5 occurred near the center of the region included in the forecast on November 13. Although this kind of forecast is far from being a complete earthquake prediction this is a step forward for short-term warnings. It does not in itself specify the epicenter of the earthquake. In this case the most likely epicenter and size had been guessed based on former activity, i.e. to complete an ongoing seismic cycle, as had been described by IMOR.DG scientists. In hindsight it was observed that the earthquake of November 13 had foreshock activity, which in fact defined the most likely epicenter for the earthquake, and also indicated that it was impending within short. Of course it is always a question if a sequence of microearthquakes is a foreshock activity or not. However, the pattern and characteristics of the foreshock activity in this case and methods for automatic evaluations of observations, give hopes that procedures can be developed to complete such a stress forecast by observations which aim at finding the place and the time of the earthquake nucleation before it ruptures.

1.2.3.2 Short-term prediction and warning before the Hekla eruption starting on February 26, 2000

The eruption of the volcano Hekla, that started on February 26, 2000, was predicted. An hour before the eruption the National Civil Defence of Iceland was warned that an eruption in Hekla was probably imminent. 20-25 minutes before the start of the eruption it was declared to the Civil Defence that an eruption would certainly start within 15-20 minutes. The warnings were based on observed microearthquakes of magnitude 0-1 which started 80 minutes before the eruption and on observations of a volumetric strainmeter in a borehole 15 km from the volcano. This warning was very significant as the ash plume reached 10 km height in a few minutes, which also was predicted. It was also significant because tourists could possibly be hiking on the mountain, which in fact showed no signs of an impending eruption except for the last 80 minutes prior to its start. The successful prediction was based on good cooperation between scientists at IMOR.DG and at UICE.SI, both involved in the PRENLAB projects. The prediction is described in Subproject 1.

1.2.3.3 Short-term warning about size and location of a magnitude 6.6 earthquake in the South Iceland seismic zone (SISZ)

Two large earthquakes occurred in the South Iceland seismic zone on June 17 and June 21, 2000, both of magnitude 6.6 (Ms). No short-term warning was issued before the first earthquake, although the sites of the two earthquakes were within 5 km of the location that had been estimated as most likely for the two next large earthquakes in the earthquake zone. This was mainly based on lack of release of moment in historical earthquakes in these two areas.

Short-term warning was issued 24 hours before the second earthquake, predicting the approximate size and the most likely area of maximum destruction within a kilometer. In hindsight very significant observations were also made before the first earthquake which may be very significant for warning in the future. The most significant observations of precursory activity were microearthquakes, water height or pressure in hot water boreholes, continuous GPS measurements and borehole strainmeters.

Warnings were issued by scientists at IMOR.DG. A fuller description is provided under Subproject 1.

1.2.4 Continuation towards new research projects and enhanced warning service based on the results of the PRENLAB projects

The results of the PRENLAB projects have paved the road for further efforts to enhance warnings and other hazards-related service. Two significant projects have started which are a direct continuation of PRENLAB-2.

1.2.4.1 A project for building an early warning system in Iceland

A project has started in Iceland for creating an early warning database and an early warning information system, with the objective to be able to utilize all available knowledge about earthquakes or volcanic hazards to mitigate risks, if possible in advance of the event, but otherwise as soon as possible after the onset of the hazard. The basis of this project is on one hand the enormous new information which is available, based on research and multidisciplinary monitoring, and on the other hand modern information technology for communication among scientists and with the public and the authorities. This project is supported by the Iceland Science Foundation. It is lead by IMOR.DG with participation of specialists on information technology from the University of Iceland and a private company.

1.2.4.2 Developing a stress monitoring site near Húsavík, N–Iceland

The town Húsavík, N-Iceland, is situated in a seismic zone of earthquakes reaching magnitude 7. Based on the success within the PRENLAB projects of monitoring stress changes by observing shear-wave splitting from local small earthquakes, a test site has been set up near Húsavík where active sources of seismic waves will be applied to observe changes in shear-wave splitting. Other observational methods, research results and experience gained in the PRENLAB projects will also be applied in this project which is supported by EU. This project (SMSITES) is shortly described under Subproject 3.

1.2.4.3 Continuation of PRENLAB-2 research based on observations of the two large SISZ earthquakes in June 2000

The multidisciplinary observations of the two large South Iceland seismic zone earthquakes in June 2000 will be of enormous significance for understanding earth processes leading to and involved in large earthquakes. Research work has started to a minor extent within the PRENLAB-2 project. The earthquakes occurred just before the end of the project. But such earthquakes were the main target of the project and thus a PRENLAB-3 would be a natural continuation of PRENLAB-2 applying the new understanding and enormous amount of data.

1.3 Meetings and workshops

The results and progress of the project were demonstrated and discussed at internal PRENLAB-2 workshops and at other workshops, and international scientific conferences, some coinciding with the PRENLAB workshops, others not.

- A whole day planning workshop was organized during the XXIII EGS General Assembly in Nice, France, April 20-24, 1998.
- The second PRENLAB-2 workshop was held in Húsavík, Iceland, July 30, 1998, attended by participants of the project in addition to several Icelandic and other European geophysicists, who are active in research related to the Húsavík fault. The workshop was also attended by representatives from the Húsavík community. The main topics of the workshop were to discuss the probability of a possibly impending destructive earthquake near Húsavík and action to be taken for research in the area as well as for enhancing the basis for providing warnings by increased monitoring.
- The third PRENLAB-2 workshop was held on March 31, 1999, coinciding with the tenth biennial EUG meeting in Strasbourg, France.
- The fourth PRENLAB-2 workshop was held on June 27, 1999, coinciding with the second EU-Japan workshop on seismic risk, Reykjavík, Iceland.
- The fifth PRENLAB-2 workshop was held on April 27, 2000, in Nice, France, coinciding with the XXV EGS General Assembly.

Among other conferences where progress of PRENLAB-2 was presented were:

- The EU-Japan workshop on seismic risk, Chania, Crete, Greece, March 24-26, 1998.
- XXIII EGS General Assembly, Nice, France, April 20-24, 1998.
- XXVI ESC General Assembly, Tel Aviv, Israel, August 23-28, 1998.
- Early Warning Conference (EWC 98), Potsdam, Germany, September 7-11, 1998.
- Workshop on recurrence of great intraplate earthquakes and its mechanism, Kochi, Shikoku, Japan, January 20-21, 1999.
- Tenth biennial EUG meeting, Strasbourg, France, March 28 - April 1, 1999.
- The conference of the Seismological Society of America, Seattle, Washington, USA, May 2-5, 1999.
- SEISMODOC and SERGISAI workshop, Brussel, Belgium, May 3, 1999.
- The second EU-Japan workshop on seismic risk, Reykjavík, Iceland, June 23-27, 1999.
- XXII IUGG General Assembly, Birmingham, United Kingdom, July 18-30, 1999.

- AGU fall meeting, San Francisco, California, USA, December 13-17, 1999.
- The third EU-Japan workshop on seismic risk, Kyoto, Japan, March 27-30, 2000.
- XXV EGS General Assembly, Nice, France, April 25-29, 2000.
- AGU spring meeting, Washington D.C., USA, May 30 - June 3, 2000.
- XXVII ESC General Assembly, Lissabon, Portugal, September 10-15, 2000.

Results and progress are described at the PRENLAB website:

http://www.vedur.is/ja/prenlab/

Chapter 2

The role of the responsible institutions

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

IMOR.DG did coordinate the PRENLAB-2 project and was responsible for Subproject 1, *Monitoring crustal processes for reducing seismic risk.* The commitments of the first year of PRENLAB-2 workprogramme 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, of build-up of the new continuous GPS network and others available for the project, and for operating these networks. It has carried out extensive work in extending, refining and standardizing the earthquake databases as well as related databases on slow changes, where continuous borehole strainmeters are most significant, together with the emerging continuous GPS measurements. It served the other subprojects with data from these databases. It was continuously working on mapping of active faults, in studying seismicity patterns, in enhancing the alert system in Iceland, for developing and testing new algorithms and methods to cope with steadily increasing data acquisition and for enhancing the automatic data evaluation processes. It did cooperate closely with all the other subprojects, and through its coordination all the subprojects were well linked together.

Work has been carried out according to the time schedule of the workprogramme, although there has been more achieved in the data collection than planned, both because of significant earthquake sequences that had to be very well observed and because the observational system has expanded more than had been planned, also because of this increased activity.

2.2 UUPP.DGEO: Uppsala University, Department of Geophysics

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

The contractor, Reynir Böðvarsson, has fulfilled his commitments according to the schedule of the workprogramme. As detailed in the first annual report of PRENLAB-2 all tasks were carried out according to schedule except Task 4, which has not been carried out in the way which was planned. The Task was implementation of these new methods in a second EU country with high seismic risk. The plan was to implement these methods within the Seismological Laboratory, University of Patras in Greece. However, the leading scientist in Patras, which was a contact person in this cooperation moved to a new position in Athens, and it has not been successful so far to re-establish the practical contact for carrying out the implementation. On the other hand the necessary preparations for being able to apply the SIL procedures at other sites have been in good advance by the contractor, both in cooperation with Subproject 1 but also in connection with the build-up of a SIL system in Sweden. The build-up of the SIL system in Sweden has to be considered a great advance for the Subproject and will further make it more feasible to export the SIL procedures to other sites.

During the second half of the project period significant new methods and algorithms have been developed by the contractor which integrate the development within the various tasks of the Subproject.

In all tasks above the closest cooperator was IMOR.DG. There has also been cooperation with UEDIN.DGG in using microearthquakes for studying shear-wave splitting.

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

UEDIN.DGG was responsible for Subproject 3, *Shear-wave splitting to monitor in situ stress changes before earthquakes and eruptions.* The contractor was Stuart Crampin. UEDIN.DGG has fulfilled its commitments in the workprogramme as a whole. However, frequent earthquakes in the Hengill-Ölfus area in SW-Iceland made it significant to change the emphasis of individual tasks to be carried out. This was reflected later in this report, in detailing the work carried out. All the problems addressed in the workprogramme are however addressed in the work carried out. The emphasis on continuous survey of temporal variations of shear-wave splitting from local earthquakes at a few stations in SW-Iceland has shown that it may be possible in many cases to see stress changes related to build-up of earthquakes or volcanic eruptions. In particular, observed temporal variations in shear-wave splitting in SW–Iceland was a basic observation in the successful forecast of the time and magnitude of a magnitude M=5 earthquake in SW-Iceland in November 1998. The success of this Subproject in explaining the relation between shear-wave splitting variations and effects of stress changes, as well as the successful stress forecast has initiated a new EU project within "Support for research infrastructures" (SMSITES: Developing stress monitoring sites and infrastructure for forecasting earthquakes, contract no. EVR1-CT1999-40002), which began on January 1, 2000. In all tasks above there was a close cooperation with IMOR.DG as concerns basic evaluation of and in providing data and applying the forecasts.

2.4 GFZ.DR.DBL: Stiftung GeoForschungsZentrum Potsdam - Solid Earth Physics and Disaster Research - Earthquakes and Volcanism

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. Tasks 1-4 were in direct continuation of the loggings carried out during the PRENLAB project, and have been successfully continued during PRENLAB-2, significant results obtained and reported.

GFZ.DR.DBL was also responsible for Subpart 7B, *Modelling the earthquake related space-time behaviour of the stress field in the fault system of southern Iceland.* Close co-operation was with IMOR.DG. Subpart 7B has been successfully carried out in accordance with the workprogramme.

2.5 NVI: Nordic Volcanological Institute

NVI was responsible for Subproject 5, *Active deformation determined from GPS and SAR.* NVI has fulfilled its commitments in the workprogramme, with some well justified modifications in the carrying out the individual tasks.

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

Subpart 5A, *SAR interferometry study of the South Iceland seismic zone*, was managed by associated contractor Kurt Feigl of the CNRS.DTP in close cooperation with Freysteinn Sigmundsson, contractor of NVI. Subpart 5A has been carried out with some modifications as compared to the workprogramme. In accordance with the high seismic activity in the Hengill-Ölfus area at the western end of the South Iceland seismic zone, the main emphasis was on observing this activity with the SAR technology.

Subpart 5B, *GPS measurements of absolute displacements*, was managed by the contractor Freysteinn Sigmundsson of NVI, in cooperation with Páll Einarsson, subcontractor, UICE.SI, and with IMOR.DG. The work has basically been carried out in accordance with workprogramme although there was some reorientation of priorities in accordance with obtained results and because of necessary concentration of activities to the Hengill-Ölfus area because of the intensive seismic and deformation processes there.

2.6 CNRS.TT: Centre National de la Recherche Scientifique, Delegation Paris B - Département de Géotectonique

CNRS.TT was responsible for Subproject 6, *Effects of stress fields and crustal fluids on the development and sealing of seismogenic faults*, and has fulfilled its commitments in the workprogramme. All the tasks have been carried out in accordance with the workprogramme, by the contractor Francoise Bergerat of CNRS.TT, and the subcontractors Jacques Angelier of the CNRS.TT, Ágúst Guðmundsson of the University of Bergen, Norway, Thierry Villemin of Université de Savoie, France, and Philip Meredith, University College London, United Kingdom, and their coworkers.

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, *Ridge-fault interaction in Iceland employing crack models in heterogeneous media*, was managed by contractor Maurizio Bonafede of UBLG.DF. All the tasks of the

Subpart 7A has been carried out successfully by the contractor and his coworkers at the same institute.

Subpart 7B, *Modelling 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. Subpart 7B has been carried out in accordance with the workprogramme.

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

See 2.5.

Chapter 3

Summary of scientific achievements by subprojects and tasks

3.1 Subproject 1: Monitoring crustal processes for reducing seismic risk

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3.1.1 Task 1: Database development and service for other scientists

3.1.1.1 Task 1.1: Data collection

Much more work was carried out in data collection and data evaluation than anticipated when the workprogramme was prepared.

This was partly due to general extensions of the applied monitoring systems, but partly due to very high seismic, volcanic and deformation activity at various places in southern Iceland.

The high seismic and deformation activity that started in 1994 in the Hengill-Ölfus area in SW-Iceland, culminated in June and November 1998, with magnitude 5 earthquakes (Figure 1).

Enormously significant data were collected in this area which contain earthquake premonitory activity and short-term precursors to earthquakes. The data collection and evaluations carried out in relation to this activity have been of basic significance in understanding crustal processes leading to earthquakes, and for creating algorithms for short–term warnings, for modelling motions involved in earthquakes and for understanding large-scale stress modifications that were caused by the two earthquakes. Most of the participants of the project have been making use of these data (Rögnvaldsson et al. 1998c). Other significant earth activity which have created significant data are the eruptions in Grímsvötn in the Vatnajökull glacier in December 1998, and the eruption in volcano Hekla in February 2000 (Stefánsson et al. 2000a; Ágústsson et al. 2000). Since July 1999 there has been a volcanic crisis in volcano Katla and in nearby volcanoes (Stefánsson et al. 2000b; Geirsson et al. 2000), based on observed activity, and on the threat which these volcanoes are for the inhabitants of the area and travellers on the nearby roads.

The two large earthquakes in the South Iceland seismic zone (SISZ) in June 2000, shortly before the end of this project and the data collected from these are of enormous significance for earthquake prediction research in general (Figure 4). Earthquakes in the SISZ, which can reach magnitude 7 have been a threat for the inhabitants in this area. Understanding large earthquakes in this area has been a basic objective for the PRENLAB projects (Stefánsson et al. 2000c). The seismic data and GPS data of the hazards shortly described here above have all been used in research actions as well as of other actions. Also significant warnings and information about these events have been provided, so significant experience has also been gained in predictions and early warnings to the public and to authorities.

The extension of the SIL acquisition and evaluation system, the SIL system, has continued during the year. The number of operating SIL stations was increased from 33 to 41.

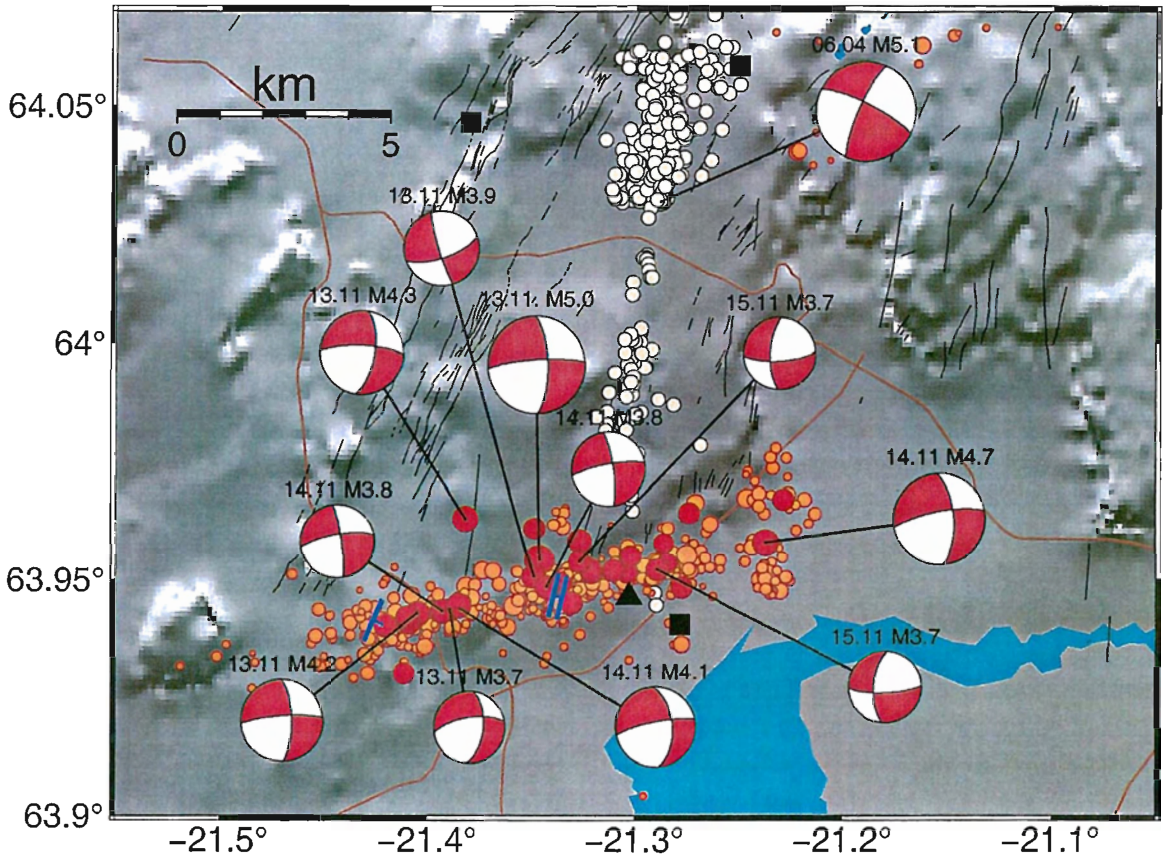

Figure 2. *Yellow and red circles show well located earthquakes (horizontal error less than 1 km and vertical error less than 2 km) from November 13-15, 1998, in Ölfus, SW-Iceland. The largest earthquake had magnitude 5.0. Red and white spheres present fault plane solutions in a conventional manner. Active faults found by accurate relative location of groups of microearthquakes are shown as blue line segments. White circles show locations of a few hundred earthquakes of the preceding earthquake swarm in Hengill in June 1998, maximum magnitude 5.1. The course of events was such that seismic activity had mostly been concentrated in the Hengill area since 1994, but ripped a fault to the south on June 4, 1998, followed by high seismic activity in an E-W elongated zone in Ölfus on November 13-15, 1998.*

Quite often during high earthquake activity the incoming data of small earthquakes is so high in the SIL system that the communication system and the computers have problems to cope with the data stream, and jams were created, which sometimes could delay the data, so the system evaluation was delayed. This could even lead to loss of data. As it is very significant to gather earthquake data down to the smallest earthquakes that provide information about crustal conditions, it was necessary to design and implement more effective procedures for doing this. For this purpose a new compression algorithm was developed for the system, i.e. the bit compression. This algorithm compresses the data very effectively at the site stations and the compressed data go directly into the evaluation procedures at the SIL center, much faster than the earlier procedures.

A new format for saving the digital earthquake waveform data will be described shortly in following:

The output of the seismometer digitizer is a series of integer values. The sample-to-sample variation is usually much less than the maximum values, which for most of SIL stations are between +/−3276800. In the AH format which was used by the SIL software, each value is stored in 32 bits.

A reduction in size of the data files of approximately a factor of 5 is achieved by storing the sample-to-sample variation in packed, variable size integers.

The access to data is thus much faster than to data that is compressed using general purpose compression programs such as *gzip* or *compress* and the files are typically 2-3 times smaller.

This new bit-compress format (bc) (Kjartansson 1996) was incorporated into the data acquisition in the SIL system during the autumn of 1998. The software on each station writes in ascii files in format that is called the SIL format. The program bc-tool can convert these files to the bc-format and back. All information in the headers are preserved.

The bc-files are then transferred to the SIL center (currently using uucp). All files from each day are kept together, with a directory for each station. An index file that contains a list of all waveforms for each day is maintained.

The index files are stored on binary form, and are sorted by the programs that read them. A major performance bottleneck in previous version resulted from sorting index files on ascii form, each time that waveform data arrived.

The new software is able to keep up with much larger levels of earthquake activity than previous software. Because the routines that read and uncompress the data are very fast and files are small, performance of all programs that use the data has been improved.

There are now 7 continuous GPS stations in S-Iceland. These stations collected valuable data during the June 2000 earthquake sequence. Although the installation cost of these stations is paid by Icelandic authorities, PRENLAB-2 has contributed significantly to the build-up and development of these measurements. The continuous monitoring of these stations has provided data which are significant for the objectives of the PRENLAB-2 project for data collection. Four of the continuous GPS stations were installed in the Hengill-Ölfus area, two south of Mýrdalsjökull and one south of Eyjafjallajökull volcanic area, as shown in Figure 3.

The project of building the continuous GPS measurements is a collaboration between IMOR.DG, NVI, and UICE.SI, with significant support for development work from PRENLAB-

Continuous GPS network in Iceland

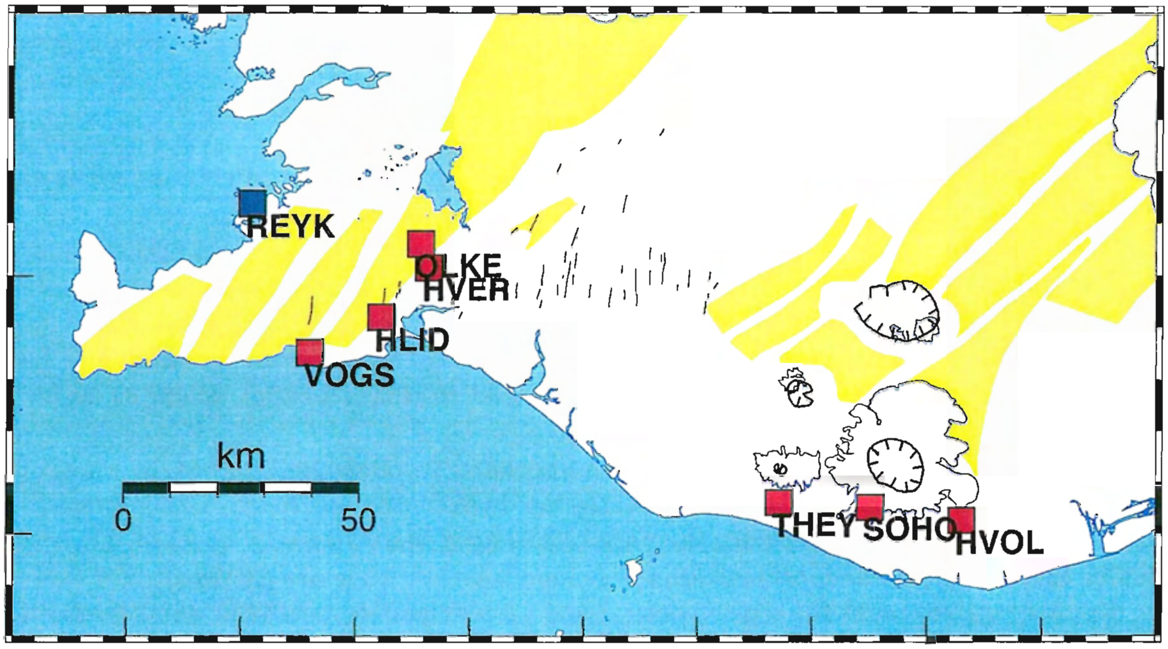

Figure 3. *Location of the continuous GPS stations in S-Iceland (red squares). The continuous GPS station in Reykjavík (REYK) is shown with a blue square. Thin black lines denote mapped faults (Einarsson and Eiríksson 1982; Einarsson and Sæmundsson 1987; Erlendsson and Einarsson 1996). The yellow areas are volcanic fissure swarms, and the calderas are shown with black lines with tick marks.*

2. The funding for purchasing the equipment comes from the Icelandic government and the Reykjavík Municipal District Heating Service. We use Trimble 4700 CORS and Trimble 4000 SSI dual frequency receivers, and Trimble Choke Ring antennas, to ensure the best data quality.

The data are automatically downloaded once every 24 hours to IMOR.DG via phone lines. Data from the IGS stations Reykjavík (REYK) and Höfn (HOFN) are included in our analysis. The data are automatically processed at IMOR.DG using the Bernese v4.2 software, and Center for Orbit Determination in Europe (CODE) predicted orbits. The displacements relative to REYK are calculated and the results posted automatically on the IMOR.DG website. The URL is http://www.vedur.is/ja/gps.html. A description of the network, data processing and results from the first year of observations are described by Árnadóttir et al. (2000).

Stations for continuous monitoring of conductivity at depth are presently operated at three sites in Iceland. A station was installed at Skrokkalda in the central highland of Iceland in July 1999, after being operated for a year at a site at the eastern end of the SISZ. This station is linked to the SIL seismic system and real-time observations are made at the SIL center at IMOR.DG. A second station is operated at Húsafell in Borgarfjörður, W-Iceland, since spring 2000, and a station started operation in Tjarnarland in Eyjafjörður, N-Iceland at the beginning 2000. This work has been carried out through cooperation between Axel Björnsson at the University of Akureyri, and IMOR.DG. The two last continuous MT stations operate off-line.

3.1.1.2 Task 1.2: Data access

Extensive work has been carried out within the PRENLAB-2 project in creating an earthquake database with easy access. The database structure used is INGRES.

Work has started in creating an early warning system, including a multidisciplinary early warning database. The objective of this system and its database is to merge together all available information that can be significant to have in case of large earthquakes and eruptions. Also to make relevant information and warnings based on them available as fast as possible to other scientists, authorities and the public, in case of an approaching or ongoing hazard situation.

SIL network seismic data since 1991 can be accessed through the Internet, by search in a simple relational database table. This table has hypocenter and magnitude information on SIL measured earthquakes since July 1991 that have been manually checked, i.e. over 160000 earthquakes. Search options for area, magnitude and time are provided.

The preparatory work for a new, general and easy accessible relational database for all seismic data is completed and the inclusion of data in the database is in good progress.

Included in the database now or in the near future is:

- Information based on historical information. This information has been gathered over the years and will be inserted into the database.

- Information on instrumentally measured earthquakes from 1926 to 1991. Available parameter data for earthquakes during the period 1926-1974 has been extracted from catalogues and inserted into relational database tables. Parameter data for the period 1975-1986 have also been inserted into relational database tables but are not complete. Work on filling gaps in time and for areas for this period is in progress. Work on 1987-1990 data is also in progress and will be inserted within short.

  Information on earthquakes that were felt but not recorded is also inserted into the tables.

- Information on SIL parameter data from 1991 to present. The data have been checked and updated to ensure compatible processing from different recording systems. The insertion of parameter data, both observed and derived, into relational database tables is up-to-date. Information on over 160000 earthquakes is now accessible through a standardized SQL database.

- Information on station parameters, such as coordinates, instrument characteristics and time corrections at each respective time of measuring. Relational database tables have been developed.

Beside preparing this general database much work has been carried out in providing the various other subprojects with earthquake data, in accordance with the progress of the research work.

The early warning system is being built up in continuation of the significant results and data collection of the PRENLAB projects. It has been shown during recent high activity in Iceland that scientists can now provide information and warnings that are very significant for mitigating risks. Thus it is a pressing need to make, as fast as possible, use of all acquired understanding for that purpose. The IMOR.DG website is already now a significant center for the very much needed fast communication among scientists, with the public and the authorities, foremost the National Civil Defence of Iceland.

3.1.2 Task 2: Enhancing the basis for alerts, warnings and hazard assessments

This work has been carried out in relation to providing information and warnings about ongoing activity. It has been linked with increased probability of the occurrence of large earthquakes, on one hand in SW-Iceland and on the other hand near the Húsavík earthquake fault in N-Iceland.

Much work which concerns all aspects of Task 2 has been devoted to the Hengill-Ölfus area in SW-Iceland (Figure 1). An earthquake sequence has been ongoing in this region since 1994, related on one hand to E-W transversal motion across the plate boundary, and on the other to an expansion source at 8-10 km depth below the Hengill area. The largest earthquakes of this sequence took place on June 4, 1998, magnitude 5.1, and on November 13, 1998, magnitude 5. This sequence of events, as observed seismologically and geodetically, is of enormous significance for understanding the build-up of stress before earthquakes and for understanding the nucleating process or the short-term precursor activity before earthquakes (Figure 2) (Ágústsson 1998; Rögnvaldsson et al. 1998c; Tryggvason et al. 2000; Stefánsson et al. 2000d). Description of work developed on data from the Hengill-Ölfus area is also found in Subprojects 2, 3 and 4.

After the earthquake of June 4, 1998, and the following earthquake sequence and deformation, stress was modified up to 50 km distance to east and west from the epicenter, along the E-W plate boundary. This appeared in widespread seismic activity, but also in increases in shear-wave splitting delay time, which lead to an earthquake forecast (Crampin et al. 1999).

Work which is concerned with the possibility of an impending large earthquake, i.e. earthquake of magnitude 7, near the town Húsavík in N-Iceland (Figure 1), was discussed at a special PRENLAB-2 workshop in Húsavík on July 30, 1998. Work is going on under several subprojects with risk related research in this region. Subproject 1 has besides providing seismological data, taken initiative in planning new observations to be made in the area, on basis of the results of ongoing work. The objective is to provide observations which can create a better basis for modelling of the Húsavík earthquake, for an improved hazard assessment and for better real-time monitoring possibly involving short-term warnings (Stefánsson et al. 1998). IMOR.DG has been much involved in preparing and starting a new project, SMSITES, an EU project within "Support for Research Infrastructures", which is based on the results of the PRENLAB projects (see further Subproject 3). This involves seismic measurements and evaluations as well as monitoring of changes of water elevations in hot water boreholes in the area. Work is ongoing within Subproject 1 regarding the Tjörnes fracture zone in general (Rögnvaldsson et al. 1998b).

Increased activity in the volcanic complex of Katla (see position in Figure 4), Mýrdalsjökull and Eyjafjallajökull in S-Iceland from summer 1999 which has involved increased research and monitoring as well as multidisciplinary cooperation, was aimed at being able to provide useful warnings in case of a suddenly occurring of a possibly very dangerous eruption there. The website of IMOR.DG has gradually developed into a center of early warning and information activities in Iceland (http://www.vedur.is/ja/jar_inn).

The progress of this work on this task was put under test in the two large earthquakes in the South Iceland seismic zone, on June 17 and 21, 2000, as well as in the Hekla eruption which started February 26, 2000 (Figure 4). These events involved decision about warnings or predictions as further described and referred in Subsection 3.1.5.3.

3.1.3 Task 3: Modelling of near-field ground motions in catastrophic earthquakes in Iceland

The M=5.1 earthquake on June 4, 1998, at Hellisheiði in the Hengill area (Figure 2) provided excellent geodetic and seismic data for modelling of near-field displacements of the largest earthquake in the area since 1955.

Results from modelling GPS data spanning the M=5.1 earthquake, June 4, 1998, were described in the first PRENLAB-2 annual report and by Árnadóttir et al. (1999). Preparations are ongoing for modelling near-field ground motions expected in large South Iceland seismic zone earthquakes on basis of GPS data, strong motion and records of the SIL network for the earthquakes on June 17 and June 21, and on basis of historical documentation of near-field destruction in historical South Iceland seismic zone earthquakes.

The modelling of ground motions expected in large South Iceland seismic zone earthquakes has been done for the M_S=7.1 earthquake of August 14, 1784, and written in a report (Árnadóttir and Olsen 2000). We use a finite-difference method to simulate the M_S=7.1 earthquake of August 14, 1784, which occurred in the South Iceland seismic zone, believed to have been the largest historical earthquake in Iceland. The August 14 earthquake was followed two days later by a M_S=6.7 event located approximately 30 km to the west.

We simulate a rupture on a N-S, vertical, right-lateral, strike-slip fault, vary the fault geometry, slip distribution and rupture velocity, and compare the peak velocities calculated at the surface obtained for the different models to a reference model. We find that the simulated peak velocities depend significantly on the depth to the top of the fault. The fault-parallel and vertical peak velocities decrease significantly if the fault does not break the surface, while the fault-perpendicular component is less affected. A model with a heterogeneous slip distribution yields a very different pattern and lower magnitude of surface peak velocities than uniform moment models (Figure 5). This is partly due to the variable slip at shallow depth in the distributed slip model.

We calculate the static Coulomb stress change for two models of the August 14, 1784, earthquake to examine if it is likely to have triggered the second large earthquake on August 16, 1784. We find that the stress change caused by a 20 km long fault is larger in the

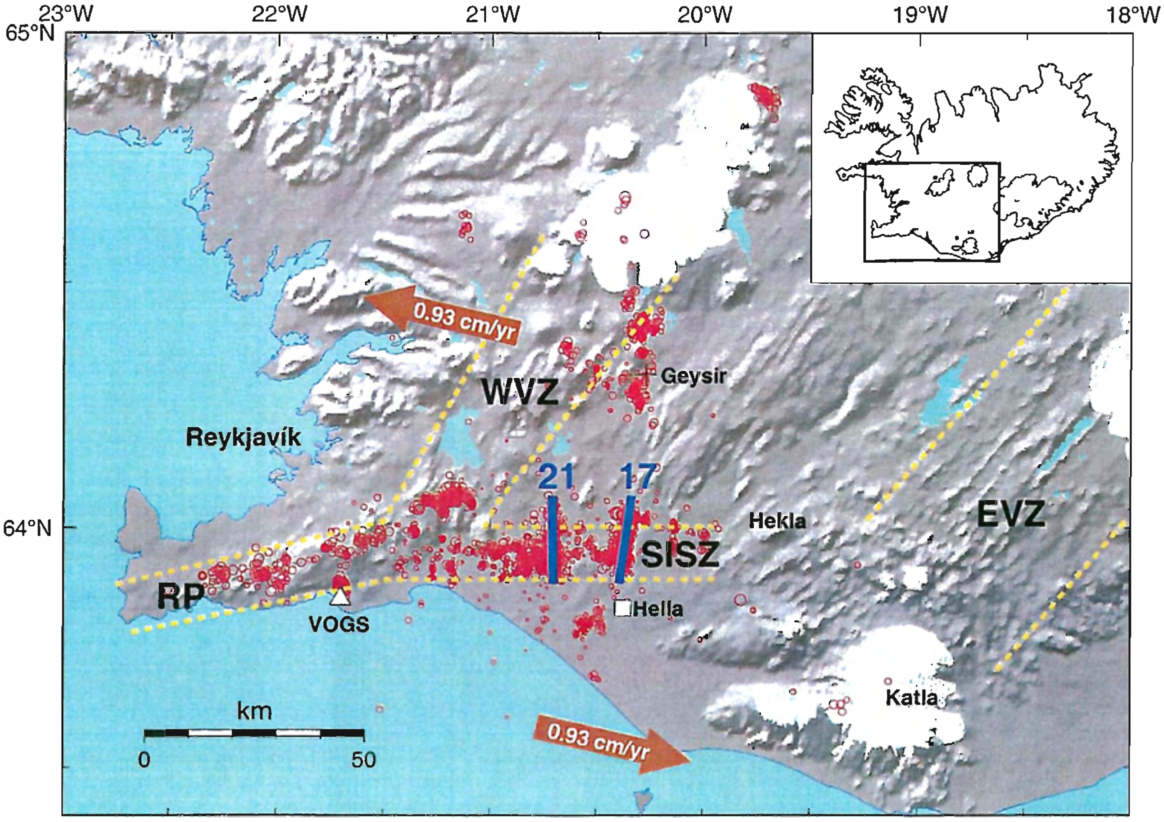

Figure 4. *The figure shows the southwestern part of Iceland. Iceland as a whole is shown in the upper right corner. Dotted yellow lines denote the western volcanic zone (WVZ) and the presently more active eastern volcanic zone (EVZ). South Iceland seismic zone (SISZ) is indicated as well as its prolongation in the Reykjanes peninsula (RP). The direction of the relative plate motion is shown by arrows. The faults of the earthquakes on June 17 and 21 are indicated by 17 and 21 respectively. Red dots, which are epicenters of small shocks following the large earthquakes, describe the area seismically activated.*

hypocentral region of the second earthquake than that for a 50 km long fault. This indicates that if the M_S=7.1 earthquake occurred on a short rather than a long fault, it is likely to have triggered the second large earthquake.

3.1.4 Task 4: Mobile stations for shear-wave splitting monitoring

The objective of this task is to investigate more in detail the shear-wave splitting effects of the crust and the spatial distribution of the observed anisotropy. Seven three-component mobile seismometers of ORION type were borrowed for this purpose from UUPP.DGEO. The seismometers were operated as a dense network near to the SIL station SAU for this purpose, from May 13 to July 5, 1998, and again from July 23 to August 13. This is in the middle of the South Iceland seismic zone and it is very significant for future use of shear-wave

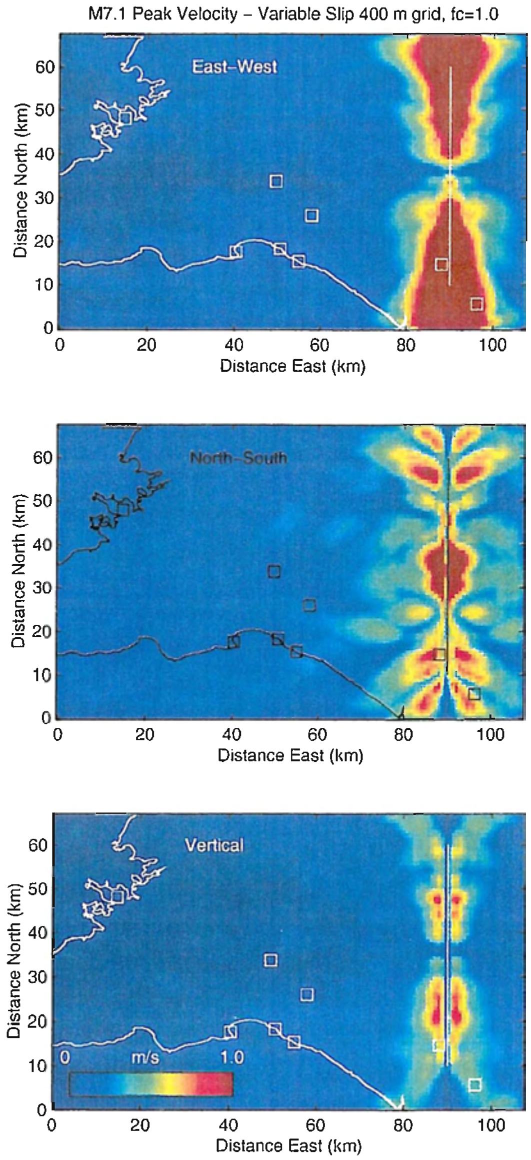

Figure 5. *Peak velocities for a model with variable slip distribution. The top panel shows the E-W component, the center panel shows the N-S component, and the bottom panel shows the vertical component. The color scale extends from 0 m/s (dark blue) to 1.0 m/s (red). The N-S line shows the surface trace of the fault model. The fault is 50 km long and extends from the surface down to 15 km depth. The rupture starts at the center of the fault at 10 km depth, and propagates bilaterally with a constant rupture velocity of 2.7 km/s. In general, the largest peak velocities correspond to areas of large slip in the model. The squares depict current locations of towns (Árnadóttir and Olsen 2000).*

splitting methods in this earthquake-prone area to carry out this study. Data were collected for this period and preparations are going on to evaluate these data. It has taken some work to merge these data with the SIL data evaluation system algorithms. This is necessary for best results, and so the high level evaluation processes of the SIL system can be utilized in full. Work on this task is ongoing, but the enormous seismic and volcanic activity in southern Iceland during the last two years has delayed this work as it has been considered more significant to save and to evaluate data of the recent large hazard events.

3.1.5 Task 5: Extending the alert system functions by real-time research

Automatic alert system at IMOR.DG as well as information from other scientific institutions and the public alert the scientists at IMOR.DG about a possibly approaching seismic or volcanic hazard. In evaluating the alert it is of enormous significance to have preprepared tools and easily accessible multidisciplinary database to help the scientists in as fast decision making as possible. The high earth activity in Iceland lately has pushed forward such a development.

Algorithms have been developed for quick visualization of direct observations, as well as of results of evaluations by many new algorithms developed within the project. Most of these tools for real-time research are available now for the scientists on the IMOR.DG website. The visualization procedures span time graphs and maps of seismic activity as well as graphs of strainmeter changes, on real-time basis as well as for comparison with earlier observations.

Several algorithms for evaluating crustal processes have been developed in the PRENLAB projects to be used on a routine basis in order to provide short-term warnings as well as for real-time research. They are used on a routine basis and are of significance for short-term warnings and thus for real-time research, as will be described in the following sections.

3.1.5.1 Methods tested and applied for short- and medium-term warnings

Following algorithms have been used and checked in Subproject 1 and will be applied at IMOR.DG in the future:

- **Monitoring stress changes from local earthquakes:**

  Stress monitoring by observing changes in shear-wave splitting time from local small earthquakes. The routine observations are carried out by UEDIN.DGG (see Subproject 3). The results are checked and discussed with IMOR.DG (see Subproject 1).

- **Variations with time in the horizontal compressions of fault plane solutions:**

  Based on automatic fault plane solutions, horizontal compressions of individual fault planes of earthquakes down to magnitude 0 are observed in real-time. It shows that the strike of the horizontal compression axis is often very stable in Iceland. Exceptions of this have been observed in the preparatory stage of large earthquakes. These variations can be observed directly in real-time on the IMOR.DG website for some areas. A tool is available on the website to monitor other areas and time periods. This work is done both on completely automatic evaluated data as well as on manually checked data (Stefánsson et al. 2000d).

- **Slungawarning:**

  This algorithm defines time and place of a possibly approaching earthquake, on basis of seismicity rate and on sizes of fault planes of small earthquakes. The method has been developed under Subproject 2 and is described there. The algorithm has been checked at IMOR.DG and is routinely used there. See further in Subproject 2.

- **SAG:**

  Spectral amplitude grouping (SAG) is a monitoring algorithm that can be a good indicator of long-term evolution of stress. Two previous algorithms are based on fault plane solutions of earthquakes. The fault plane solutions are based on spectral amplitudes of P- and S-waves, and signs of the P-waves. SAG is based on grouping the earthquakes by using spectral amplitudes of many different phases at some seismic stations. The method is applied to monitor the of state of stress in a region as described in Subproject 2.

- **Monitoring rock stress tensor:**

  Inversion for rock stress tensor based on microearthquake locations and fault plane solutions is a very significant tool in real-time investigations. Algorithms for this are available and routinely applied at the IMOR.DG, and described under Subproject 2.

- **Subcrustal mapping of faults:**

  An algorithm for relative location based on multievent location technique is available for investigation and testing at IMOR.DG. By this technique which provides relative locations for groups of microearthquakes with an error within 10 m, it is possible even to discriminate between the fault plane and the auxiliary plane (Rögnvaldsson et al. 1998b).

3.1.5.2 An early warning system and an early warning database

In case of a dangerous earthquake or a dangerous eruption it is vital to be able to access as soon as possible all available observations and knowledge to try to mitigate risks. This is significant during the often short time between the first suspicious signs of an impending hazard and the hazard itself. But it is also significant even if no prewarning can be given. Communication between scientists, the public and authorities is enormously significant during such times.

An early warning system is in development at IMOR.DG to serve such needs. Although it is only in its initial ages of development it is already applied in practice for supplying warnings and information and for testing (Stefánsson 2000a; Halldórsson et al. 2000; Stefánsson 2000b). This project is lead by IMOR.DG in cooperation with participation of specialists on information technology from the University of Iceland and a private company. The project is supported by the Iceland Science Foundation and the government of Iceland.

3.1.5.3 Warnings for hazards in practice

The experience gained in warning service is maybe the most significant in extending the alert system and for developing real-time research. During the PRENLAB-2 period there were three eruptive crisis in Iceland, two of which have already ended with eruptions and two earthquake sequences occurred in S-Iceland where warnings and information was significant.

- **Short-term warning and information before the eruption in volcano Hekla, February 2000:**

  The eruption that started in the volcano Hekla in S-Iceland at approximately 18:17-18:19 GMT on February 26, 2000, was preceded by precursory signals on seismographs and volumetric strainmeters during the last 79 minutes prior to the outbreak.

  The National Civil Defence of Iceland was warned of a probable imminent eruption about an hour before the ash plume was observed. By time the precursory signals became more prominent and at 17:53 a prediction was issued to the Civil Defence claiming that an eruption was certainly to be expected within 15-20 minutes, with the recommendation that a warning should be issued and broadcast to the public. The main immediate hazard caused by recent Hekla eruptions is the 10 km high ash plume during the first minutes of the eruption that endangers flight traffic. Therefore, well before the final prediction was made, probable ash trajectories were calculated and the Civil Aviation Administration was notified that an ash plume from Hekla could be expected to rise to cruising altitudes of air traffic within short. The first signs of the coming eruption were seen at 17:00 from a seismometer situated within 2 km of the top of the volcano. These were earthquakes of magnitude below 1. The earthquake swarm became more intense in the next half hour and events were located by the automatic location system and detected by the alert system at 17:29. Earthquake sequences of similar size are unknown at Hekla except as a prelude to eruptions. A volumetric strainmeter at a distance of 15 km from Hekla showed rapidly increasing contraction starting 30 minutes before the eruption. Based on modelling of the 1991 Hekla eruption this was a clear sign of an opening of a feeding dyke for an eruption. This observation was used to refine the timing of the final prediction. The rapid response to the premonitory signals of the eruption was possible because of a combination of improved instrumentation in the region of Hekla, improved facilities for real-time analysis and alerting, and raised general alert caused by recent unrest in the neighbouring volcanoes, mainly Katla and Eyjafjallajökull (Stefánsson et al. 2000b; Ágústsson et al. 2000).

- **Stress forecast before the magnitude 5 earthquake in November 13, 1998, in the Ölfus area:**

  The Hengill-Ölfus area in SW–Iceland (Figure 1) was a very significant research and test area for the PRENLAB-2 project as it was for the PRENLAB project for development of warning algorithms as well as for general understanding of earthquake related crustal processes (Rögnvaldsson et al. 1998a) (Figure 2).
  The reason is basically the very high seismic activity in this area since 1994. It has been possible to carry out deformation measurements of various kinds to keep track of the deformation, both by GPS and SAR in addition to very detailed observations

of frequent seismic swarms and individual earthquakes up to 5.1 in magnitude. Stress modifications related to the largest earthquakes have been observed. Thus an earthquake cycle has been observed from the start time of build-up of stress on June 4, 1998, in a large area towards concentration of stress in a focal region and foreshocks of an earthquake that occurred on November 13, 1998. After the earthquake of November 13, it was then observed how an E-W fault zone served as a stress guide, and how a sequence of earthquakes was observed related to that guide.

On basis of experience in studying shear-wave splitting time patterns in this area and on basis of the general understanding achieved of crusal processes there, stress forecast was issued by Stuart Crampin at UEDIN.DGG, on November 10, 1998, to IMOR.DG. This forecast said that an earthquake of magnitude 5-6 could occur anytime between the issuing of the forecast (M=5) and the end of February 1999 (M=6) if stress kept increasing. An earthquake of magnitude 5 occurred near the center of the region included in the forecast on November 13. Although this kind of forecast is far from being a complete earthquake prediction this is a step forward for short-term warnings. It does not in itself specify the epicenter of the earthquake. In this case the most likely epicenter and size had been guessed based on former activity, i.e. to complete an ongoing seismic cycle, as had been described by IMOR.DG scientists. In hindsight it was observed that the earthquake of November 13 had foreshock activity, which in fact defined the most likely epicenter for the earthquake, and also indicated that it was impending within short. Of course it is always a question if a sequence of microearthquakes is a foreshock activity or not. However, the pattern and characteristics of the foreshock activity in this case and methods for automatic evaluations of observations, give hopes that procedures can be developed to complete such a stress forecast by observations which aim at finding the place and the time of the earthquake nucleation before it ruptures (see further Subproject 3).

- **Hazard assessments and short-term warning related to the two M=6.6 earthquakes in the South Iceland seismic zone in June 2000:**

In June 2000 two earthquakes with magnitude 6.6 (Ms) struck in the central part of the South Iceland seismic zone (SISZ), immediately followed by seismic activity along zones of 100 km length (Stefánsson et al. 2000c). This occurred after 88 years of relative quiescence in the 70 km long EW transform zone in SW-Iceland (Figure 4).

Earthquakes in this region have, according to history, frequently caused almost total destruction in areas encompassing 1000 km^2 and have been a threat for inhabitants of this area, which is a relatively densely populated farming area. In spite of open surface faults and measured accelerations higher than 0.8 g no serious injuries were reported and no homes collapsed. In light of the fear which the expected SISZ earthquakes have caused among Icelanders, the relatively minor destruction has lead to some optimism regarding the safety of living in the area. Many of the ideas about the nature of strain release in the area have been confirmed. As far as the epicenter of the first earthquake is concerned, hazard assessments or long-term predictions were confirmed, and in hindsight precursors have been observed. Useful short-term warnings regarding the epicenter, size and time of the second earthquake could be issued beforehand. Significant observations were made of the earthquakes as well as of their premonitory and following processes which will lead to better models of the SISZ earthquakes as well as to better hazard assessments and warnings in the future. Among significant observational systems are the SIL system, which is especially aimed at retrieving information from microearthquakes, strong motion instruments with a good coverage in the area, continuous GPS measurements, borehole strainmeters and hydrological observations in boreholes. Earlier GPS net measurements were repeated after the earthquakes, and detailed analysis of extensive surface fissures was carried out. It is expected that no more than 1/4 of the moment build-up in the zone has been released in these two earthquakes, and that even larger earthquakes may occur in the zone during the next decades.

The short-term warning, hazard assessment and premonitory activity are further described in Stefánsson et al. (2001).

3.1.6 Task 6: To prepare the SIL system and the alert system for use in other risk areas

The main objective here was, led by Subproject 2, to prepare the SIL system for a possible implementation at Patras in Greece. This has not been carried through because the contact in Patras failed. However, considerable work has been carried out to enhance the SIL system functions (Böðvarsson et al. 1999), as described under Task 1 above. It can also be mentioned here that installation of SIL type network in Sweden includes many refinements based on experiences in operating and continuously developing the SIL system in Iceland within the PRENLAB projects (Böðvarsson et al. 1999).

3.1.7 References

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3.2 Subproject 2: Applying new methods using microearthquakes for monitoring crustal instability

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In the first annual report of the PRENLAB-2 project the work on individual tasks of this Subproject were detailed. In the following we report results based on integrating results of those individual tasks.

3.2.1 Real-time mass evaluation of relative locations

One of the successes of the PRENLAB project was development of methods for subcrustal mapping of faults based on the algorithm by Slunga et al. (1995). Location of groups of similar, well correlated microearthquakes with relative accuracy of the order of 10 m, even at great depth in the crust, made it possible to map with a great accuracy complicated network of faults within active fault zones. The method has been further developed within PRENLAB-2, with applications in some areas of Iceland, where comparison has been made with geological studies. This method together with the fault plane solutions of microearthquakes is also the basis for using microearthquakes to study crustal instability in fault zones.

A new way of handling the multievent locations has been designed within the PRENLAB-2 project, which makes it possible to treat a large mass of data from a complicated fault system.

This method is suited for automatic on-line analysis where the new incoming microearthquake events are located in groups together with the previously located events and where the previous results are used. The analysis of the new events may improve all previous locations successively. This new algorithm consists of three main software programs. One correlates the new event with the previously analyzed and defines the group of events based on both location and signal correlation. The second performs the multievent location based on arrival time differences from the correlations and on the absolute arrival times. The third program fits the absolute locations to the previously achieved absolute locations and stores the results in a library.

This method has been installed for testing and routine application at IMOR.DG.

3.2.1.1 Slungawarning, an algorithm based on microearthquakes for alerting about time and site of impending earthquakes

The Slungawarning algorithm involves to watch in real-time seismicity of microearthquakes as well as of their source dimensions, and to detect anomalies based on a physically established source model and experience of observations of the SIL microearthquake system for 9 years.

The physical basis for developing and testing such an algorithm is a recently evolving rate-and-state dependent model of friction of fault planes. This model suggests that for any given earthquake generating fracture and loading system, there exists a minimum fault radius for earthquakes, again suggesting that different parts of the faults with different minimum fault radius of earthquakes may be active at different stages of the premonitory process leading to large earthquakes. Thus by evaluating microearthquakes it may be possible to resolve a process that sometimes has been assumed and treated as totally chaotic.

Based on such physically based ideas and observations a number of earthquake warning parameters have been defined and an earthquake warning algorithm has been developed which has been tested retrospectively on SW-Iceland (Slunga et al. 2000).

A study of the microseismicity during the 9 years within SW-Iceland where the large earthquakes occurred has been made (Slunga et al. 2000). A detailed description of that work is given in Slunga (2001). Here some main results are summarized.

The most obvious result is the close relation between the microearthquake fault radii and the geodynamic processes (coinciding with large earthquakes, and the large eruption below Vatnajökull glacier in 1996). The 3 largest earthquakes are preceded by large fault radius microearthquakes 3-4 months before the events. In addition the larger earthquakes in the Hengill area are preceded by an increase in microearthquake fault radii one or a few days before the events.

Most larger earthquakes are also preceded by an increased microearthquake activity culminating with foreshocks within the last day or days before the events. For the largest earthquake of the period the foreshock activity is lacking ML>1 events. For the quiet part of the SIL area with large earthquakes on N-S faults a "sandwich" seismicity ratio method was proposed. It compares the seismicity rate within a N-S strip to the seismicity of the surroundings. It was found that the last month before the large June 17, 2000, earthquake the surroundings became silent while the N-S strip became more active (the microearthquake sizes typically between ML= -0.2 to 0.4).

All these aspects were tested within an EQWA (EartQuake Warning Algorithm) and it was found that during times of warnings (24 hour after each warning and within a distance of 6 km) the probability to have a large earthquake within the warned area was about 500 times larger than the probability based on total randomness.

Finally it was also found that most false warnings were at places of coming earthquakes. Such warnings during the last years before major earthquakes may increase the awareness of the risks.

In general the results of the study (Slunga et al. 2000) are in agreement with other precursory studies of shallow strike-slip earthquakes in other places of the world.

This algorithm is now being installed to be applied routinely for short-term warnings and for testing at IMOR.DG.

A thorough description of the method and of results of tests is found in Slunga (2001).

3.2.2 The Spectral Amplitude Grouping method (SAG) for analyzing crustal stress conditions. A potential for intermediate-term warnings

A new method called Spectral Amplitude Grouping (SAG) has been developed (Lund and Böðvarsson 2000). This method addresses the problem of similarity of focal mechanisms used in stress tensor inversion. SAG has shown to be useful for analysis of temporal evolution of the earthquake grouping patterns. The SIL system calculates spectral amplitudes on three component data rotated into vertical, radial and transverse components. Windows are placed on the direct P- and S-wave arrivals and transforming to the frequency domain the low frequency asymptotes, or DC-level spectral amplitudes, are estimated for the different components (Rögnvaldsson and Slunga 1993). We obtain five amplitude values at each recording station; vertical and radial P (PZ and PR) and vertical, radial and transverse S (SZ, SR and ST), which we refer to as amplitude components. These amplitude components, together with first motion directions, form the basis for the focal mechanism calculation in the SIL system and will be utilized in the spectral amplitude correlation and grouping scheme. In order to assess the similarity of the focal mechanisms of two different events all amplitude components in common for the two events are correlated using linear cross-correlation

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}}$$

where r is the correlation coefficient, $\bar{x}$, is the mean of the logarithms of one event's amplitude components, x_i, and $\bar{y}$ the mean ofthe logarithms of the other event's amplitude components,

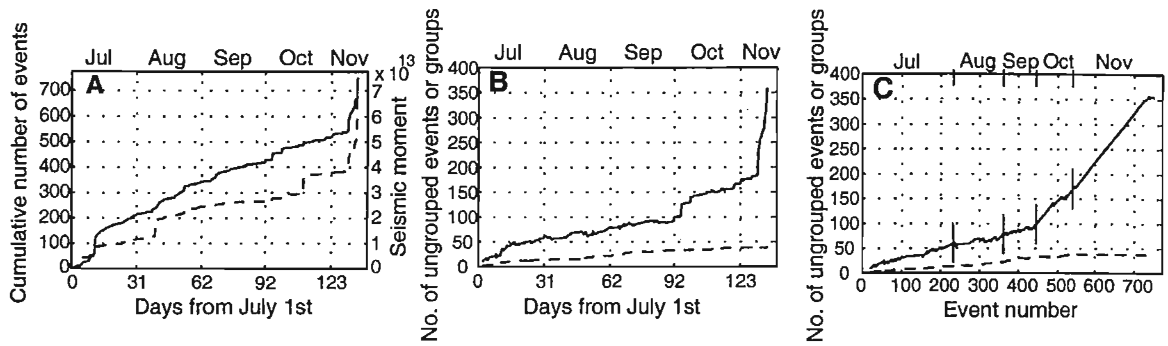

Figure 6. *Correlation results in Ölfus, July 1 to November 13, 1998. A) Plotted versus time in days is the cumulative number of events (solid line, scale to the left) and the cumulative scalar seismic moment (dashed line, scale to the right). B) Number of ungrouped events (solid line) and the number of groups (dashed line) versus time in days. C) Number of ungrouped events (solid line) and number of groups (dashed line) versus the event number.*

y_i. The logarithms are utilized to decrease the importance of the nearest stations, thereby stabilizing the correlation. We use the correlation coefficient as the measure of how similar two events are. All events are correlated with all other events and the events are then grouped according to the correlation coefficients. The grouping is controlled by three parameters; a lower limit on the correlation coefficients, r_{min}, a lower limit on the fraction, f_{min}, of fellow events in the group that a single event is allowed to have below r_{min} and the minimum number of events needed to have a group. After some testing we adopted $r_{min} = 0.9$, $f_{min} = 0.8$ and at least four events in the group, as our parameters for studying larger amounts of seismicity. If a more detailed study on fewer events is desired, the r_{min} and/or f_{min} values should be increased. We define two modes of running the correlation and grouping, the first correlates all events in a catalogue with all other events in one large run, and then performs an iterative grouping that allow us to find the optimal homogeneity within the groups. The second mode starts with a small group of events that are correlated and grouped, and then the events are correlated and grouped one by one with the previous events. This mode will not obtain the optimal group homogeneity but instead it allows us to study the time variations in correlation and grouping. During the development of the correlation and grouping scheme we discovered that it is useful also for applications other than as a preprocessor to stress tensor inversion. If we run the correlation in the second mode the temporal evolution of the earthquake grouping patterns can be studied and the groups of similar events produced by the grouping can be utilized either for composite focal mechanism calculations or as a starting group for relative relocation. We tested the correlation and grouping algorithm on a set of 636 microearthquakes, $0.0 \leq M_L \leq 2.7$, occurring between July 1, 1998, and November 13, 1998, in Ölfus, southwestern Iceland. On November 13 there was a magnitude 5.0 earthquake in the Ölfus area. Cumulative number of events and cumulative seismic moment is plotted in Figure 6.

Studying the Ölfus seismicity using the second mode of correlation and grouping we obtain the plots in Figures 6B and 6C. In Figure 6B we see that the seismicity in July correlates very well, the rapid increase in number of events is not mirrored by an increase in the number of ungrouped events. Conversely, the increase in seismicity in November has an associated increase in the number of ungrouped events. The grouping pattern becomes clearer if we plot the number of ungrouped events and number of groups as a function of the event number (Figure 6C). We now clearly see a change in the grouping pattern around event 430, which corresponds to late September, where the slope of the curve significantly changes. We interpret the lack of correlation after September as an indication that the microseismicity changed characteristics. Before late September many events occur on the same fault (or a very close, similarly oriented fault) with very similar slip directions. We refer to these events as *repeated* events. After September, spectral amplitude correlation indicates that either the focal mechanisms are different, both compared to earlier and to current seismicity, or the events occur at different locations compared to earlier and current seismicity.

A version of this program program has been installed for real-time monitoring of earthquake grouping patterns.

3.2.3 Real-time inversion of stress tensor

Programs for stress tensor inversion described in the PRENLAB final report and in PRENLAB-2 first annual report (see Lund and Slunga 1999) have being modified for real-time operation. We utilize the SAG method (Lund and Böðvarsson 2000) to preprocess the data prior to the stress tensor inversion. The preprocessor allows for a stable inversion with minimum amount of data thus gives a new measure of the stress tensor at earliest possible time.

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3.3 Subproject 3: Using shear-wave splitting to monitor stress changes before earthquakes and eruptions

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3.3.1 Task 1: Continuous monitoring of shear-wave splitting

The basic remit of the project is to respond to any observed changes in shear-wave splitting and analyze data for hazard assessment. The bulk of the activity has been in this task as changes in shear-wave splitting are now observed routinely before larger earthquakes and before volcanic eruptions and subsurface movements of magma.

Shear-wave splitting is sensitive to changes in stress. In anisotropic media, the two shear-waves split into two orthogonally polarized waves that propagate with different velocities. Examination of the seismograms can identify the polarization direction of the first (or faster) shear-wave and the time delay between the two arrivals (Figure 7). Time-delays are particularly sensitive to changes in azimuthal anisotropy induced by stress-induced changes to microcrack distributions (Crampin 1999).

Shear-wave data from earthquakes provided by IMOR.DG are identified and analyzed routinely. Seismic stations in Iceland are shown in Figure 8 with all earthquakes with $M \geq 2$ in the period January 1997 to December 1999. The stations with sufficient shear-wave arrivals for analysis of temporal changes, KRI, BJA, and SAU are marked with red triangles. Stations throughout Iceland with more than 10 polarization measurements during the four years of the PRENLAB projects, 1996-1999, are shown in Figure 9 (after Volti and Crampin 2000). The alignment of polarizations show average directions of the maximum horizontal stress SW-NE.

As in previous years, the stations with sufficient polarization and time-delay data are BJA, SAU and KRI, situated along the South Iceland seismic zone (SISZ) (Figure 8) and marginally GRI on the island of Grímsey, north of Iceland. During 1998, analysis was concentrated on station BJA, which had the best quality shear-wave arrivals. However, activity near BJA has declined during 1999 and 2000, whereas activity near KRI and SAU has increased (Volti and Crampin 2000).

3.3.1.1 Temporal variations in time-delays

Polarization directions and time-delays were measured during March 1998 - June 2000. The suitable events recorded within the shear-wave window (station-to-epicenter distance less than hypocentral depth) ensures that the shear-waves are not distorted by surface conversions. This constrains the number of events that can be used for shear-wave splitting analysis. There is also need for sufficient activity to show temporal variations. Other constraints include restrictions in focal depths, location errors, and deviations from the mean polarization direction. In the PRENLAB-2 period, these criteria were fulfilled mainly for station BJA, SAU and KRI. Variations in time-delays for the above stations are shown in Figures 10a, 10b and 10c. At each station the mean polarization is calculated and time-delay measurements with polarizations within a standard deviation of this direction are selected. There were 4230 observations at BJA, 5145 at KRI and 44 at SAU. The time-delay measurements are normalized over straight-line path distance and separated into two bands defined by incidence to the vertical plane of symmetry parallel to the mean polarization direction (the average strike of aligned near-vertical cracks). Band-1 (15°-45°) is more sensitive to changes in crack aspect-ratio, the result of gradually increasing stress. Band-2 (0°-15°) is more sensitive to crack density, which does not vary consistently with increasing stress.

Figures 10a, 10b, and 10c show data from March 1998 to June 2000. The middle cartoons show nine-point moving averages through the time-delays in Band-1. The least-squares lines begin before a minima in the nine-point moving average and end when a large earthquake occurs. This is followed by an abrupt decrease in time-delays. The upper cartoons show nine-point moving averages through the time-delays in Band-2. No consistent pattern or relationship to earthquakes can generally be seen in Band-2. The lower cartoons show the magnitudes of all $M \geq 2$ earthquakes within 20 km of the station.

Since 1996, station BJA displayed a relatively simple relationship between the magnitude of an earthquake and the duration (and slope) in the increase of time-delays before the event: the magnitude was proportional to the duration of the increase, and inversely proportional to the slope (Volti and Crampin 2000). In Figure 4a, Band-1 of BJA, variations before two large earthquakes (M=5.1 and 5) are indicated. They both show similar patterns of increase and reach maximum time-delays up to 14 ms/km after an increase of about four months. The second event was stress-forecast (see Subsection 3.3.1.2).

(Note that earthquake magnitudes, written as M, are local magnitudes approximately equivalent to body-wave magnitudes, mb, where in this magnitude range M=5 is approximately equal to surface wave magnitudes, Ms=6).

Three months later, there was a M=4 earthquake, with longer duration and smaller slope from that expected from previous events. The time-delays do not drop immediately afterwards, but show a slight increase. Two months later, July 1999, a volcanic event in Katla took place, after which time-delays started to drop gradually. Also, in contrast with the previous earthquakes, a similar pattern exists in Band-2. In February 2000, there was

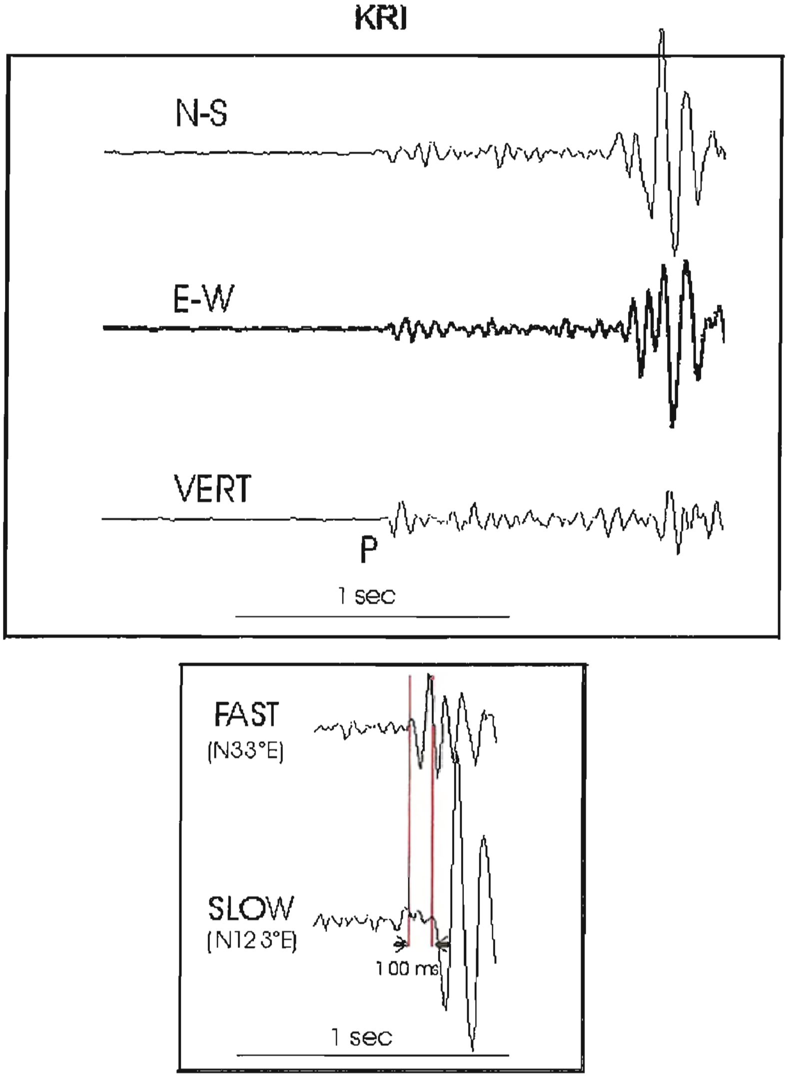


Figure 7. *Example of shear-wave splitting at station KRI. The upper diagram shows the three recorded components. On the bottom the rotated N-S and E-W components show the time-delay between the two shear-wave arrivals. (Event occurred at 03:02:40:6, April 9, 2000, at 5.7 km depth, 4.5 km from KRI).*

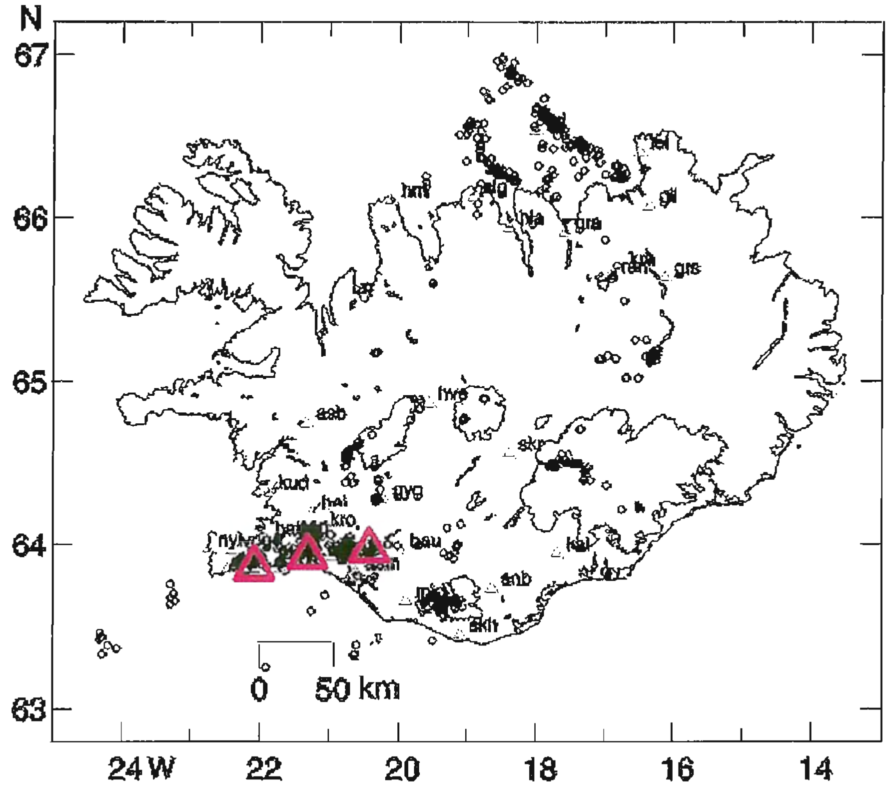


Figure 8. *Map of Iceland showing all earthquakes with $M \geq 2$, during the period March 1998 – June 2000. The small green triangles show the majority of SIL stations, whereas the stations KRI, BJA and SAU (from left to right) are shown with large red triangles.*

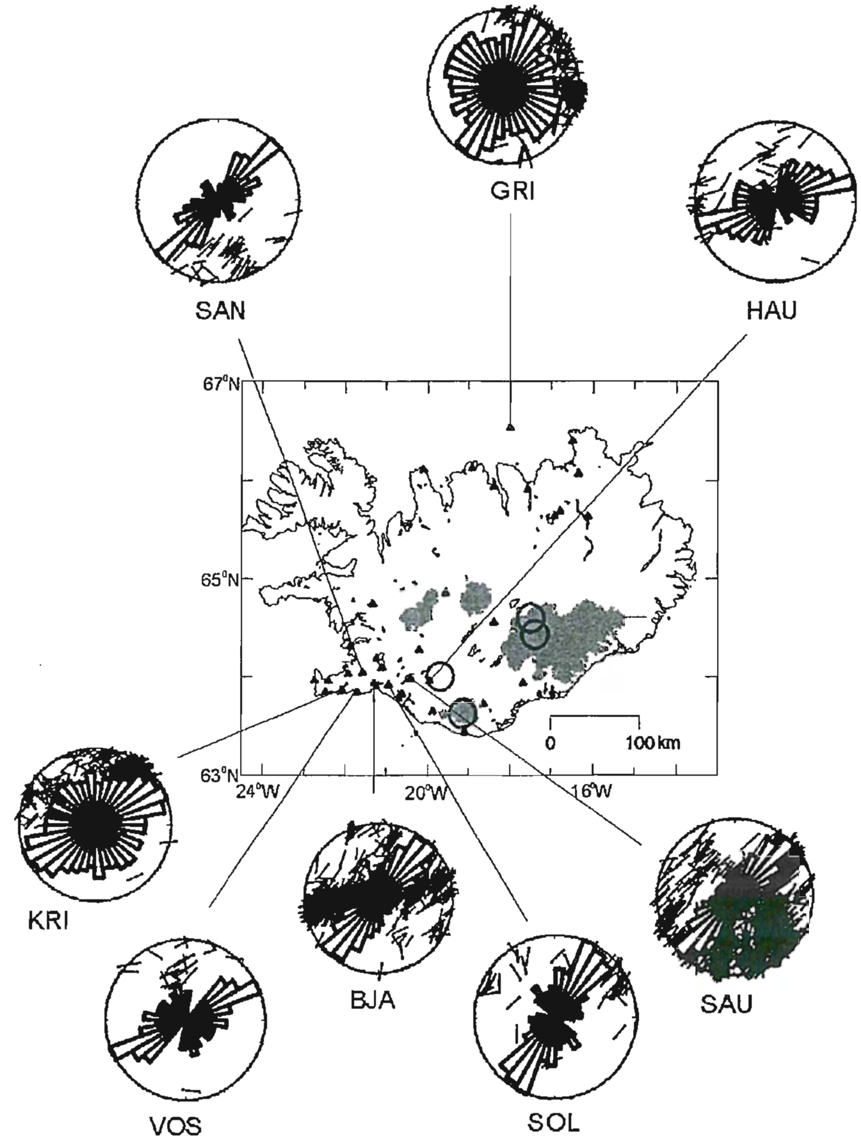


Figure 9. *Map of Iceland, showing the seismic network. Shaded areas are ice fields. Open circles mark the active volcanoes of, from north to south, Bárðarbunga, Grímsvötn, Hekla and Katla. The roundels are equal-area polar plots of polarizations of the faster split shear-wave arrivals in the shear-wave window (out to* 45°*) and rose diagrams, during 1996-1999. Roundels are shown only for those stations where there are more than 10 arrivals within the shear-wave window. The named stations without roundels (ASM, KRO, MID) have sufficient arrivals but the polarizations are severly disturbed by local rifting and/or local topography (after Volti and Crampin 2000).*

a further eruption at Hekla. It appears that magmatic activity complicates the behaviour of the stress-field, so the simple behaviour before earthquakes in 1997 and 1998 is no longer apparent in 1999 and 2000 (Volti and Crampin 2000).

In Figure 10b, the middle cartoon shows time-delays variations in Band-1 at station SAU. The nine-point moving averages in Band-1 show several broad maxima, one during 1998, three during 1999 and two in 2000. The first can be associated with the M=5.1 event (which is 43 km from SAU). Although during 1999, the peak in March does not seem to correlate with any nearby activity, the other, in July, may be correlated with the event in Katla (75 km SW of SAU). There are two earthquakes of M=4.2 and M=3.8 in September, 1999, but the time-delays do not show any increase. Again, the complications are believed to be due to the combined effects of the build-up of stress before earthquakes and the movement of magma before eruptions.

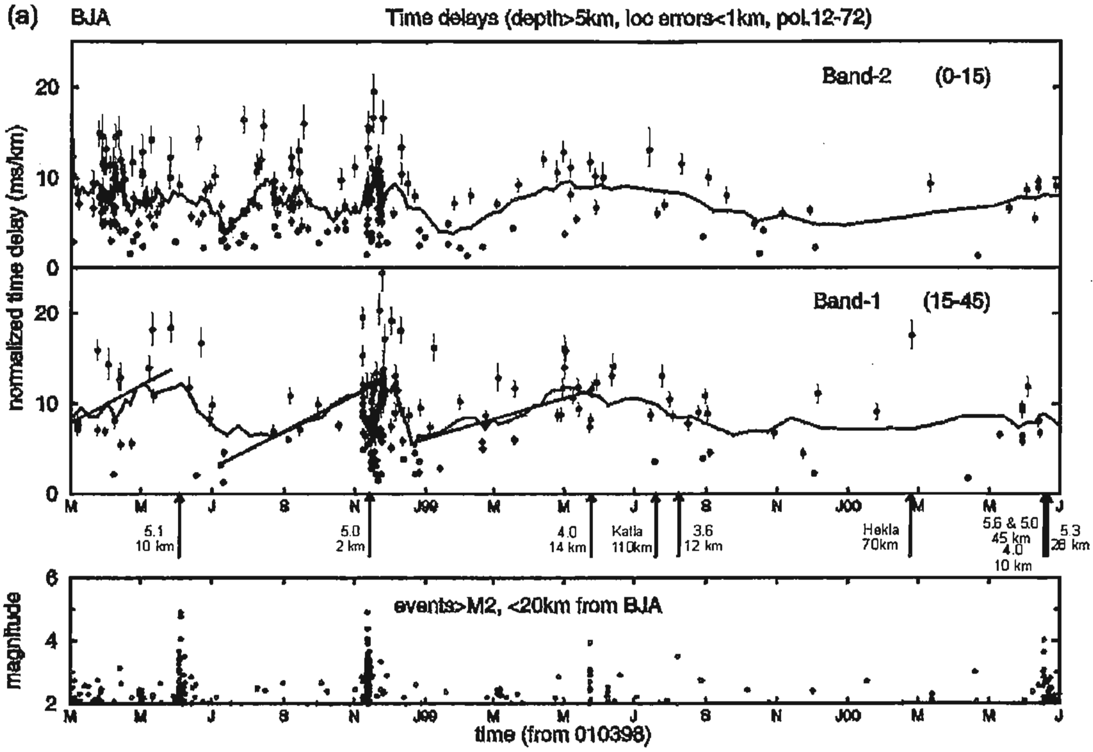
Recently, (June 17 and 21, 2000) three large earthquakes of M=5.6, M=5 and M=5.3 ($Ms \cong 6.6$, M=6, and M=6.3) occurred near SAU. These are the largest earthquakes in Iceland since 1963. Time-delays increased before the events for about four months, with the rate of increase being almost consistent with a M=5.6 earthquake, but the duration was too short. The complication is that there is a period of about seven weeks without source earthquakes to monitor the rockmass. As a consequence the start of the increase in time-delays in Band-1 was not recognized, and the events were consequently not stress-forecast (Volti and Crampin 2000). Such irregularities indicate the need for controlled source seismology, as is proposed in the SMSITES project, even in highly seismic SW-Iceland.

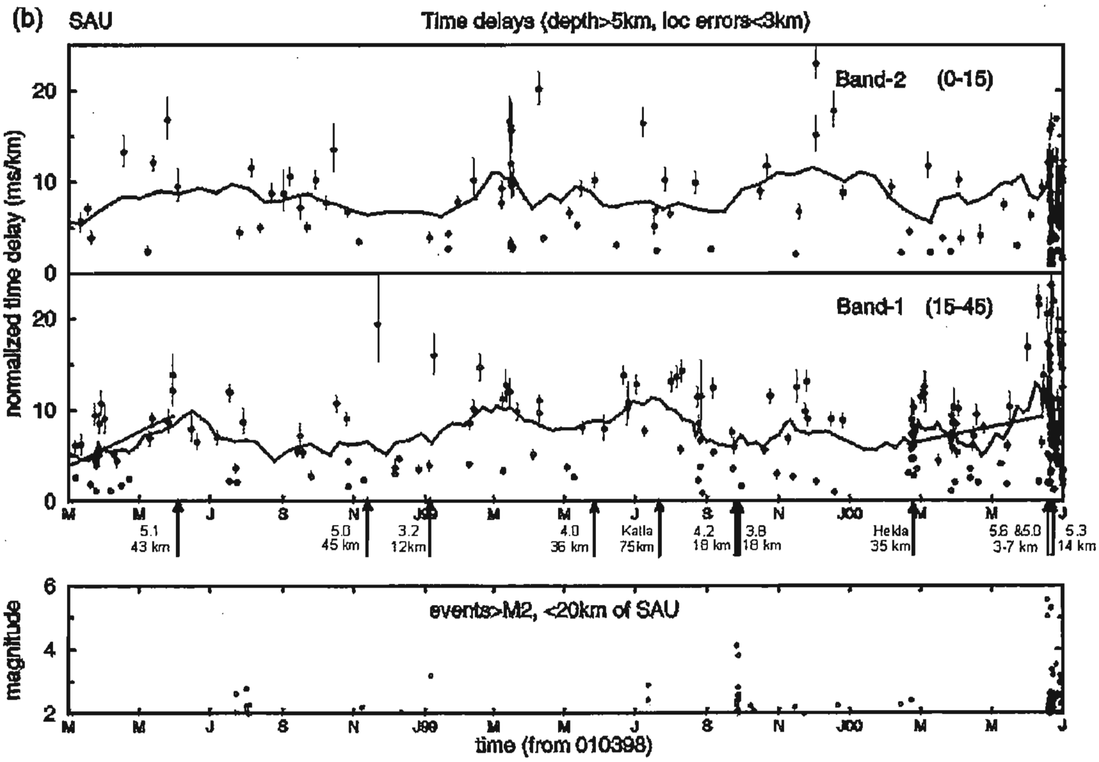
Figure 10c shows variations in station KRI. The there are two increases in time-delays. The first is associated with the M=5 event, November 13, 1998, which was stress-forecast. The second increase is gradual but steady increase in time-delays in Band-1 since December 1998 which may indicate the build-up of stress, and subsequently a future large earthquake.

3.3.1.2 Stress-forecasting earthquakes

Stress-forecasting is based on the assumption that the build-up of stress before earthquakes causes progressive changes in aspect-ratios until a level of cracking, known as fracture criticality, is reached and the earthquake occurs. Therefore, changes in shear-wave splitting in Band-1 are used to monitor crack aspect-ratios and estimate the time and magnitude that crack distributions reach fracture criticality.

It was recognized at the end of October 1998 that the time-delays in Band-1 were increasing since July 1998 at both stations BJA and KRI which are about 38 km apart (Figures 9, 10a and 10c). The increase had approximately the same duration and slope as the increases before the M=5.1 earthquake on June 4, and started at about the lowest level (~4 ms/km) of any of the increases associated with previous earthquakes. The increase at BJA was already nearly 10 ms/km which was close to the level of fracture criticality of the previous earthquakes. These features suggested that the crust was approaching fracture criticality before an impending larger earthquake. Consequently, the e-mail exchange in Table 1 between UEDIN.DGG and IMOR.DG was initiated. The final specific stress-forecast (November 10, 1998), was that an earthquake could occur any time between now (M=5) and end of February (M=6) if stress kept increasing. Three days later, on November 13, 1998, there was a M=5 earthquake with epicenter 2 km from BJA. This is considered to be a successful


(a)
BJA
Time delays (depth>5km, loc errors<1km, pol.12-72)
Band-2 (0-15)
Band-1 (15-45)
normalized time delay (ms/km)
M
M
J
S
N
J99
M
M
J
S
N
J00
M
M
J
5.1
10 km
5.0
2 km
4.0
14 km
Katla
110km
3.6
12 km
Hekla
70km
5.6 & 5.0
45 km
4.0
10 km
5.3
28 km
events>M2, <20km from BJA
magnitude
time (from 010398)


(b)
SAU
Time delays (depth>5km, loc errors<3km)
Band-2 (0-15)
Band-1 (15-45)
normalized time delay (ms/km)
M
M
J
S
N
J99
M
M
J
S
N
J00
M
M
J
5.1
43 km
5.0
45 km
3.2
12km
4.0
36 km
Katla
75km
4.2
18 km
3.8
18 km
Hekla
35 km
5.6 &5.0
3-7 km
5.3
14 km
events>M2, <20km of SAU
magnitude
time (from 010398)

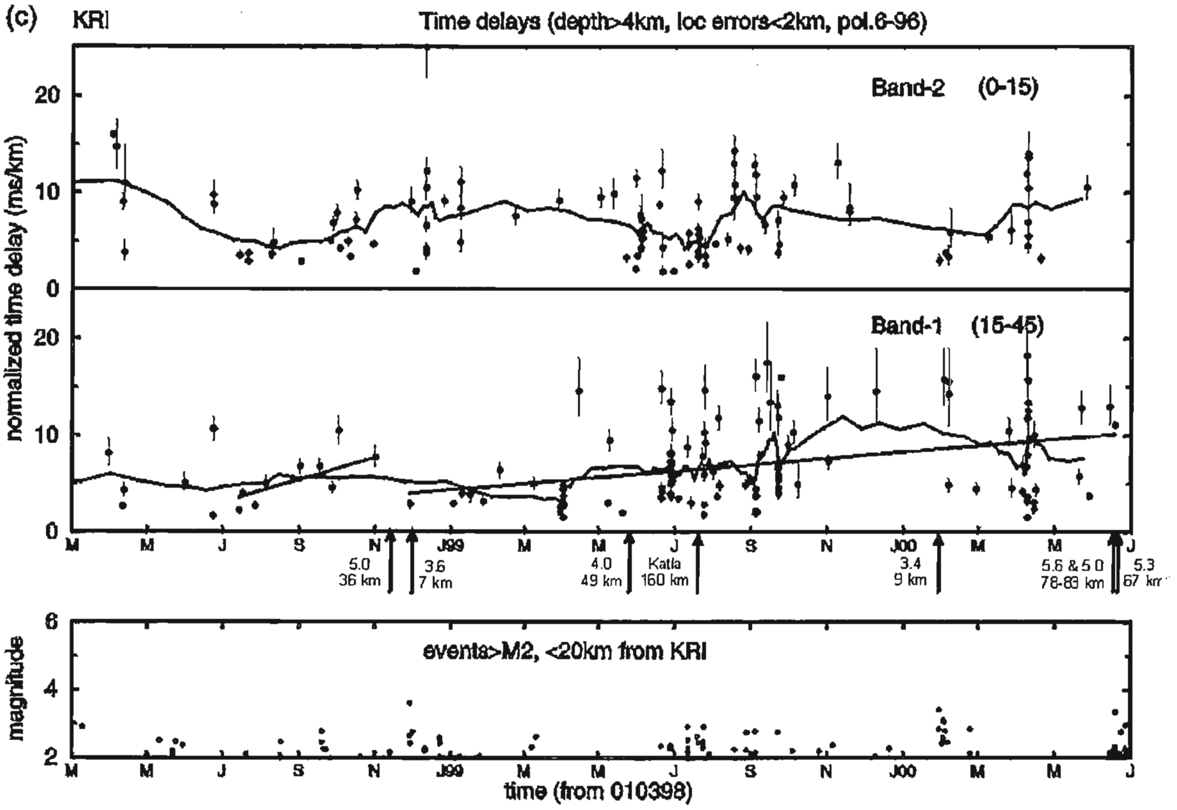


Figure 10. *Shear-wave splitting at BJA (a), SAU (b) and KRI (c) from March 1, 1998 to June 31, 2000. The upper and middle cartoons show variaton of normalized time-delays with time, for ray paths in bands with incidence* 0° *to* 15° *to the crack face (Band-2) and with incidence* 15° *to* 45° *to the crack face (Band-1). Band-2 is sensitive to crack density whereas Band-1 is sensitive to aspect ratio. There are nine-point moving averages through the time-delays. Lines are least square fits to data before a major earthquake. The lower cartoons show the magnitudes of* $M \geq 2$ *earthquakes within 20 km of each station.*

stress-forecast within a comparative narrow time-magnitude window.

During June 2000, three large earthquakes occurred near SAU. Although time-delays in Band-1 seemed to increase about four months before the first event of June 17, these earthquakes were not stress-forecast. The main reason was that before the swarm of activity in February associated with Hekla (Figure 10b), there was a period of about four weeks without any suitable shear-wave source earthquakes, and consequently no reliable time-delay measurements and reliable slopes and durations of the increase could not be identified.

October 27	UEDIN.DGG emails IMOR.DG reporting shear-wave time-delays in Band-1 increasing from July at stations BJA and KRI and suggests: *". . . there was an 80% chance of something significant happening somewhere between BJA and KRI within three months."**
October 28	UEDIN.DGG faxes data for BJA and KRI to IMOR.DG. IMOR.DG suggests M=5.1 earthquake near BJA in June 1998 may be linked to current increase in time-delays.
October 29	UEDIN.DGG updates current interpretation and suggests: *"Shear-wave splitting at both BJA and KRI indicate something is going to happen soon, probably within a month . . ."**
October 30	IMOR.DG sends notice to National Civil Defence (NCD) in Reykjavík suggesting a meeting.
October 31 -November 4	Faxes and emails updating information. UEDIN.DGG refines data and interpretation. IMOR.DG creates local geophysical and geological investigations.
November 5	IMOR.DG presents stress-forecast and other data from surrounding area to scientific advisors of NCD, who conclude no further action was required of them.
November 6-9	Exchange of various faxes and emails updating information and interpretation.
November 10	UEDIN.DGG concludes: *". . . the last plot . . . is already very close to 10 ms/km. This means that an event could occur any time between now (M≥5) and end of February (M≥6) ."**
November 11	UEDIN.DGG faxes updated data for KRI and BJA, with SAU now also suggesting increasing time-delays from September.
November 13	IMOR.DG reports: *". . . here was a magnitude 5 earthquake just near to BJA (preliminary epicenter 2 km west of BJA) this morning at 10:38 GMT."**

Table 1. *Timetable 1998, e-mails, facsimiles, and actions. *Quotations ("italics") are exact texts from e-mails.*

3.3.2 Task 2: Analysis of shear-wave splitting measurements

We had hoped to use several additional stations in the shear-wave window at SAU to investigate why observed time-delays between split shear-waves in Iceland are approximately twice those usually observed elsewhere, and why time delay values show large scattering. Unfortunately, financial constraints prevented installation of additional SIL stations.

The range of time-delays between split shear-waves is found to vary between different regions worldwide and sometimes between different stations in the same region. Time-delays vary with crack density, crack aspect ratio, and isotropic P- and S-wave velocities. These effects can be calculated, and are reasonably well understood. Time-delays are also observed to be higher in regions with high heat flow (Crampin 1994) and this is believed to be the main reason for the larger values observed in Iceland. Also following the increase in Band-1 time-delays before the Vatnajökull eruption in 1996, the level of time-delays has been decreasing for both Band-1 and Band-2 by approximately 2 ms/km over 1997-1998. It would appear that the crust has been slowly adjusting to the strain released by the eruption as the mid-Atlantic ridge gradually takes up the change in strain.

However, the large scatter of time-delays and polarizations is difficult to explain. During the last two big earthquakes (November 1998 near BJA and June 2000 near SAU) it was observed that the scatter in time-delays increases considerably with the onset of the earthquake and the large scatter continues for several weeks thereafter (Figures 10a and 10b). It is hoped that the controlled source SMSITES project will help to resolve this difficulty.

3.3.3 Task 3: Establish shear-wave splitting map of Iceland

Figure 9 shows a map with roundels and equal-area rose diagrams of shear-wave splitting polarizations at stations with more than about ten arrivals within the shear-wave window out to 45°. Experience suggests that an overall shear-wave splitting map is not particularly useful as was first thought. Optimum procedures seem to require individual studies of shear-wave splitting at individual stations.

3.3.4 Task 4: Calibrate techniques and behaviour if and when changes are identified

Stress-forecasting using small earthquakes as the source of shear-waves is only possible when there is a more-or-less continuous source of small earthquakes. As we have seen, this is extremely rare. To stress-forecast earthquakes without such persistent activity, requires cross-well seismology using a borehole source transmitting orthogonally polarized shear-waves along appropriate ray paths in Band-1 to three-component borehole receivers in further boreholes.

These boreholes exist in northern Iceland near Húsavík close to the Flatey-Húsavík fault of the Tjörnes fracture zone, and an EU project (*SMSITES: Developing stress-monitoring sites and infrastructure for forecasting earthquakes*, contract no. EVR1-CT1999-4000) developing a Stress-Monitoring Site (SMS) has recently started. The SW of Iceland has proved to be a very active seismic area during the last years. However, shear-wave splitting analysis near the Húsavík transform fault and Grímsey zone has not been very productive up to now, due to lack of continuous swarm activity in the shear-wave windows of the northern stations, GRI, SIG, LEI, and others. The new technique of controlled source measurements are expected to monitor changes in shear-wave splitting near Húsavík more efficiently, as well as reduce the scattering in the time-delays.

3.3.5 Task 5: Incorporate shear-wave splitting interpretations into routine analysis

The only successful technique yet established for automatically identifying polarization directions and time-delays from digital records of shear-wave splitting is the Cross-Correlation Function, or CCF technique of Gao et al. (1998). CCF was used on SIL records from SW-Iceland. It was not successful (Volti and Crampin 2000). The reason is thought to be that the data that was used to test CCF was an isolated swarm of small earthquakes, whereas the foci in Iceland are more distributed so that shear-waves propagate along significantly different ray paths. This suggests that reliable automatic reading of shear-wave splitting in Iceland is unlikely to be successful.

3.3.6 Meetings and conferences

PRENLAB contractor meetings:
Stuart Crampin and Theodora Volti: The second PRENLAB-2 workshop, Húsavík, Iceland, July 30, 1998.
Theodora Volti: The fifth PRENLAB-2 workshop, Nice, France, April 27, 2000.

Presentations of PRENLAB results:
Stuart Crampin: 60th annual EAGE meeting, Leipzig, Germany, June 8-12, 1998.
Stuart Crampin: Tenth biennal EUG meeting, Strasbourg, France, March 28 - April 1, 1999.
Stuart Crampin: 61th annual EAGE meeting, Helsinki, Finland, June 7-11, 1999.
Stuart Crampin: The second EU-Japan workshop on seismic risk, Reykjavík, Iceland, June 23-27, 1999.
Stuart Crampin: XXII IUGG General Assembly, Birmingham, United Kingdom, July 18-30, 1999.
Stuart Crampin: 9th International Workshop on Seismic Anisotropy, Houston, Texas, USA, March 26-31, 2000.
Stuart Crampin: 62nd annual EAGE meeting, Glasgow, United Kingdom, June 25-30, 2000.
Stuart Crampin: 70th annual SEG meeting, Calgary, Alberta, Canada, August 6-11, 2000.

3.3.7 References

Crampin, S. 1994. The fracture criticality of crustal rocks. *Geophys. J. Int.* 118, 428-438.

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Gao, Y., P. Wang, S. Zheng, M. Wang & Y.-T. Chen 1998. Temporal changes in shear-wave splitting at an isolated swarm of small earthquakes in 1992 near Dongfang, Hainan Island, Southern China. *Geophys. J. Int.* 135, 102-112.

Volti, T. & S. Crampin 2000. Shear-wave splitting in Iceland: four years monitoring stress changes before earthquakes and volcanic eruptions. *Geophys. J. Int.*, submitted.

3.4 Subproject 4: Borehole monitoring of fluid-rock interaction

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3.4.1 Geophysical logging

In the preparatory phase of an earthquake, stress accumulation is expected to be connected with the creation of borehole breakouts (BOs), changes in the number and size of cracks, a possible variation of the stress direction, etc. Therefore it is very important to monitor the following set of geoparameters:

- P–wave travel time.
- electrical conductivity.
- stress information from borehole breakouts (orientation and size).
- crack density.

In the framework of this project, we had the chance to carry out repeated logging 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) was used and provided 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 could be obtained for a depth interval of more than 1000 m, uninfluenced by the sedimentary cover and less disturbed by surface noise.

This was achieved by repeated logging with tools as: sonic log (BCS), gamma-ray (GR), spectral gamma-ray (SGR), neutron-neutron log, dual induction/latero log (DIL), 16"- and 64"-normal resistivity log, spontaneous potential log (SP), a borehole temperature log (BHT), four-arm-dipmeter (FED), and borehole-televiewer (BHTV).

The neutron-neutron log, the 16"- and 64"-resistivity log, the SP log, and temperature logs were run with the logging equipment of OS, the rest with the Halliburton logging truck of GFZ.

Investigations on the stress field in the SISZ

Besides the repetition of logs in borehole LL-03 (Nefsholt), we performed single logging campaigns at other boreholes to check the state of the regional stress field. This is important for two reasons:

- From the San Andreas fault we know (Zoback et al. 1987) that fault zones may be in a low stress state between earthquakes, which gets visible through stress orientations perpendicular and not pointing at an angle of 30° to 45° to the strike-slip fault. To determine the present state of stress in the SISZ, it is important to see if there are stress components, that are not perpendicular to existing faults and thus favour earthquakes on them.

- The SISZ is no typical transform zone. Looking at the orientation of rift opening and the adjacent rifts, one would expect a left-lateral strike-slip zone in NW-SE direction (N103°E) to connect the Reykjanes ridge and the eastern volcanic zone (EVZ) of Iceland. Instead earthquakes occur on en-echelon N-S striking right-lateral faults. Assuming an angle of 45° between the maximum horizontal compressive stress and the fault (as it is done constructing fault plane solutions) both planes are equivalent. However, from a rock mechanics point of view, expecting an angle of about 30° between fault and maximum horizontal principal stress, the stress orientation at N-S striking faults should be N30°E, compared to N60°E at an E-W striking transform.

3.4.2 Task 1: Repeated logging in borehole Nefsholt

All together 7 logging campaigns took place. The locations are shown in Figure 11. Table 2 lists the logs performed during the project.

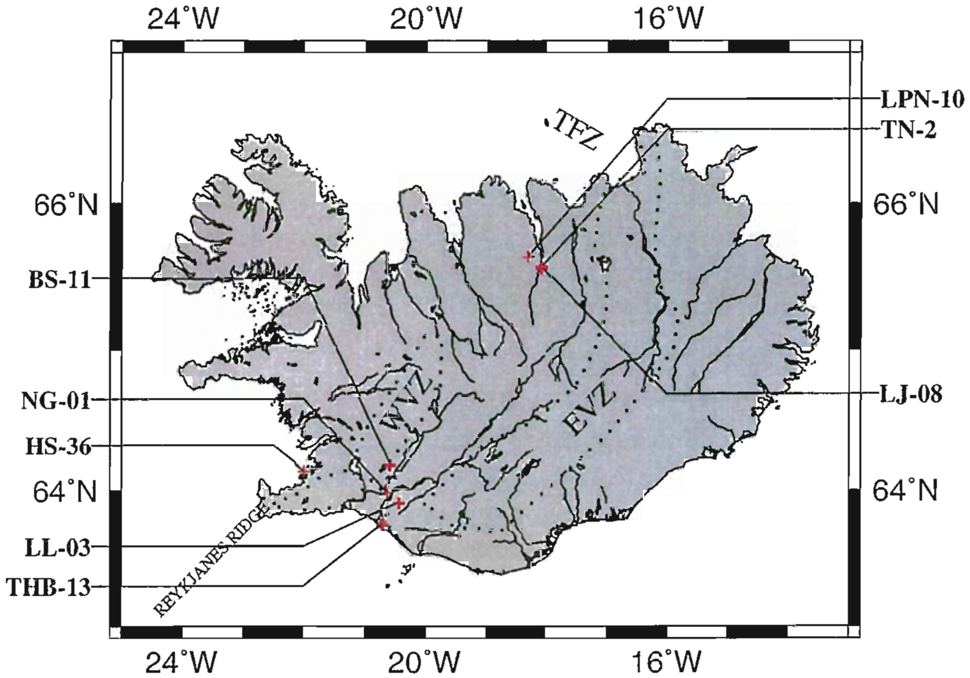

Figure 11. *Map of Iceland showing the location of the site of repeated logging (LL-03) and of the other boreholes, where measurements have been performed. The SISZ extends between the southern ends of the WVZ and EVZ. Wells LL-03 and NG-01 are inside the SISZ, BS-11 is north, THB-13 is south of the zone.*

Altogether, the seven campaigns have contributed to the two aims of this Subproject, that are:

- Observation of changes in physical parameters of the rock, in the degree of fracturing, and in the 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. For that, the borehole geometry was observed for certain structures, that allow to determinate the orientation of the horizontal principal stress, as there are borehole breakouts and vertical tensile fractures. Borehole breakouts are failures of material of the borehole wall, that result from accumulation of tangential

stress at the borehole wall at the azimuth of the lower horizontal principle stress (σ_h), caused by the free surface produced by drilling. In a linear elastic isotropic theory, this would be perpendicular to the maximum horizontal principal stress (σ_H). Alternatively, at this free surface, the tensile strength of the borehole wall can be exceeded at the azimuth of the maximum principal horizontal stress, what produces vertical fractures along σ_H. These vertical fractures extend in the direction of the maximum and open in the direction of the minimum horizontal principal stress. The occurrence of these tensile fractures can be enhanced by thermal stress caused by cold water pumped into the well.

Orkustofnun provided a lithology log of the well LL-03 at Nefsholt. This log is based on cuttings (rock pieces crushed while drilling), not on cores, what strongly limits its depth resolution. It shows a nearly continuous sequence of altered basalt, interrupted only by a few thin sedimentary layers and some thin layers of dolerite, hyaloclastites and fresh basalt. Different kind of layers show different characteristic sets of logs, that allow to distinguish between the lava flows and the sediments (Figure 12, Table 4). The result, i.e. the correlation with the rock physical parameters, is very reasonable: The sedimentary layers seem to contain more water (larger pore space) entailing higher travel times of elastic waves, lower resistivity and higher absorption of neutrons. The correlation is an important indicator that the log results have good quality.

Name:	Location:	Max. depth:	Logged interval:	Tools used:	Date:
NG-01	Ólafsvellir (inside SISZ)	1070 m	180–1070 m	FED, GR	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	Syðra-Laugaland near Akureyri	2740 m	120–1890 m 120–1330 m 500–1980 m	FED, BHTV, BCS-DIL-GR, BHTV	July 1996 June 1998
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 SGR BHT neutron–neutron X-Y-caliper 16"- and 64"- resistivity SP	July 1996 October 1996 September 1997 December 1997 June 1998 September 1997 June 1998 April 1999 August 2000 April 1999 October 1999 September 1996 April 1999 October 1999 August 2000 October 1999
THB-13	Þykkvibær SW of Hella near the south coast	1254 m	466–1225 m	BHTV	December 1997
BS-11	Böðmóðsstaðir near Laugarvatn, north of the SISZ	1193 m	703–1090 m 500–1090 m	BHTV	December 1997 June 1998

Table 2. *All logs performed during both PRENLAB projects. 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, 16" for short normal resistivity tool, and 64" for long normal resistivity tool. FED means four-arm-dipmeter, which includes an oriented four-arm-caliper. BHTV and BHT mean ultrasonic borehole televiewer and borehole temperature, respectively. BCS is borehole compensated sonic log; DIL is dual induction/latero log. The deepest parts of wells LJ-08, LL-03, THB-13, and BS-11 were not accessible anymore.*

Log type:	Date:	Depth range:	File name:	Remarks:
Temperature log (T)	07-07-1977	0–920	T07071977	
Temperature log	18-10-1977	0–1100	T18101977	
Temperature log	17-09-1980	0–1060	T17091980	
Temperature log	25-06-1992	0–1106	T25061992	
Temperature log	23-04-1999	4–1080	21415	
Temperature log	03-08-2000	0–1087	T03082000	
Natural gamma log (GR)	23-04-1999	0–1080	21424	
Natural gamma log	27-10-1999	10–1080	22588	
Neutron-neutron log (NN)	23-04-1999	3–1080	21421	
Neutron-neutron log	27-10-1999	10–1080	22585	+
Neutron-neutron log	03-08-2000	7–1087	N03082000	
Self potential log (SP)	27-10-1999	25–1080	22570	
16" normal resistivity log (SN)	27-10-1999	25–1080	22568	*
16" normal resistivity log	03-08-2000	27–1087	S03082000	*
64" normal resistivity log (LN)	27-10-1999	25–1080	22569	*
64" normal resistivity log	03-08-2000	27–1087	L03082000	*
LL3 of DIL	07-1996	36–1070	LL3-07/96	
LL3 of DIL	12-1997	37–1071	LL3-12/97	

Table 3. *Repeated logging by Orkustofnun in Well LL-03, files used for comparisons. + : depth adjusted to neutron-neutron log of August 2000. * : calibrated and depth adjusted to neutron-neutron log of August 2000.*

Depth interval:	GR:	BCS travel time:	neutron–neutron water content porosity:	DIL, 16", 64" resistivity:	Lithology:
265-275 m	low	low	low	high	altered basalt
275-280 m	low	high	high	low	sediment
280-285 m	low	low	low	high	altered basalt
285-298 m	high	high	high	low	sediment
298-305 m	high	low	low	high	fresh basalt

Table 4. *Characteristic set of log values for different kinds of layers, derived from Figure 12.*

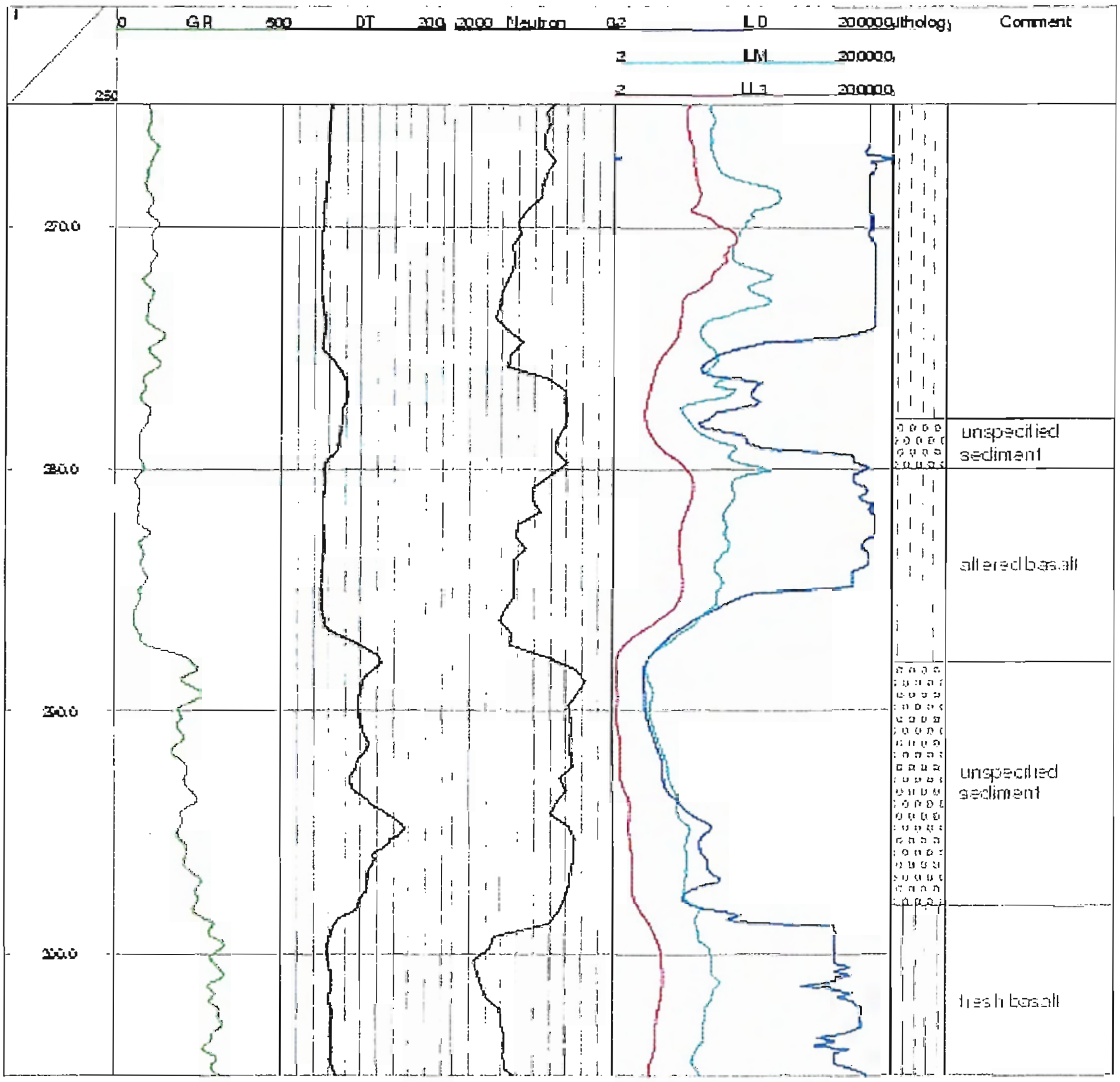

Figure 12. *Data example showing the correlation between the performed logs and the lithology based on the analysis of cuttings provided by Orkustofnun. GR = gamma-ray in API units, DT = compensated travel time in microseconds per foot, Neutron = neutron-neutron log in API units, ILD = induction log of deep penetration in* Ωm*, ILM = induction log of medium penetration in* Ωm*, and LL3 = latero log in* Ωm*.*

3.4.3 Tasks 2, 3, and 4: Cross correlation of logs of the same type from different campaigns and earlier loggings; comparison of changes in logs of different type; comparison of changes in logs with changes in seismicity, etc.

Due to a delay in the year 2000 logging campaign, we had the chance to take at least some data after the two June 2000 earthquakes in the SISZ. Comparing the data of July 1996 to October 1999 with those of August 2000 gives the opportunity to see which parameters have changed across the time from before the event to 6 weeks after.

And there were remarkable changes at the borehole. Our coworker Steinar Þór Guðlaugsson reports: "Water started to flow from well LL-03 on July 20–22 after a rapid rise in the water table from a depth of several meters since the earthquakes. This was probably caused by changes in crustal stress resulting from the earthquakes, although reinjection into the Laugaland geothermal field, which was initiated recently, may also have played some role. On August 3, the flow-rate was 0.5 l/s." The effects seen in the logs will be described below.

Repeated logs in LL–03: borehole temperature

The longest time series of logs is available in the temperature logs (BHT). There are data from the time of the drilling of the well (1977), later from 1980 and 1992, and finally from 1999 and 2000 taken during the work in the PRENLAB projects. The temperature logs are plotted together in Figures 13 and 14. Following a heating phase after drilling, the temperatures went down. The most recent of the logs predating the earthquakes show a regime of inflow into the well at several feed-points and downward flow of this fluid to a depth of 830 m where it re-enters the formation. The new log of August 2000 can be interpreted in two different ways: (1) The fracture at 830 m now feeds water into the well in addition to the other feed-points and above this depth water everywhere flows upwards; (2) Water now flows upwards above the feed-point at 120 m, whereas below this depth water continues to flow down the well to a depth of 830 m as before. In either case, it is evident that water entering the well at feed-points in the 200-250 m depth range is warmer than before. Temperature differences between the feed-points in this depth range also seem to have increased. At present it is unclear whether this is caused by changes in the fracture network feeding this interval or by the reinjection.

In conclusion, a comparison of the August 2000 temperature log with the earlier ones does not reveal any new water-conducting fractures (feed-points), but does show changes in the temperature and flow rate of the water flowing through previously existing fractures. These changes may probably be explained by a combination of stress change (general increase in formation pressure) associated with the earthquakes and reinjection, but do not rule out movements on some of the fractures feeding the well.

Repeated logs in LL–03: latero log and "normal" resistivity tools, self potential
The latero log (the one included in the GFZ DIL tool is of LL3 type) and the "short normal" resistivity tool of OS (16" electrode spacing) are designed for shallow penetration into the formations. Whereas the "induction log medium" and "induction log deep" of the DIL tool and the "long normal" resistivity tool (64") are dedicated for investigations deeper into the rock surrounding the borehole.

The latero log resistivity shows good repeatability (see red curves in Figure 15). So do the 16" and 64" tools, as will be discussed later. Figure 16 gives a comparison of LL3 logs from 2 different campaigns with logs of the short and long normal resistivity tools. The LL3 curves correlate very well besides a small depth shift. They also correlate qualitatively well with the other two logs, but there seems to be a calibration problem in the LL3, leading to much lower values than the other tools. We did not care about this, as only changes in the logs were of interest here. The match between the normal resistivity tools is expected to be moderate as their penetration depths are different. There was no indication of changes in LL3 logs before June 2000.

The resistivity logs from before and after the June 2000 events are plotted together in Figure 17. Two kinds of adjustments were made to the final logs before they were plotted: Firstly, a correction was applied to the logs based on a calibration carried out at the surface with a set of known resistances. Secondly, the origin of the August 2000 neutron-neutron log was taken as a common depth reference and the logs shifted to this datum.

The new logs agree remarkably well with those obtained in 1999. The main change observed is a decrease in the 16" resistivity log above 110 m. This can probably be explained by the increased temperature (and – less likely – salinity) in this depth range caused by the newly established upflow. Too much should not be read from the differences between the 16" logs in the 400-700 Ohmm range, because of the large correction that was applied to the 1999 log as a result of the surface calibration. The differences may simply reflect the inaccuracy of the correction. Keeping this in mind, the only significant difference between the 16" resistivity logs that may require other explanations seems to be a decrease in resistivity in the 465-470 m depth interval.

The main change in the 64" resistivity log is a decrease in resistivity from 150-155 m. This may or may not be associated with the upflow. We also note a slight decrease in the 465-470 m range which correlates spatially with the main anomaly in the 16" log. At the same depth, the spontaneous self potential log (SP) of October 1999 shows an anomaly too (cf. Figure 18), which could indicate a crack, existing already at that time (there is no SP log of August 2000). A possible interpretation of the 3 correlating signals might be a crack that has widened but does not feed-in water with a temperature different from the local temperature in the borehole.

The long normal tool shows variations between October 1999 and August 2000 also at depths other than 465 m and at resistivities lower than 400 Ohmm. They usually display lower values in August 2000, which could mean that water filled cracks have opened. However, none of the variations is also seen in the "short normal" log, which leads to doubts on real changes in rock physical parameters, as new cracks could be formed much more easily near the borehole wall, an area sampled by the 16" tool. See also the discussion on the neutron-neutron log.

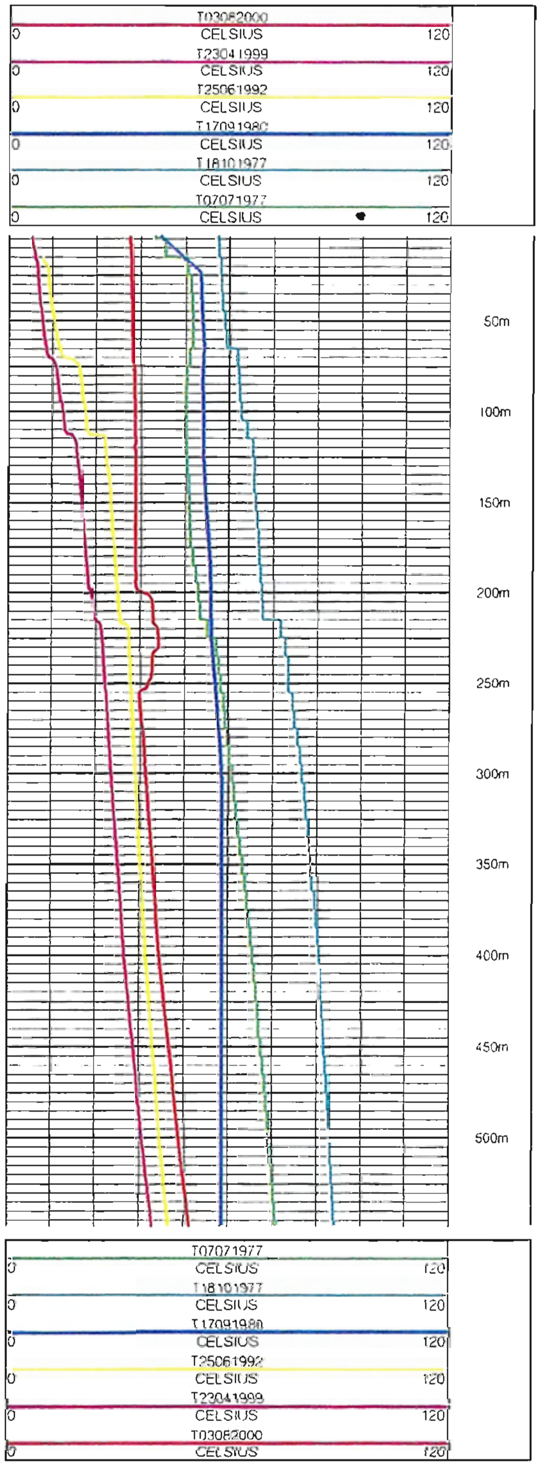

Figure 13. *Borehole temperature logs since the drilling of well LL-03. Numbers following "T" give date of log.*

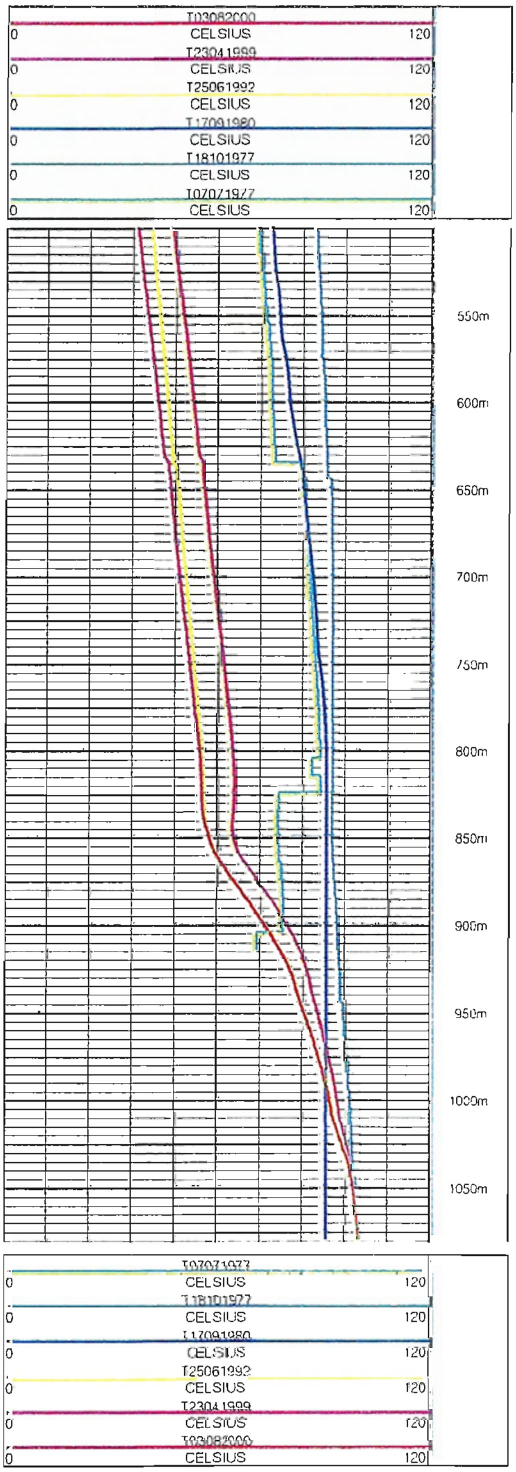

Figure 14. *Borehole temperature logs since the drilling of well LL-03. Numbers following "T" give date of log.*

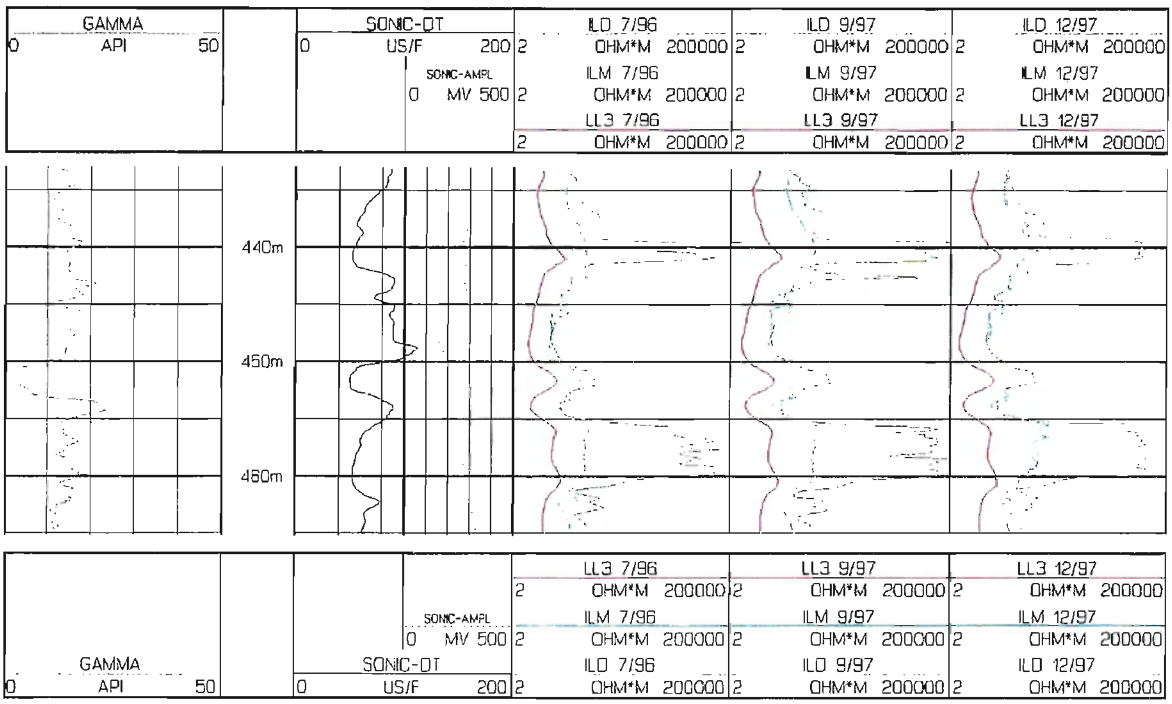

Figure 15. *Data example showing from left to right: gamma–ray log in API units, compensated travel time in microseconds per foot and the sonic amplitude, and three repeated measurements of latero log (LL3), induction log of medium penetration (ILM) and induction log of deep penetration (ILD). Month and year of campaign are given.*

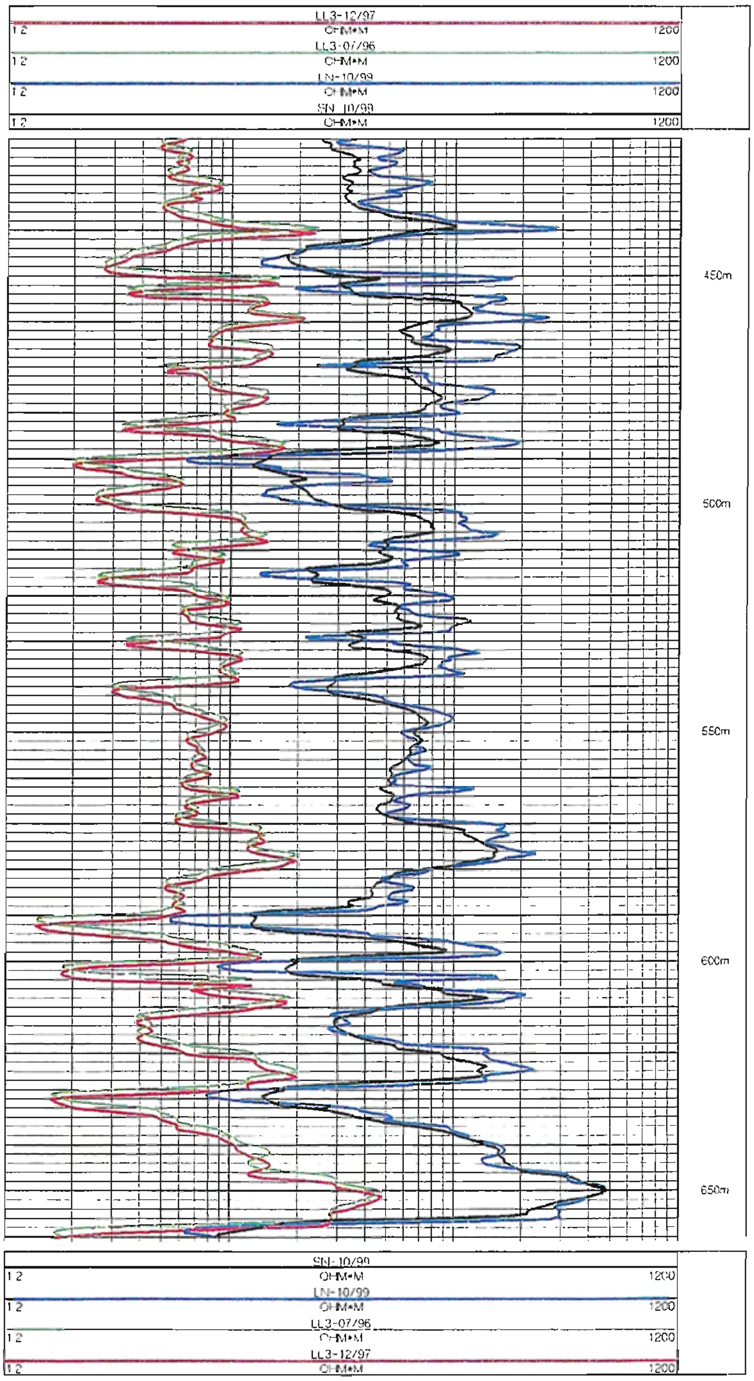

Figure 16. *Data example showing latero log data (LL3) from July 1996 and December 1997 together with short (SN) and long normal (LN) resistivity data from October 1999.*

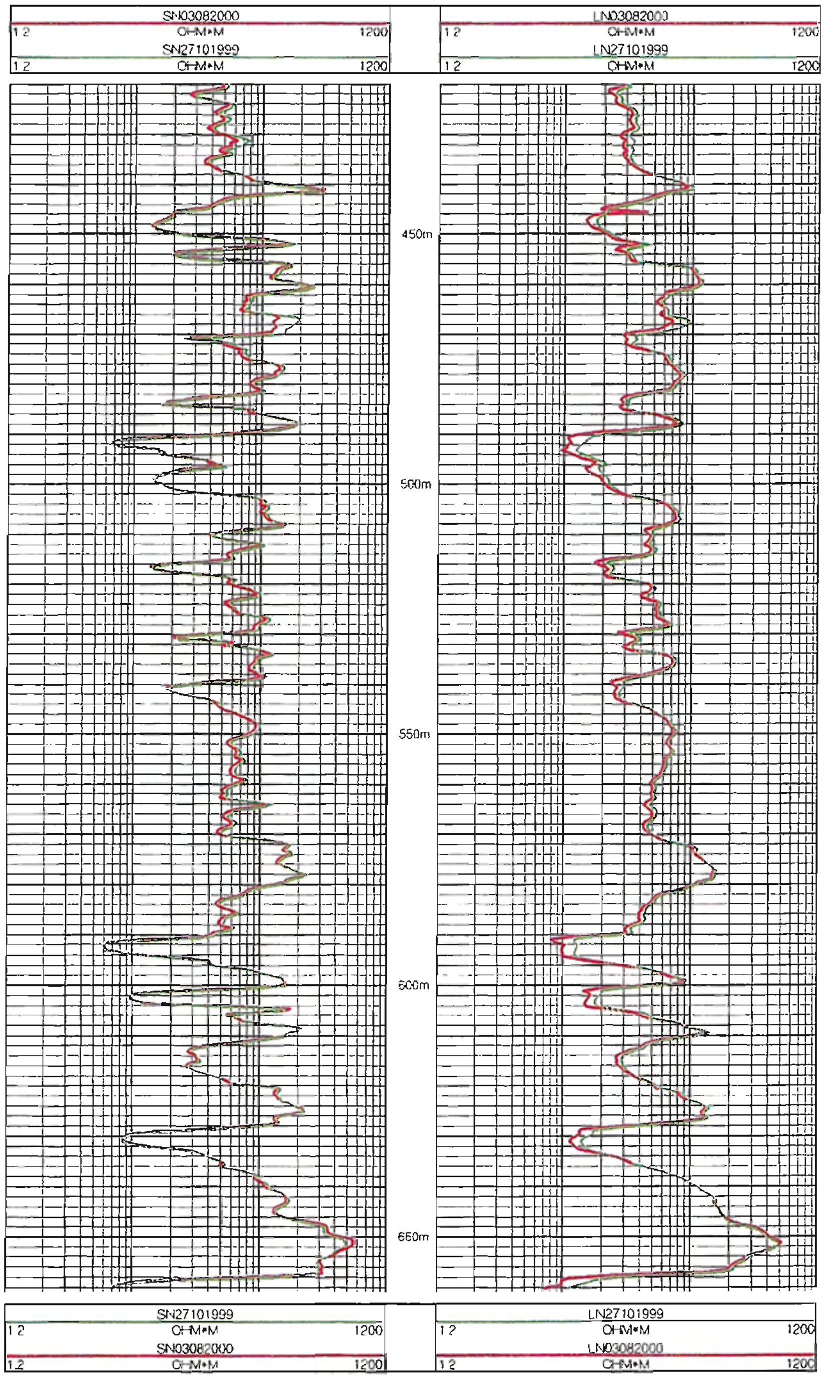

Figure 17. *Data example comparing short (SN) and long normal (LN) resistivity data from October 1999 and August 2000.*

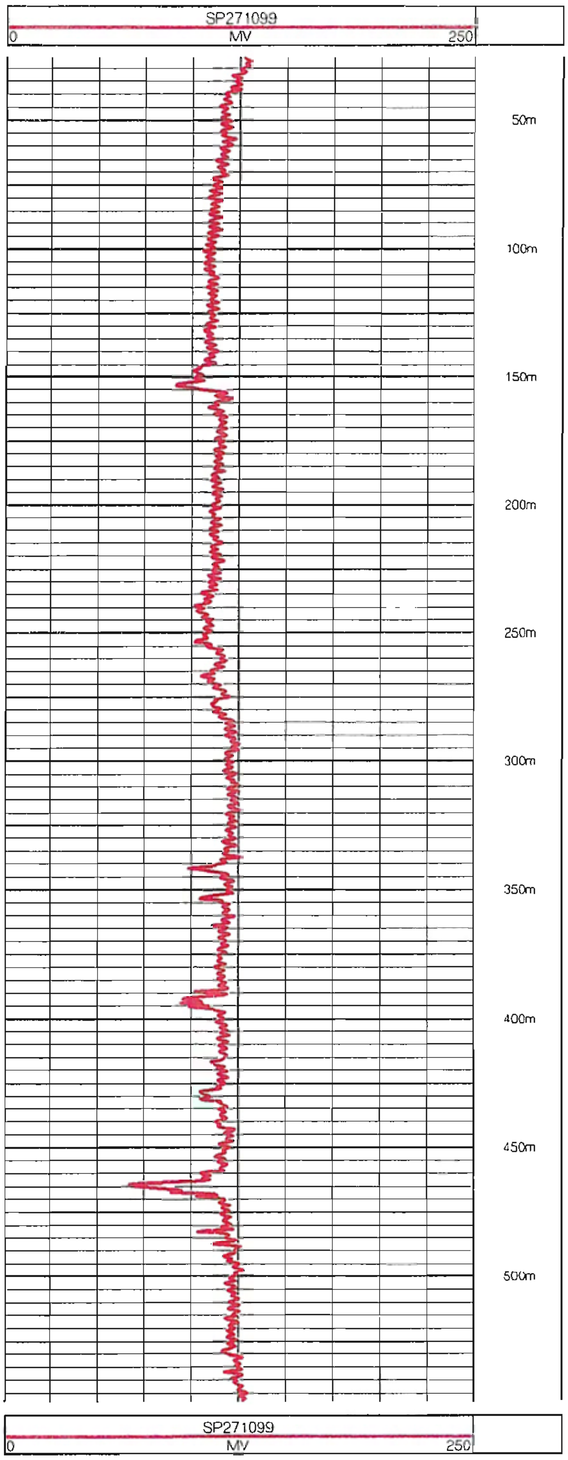

Figure 18. *Data example comparing short (SN) and long normal (LN) resistivity data from October 1999 and August 2000.*

Repeated logs in LL–03: dual–induction log (deep and medium penetration)
The repeated measurements with the dual–induction log (deep and medium penetration) show variations in resistivity even between different logs of one day, therefore these values cannot be used for an analysis of changes. More details can be found in the first annual PRENLAB-2 report.

Repeated logs in LL–03: sonic logs, P-wave travel times
The difference in the sonic velocity of logs measured at one day is in average 3.0% of the average value (Figure 19). At some depth intervals greater differences between repeated logs are caused by inaccurate depth matching, e.g. at 740 m in Figure 19. Depth intervals where the amplitude of the measured signal is very low showed significant variation in the (automatically) picked travel times, thus cannot be considered for an analysis of changes. Greater variations between logs of different logging campaigns could not be found.

Repeated logs in LL–03: neutron-neutron logs
Neutron-neutron logs were run before and after the June 2000 earthquakes. In the environment of borehole LL-03 at Nefsholt they are expected to reflect mainly the water content of the rock. They are plotted together in Figures 20 and 21. The one of April 1999 was measured with a log speed of 40 m/min. Those of October 1999 and August 2000, both were measured with a logging speed of 6 m/min. The April 1999 and the August 2000 logs were measured at 0.5 m depth interval. The 1999 log was measured at a depth interval of 0.1 m. The depth scale was shifted as described above.

Small changes can be found as well as between logs of April and October 1999 as between those of October 1999 and August 2000. The differences in logs of 1999 are larger than between those of October 1999 and August 2000. This might be due to the comparatively high logging speed in April 1999. At the depth of 465 m the neutron logs do not show a difference, as would be expected if a crack would have widened there. Generally, the match between the logs is remarkably good – so good that all of the observed differences can probably be attributed to statistical fluctuations.

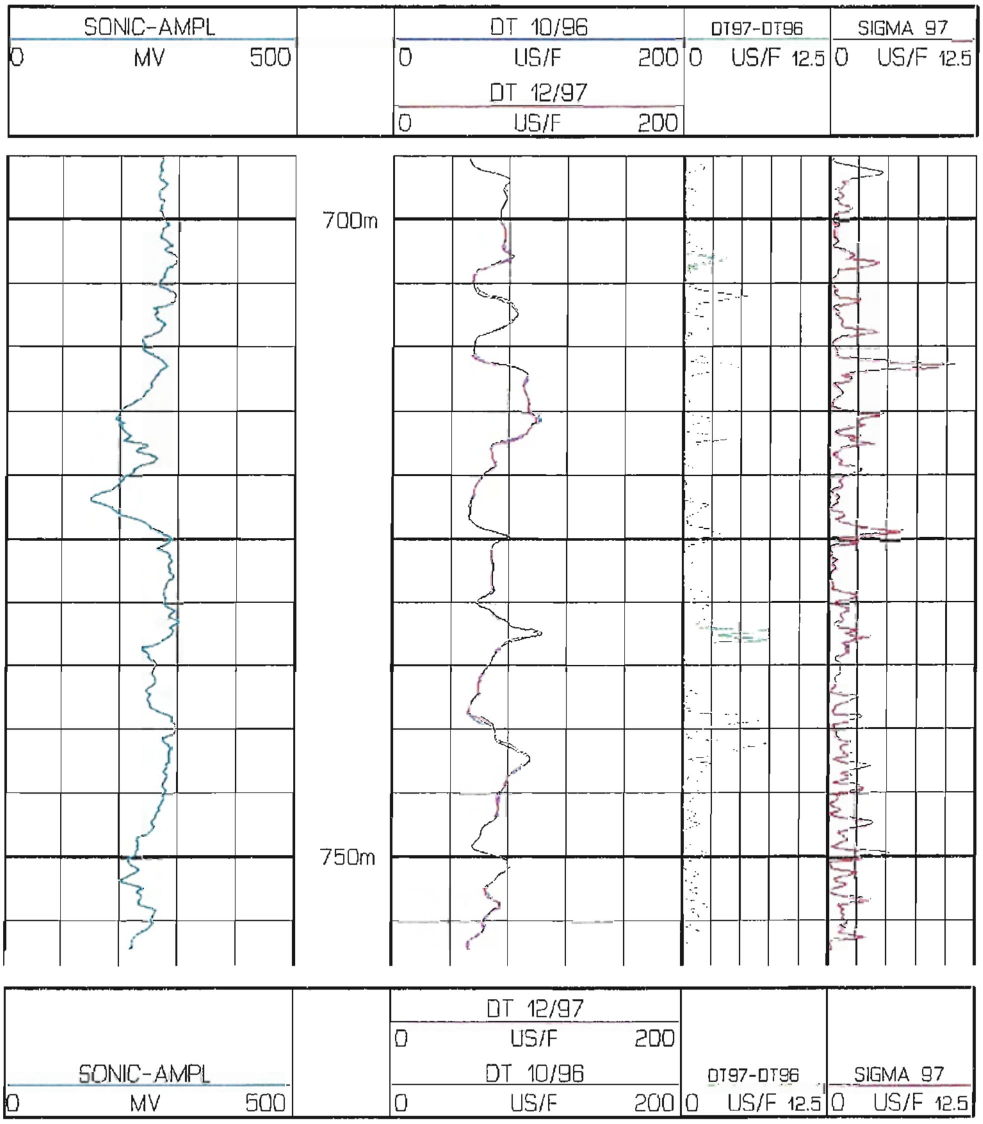

Figure 19. *Data example showing from left to right panel: an average curve of sonic amplitude, a superposition of the average compensated travel times measured in October 1996 and in December 1997 (each averaged over four runs performed immediately one after the other), the difference between these 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).*

Borehole-televiewer measurements

Nefsholt:

In drillhole LL-03 (63.92°N, 20.41°W), the orientation of the borehole breakouts found is about 120.5° to 126°, implying 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. They are supposed to have formed while drilling, i.e. in 1977.

Þykkvibær:

Borehole breakouts have been found in the depth intervals 925 m to 927 m and 937 m to 941 m in THB-13 (63.77°N, 20.67°W). The breakouts in these two depth intervals sum up to approximately 3.5 m. Data quality is rather poor due to weak reflection amplitudes. Figure 22 shows a data example. The average breakout azimuth is between N105°E (upper depth-interval) and N121°E (lower depth-interval). Statistical 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 oriented N21°E. This is in agreement with the stress directions expected from the overall tectonics as well as with the results from Nefsholt. The breakouts in THB-13 have most likely formed during drilling in 1997, i.e. just before they were measured.

Böðmóðsstaðir

No breakouts have been observed in borehole BS-11 (64.20°N, 20.55°W), 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 not of natural origin but drilling induced; so they stem out of 1992. These fractures occur at an azimuth of N45°E to N90°E. A data example is presented in Figure 23.

Breakout orientations and fracture statistics from the measurements in the SISZ are shown in Table 5 and Figure 24 as an overview. In Subpart 7B stress orientations were calculated for the SISZ using the co-seismic stress release of large earthquakes in the SISZ since 1706 and taking into account the stress build-up by plate motion. For comparison, we give the values for the boreholes where measurements were performed in Figure 25. Both results show stress orientations similar to each other. In general, the modelled values are more oriented to E-W than the measured ones.

Well:	Logged interval:	Interval with BOs / vert. fractures:	Total length of BOs/ vert. fractures:	Orientation of σ_H:	circ. std. devi.:
BS-11	703-1090 m	713-934 m	45.0 m fract.	N45°E–N90°E	—
LL-03	80-1100 m	780-983 m	5.0 m BOs	N30°E	12°
THB-13	466-1225 m	925-941 m	3.5 m BOs	N21°E	10°

Table 5. *Stress orientations found from borehole-televiewer logs.*

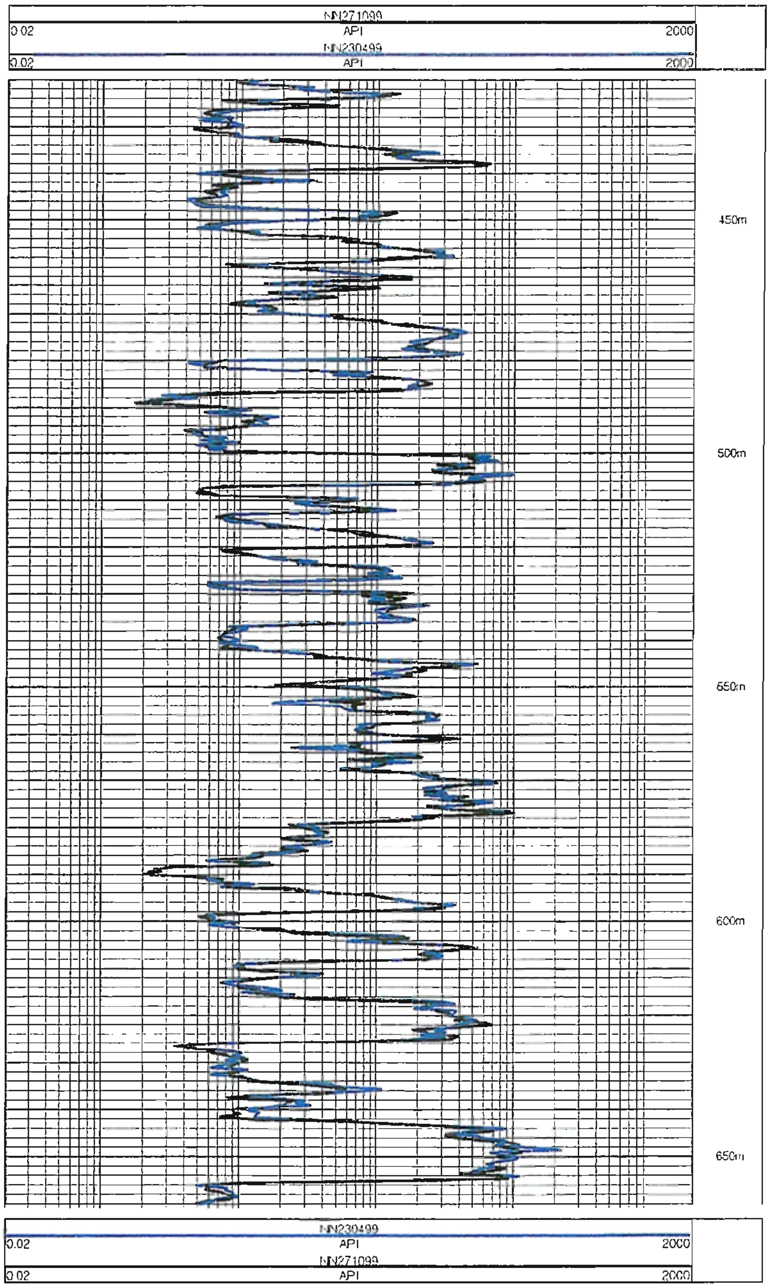

Figure 20. *Data example comparing short (SN) and long normal (LN) resistivity data from April 1999 and October 1999.*

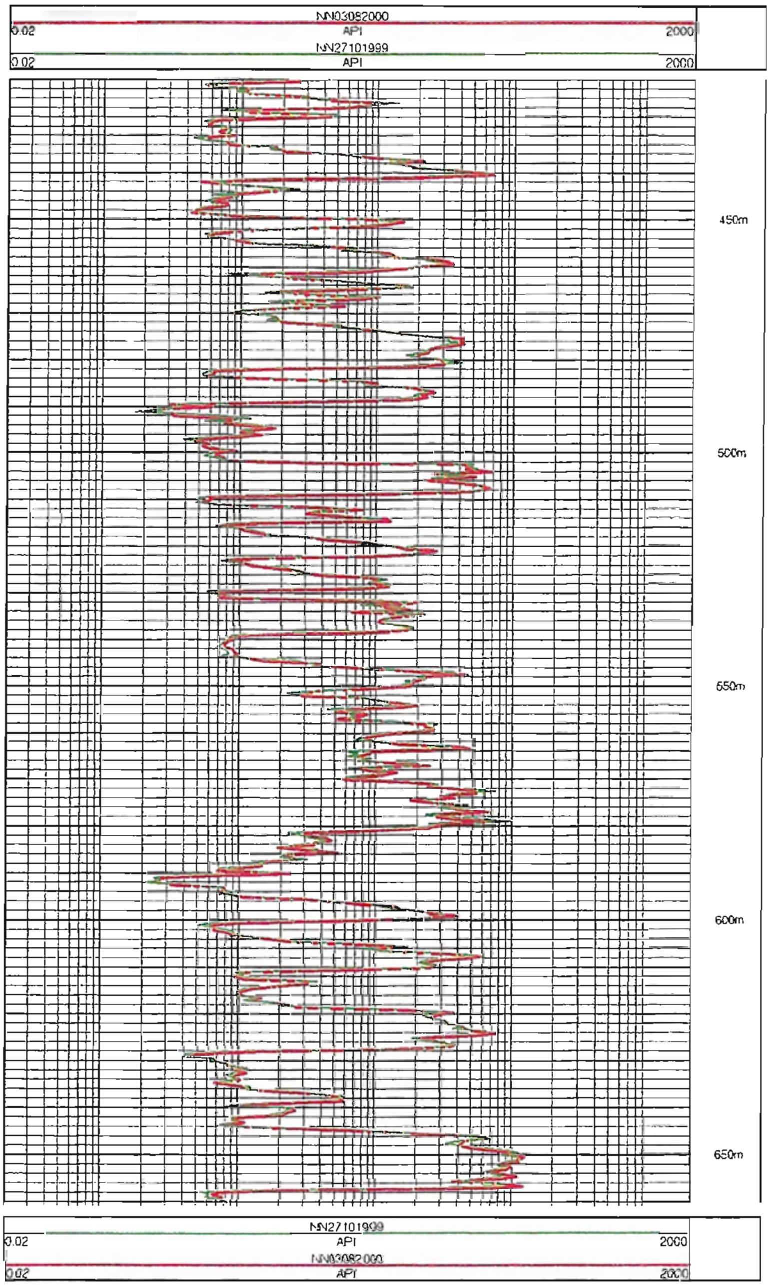

Figure 21. *Data example comparing short (SN) and long normal (LN) resistivity data from October 1999 and August 2000.*

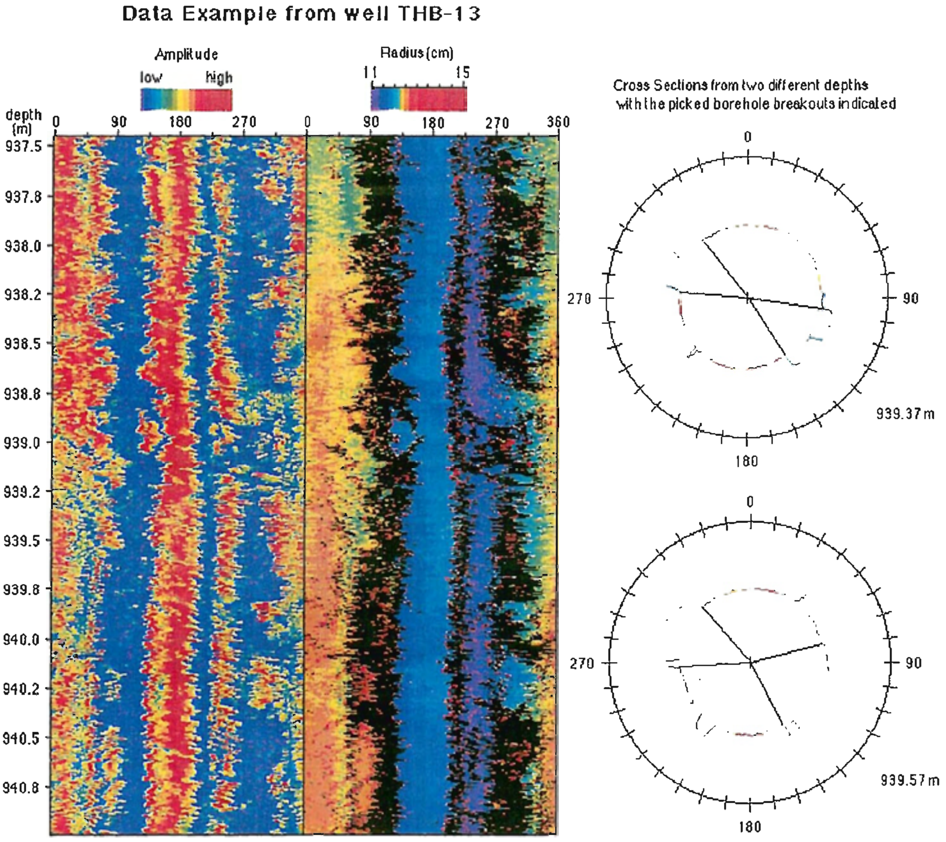

Figure 22. *Example of the borehole breakouts found in well THB-13 with two cross sections. The two panels show the amplitude of the reflected signal (left) and the radius calculated from the travel time (right), both unwrapped from north over east, south, west to north. Vertical axis: depth in meters. Breakouts appear as vertical bands of low reflection amplitudes. Due to poor reflection amplitudes, the values for the radius are often missing in these parts, resulting in black bands. In the two cross sections, the black lines indicate the range in azimuth of the picked breakouts.*

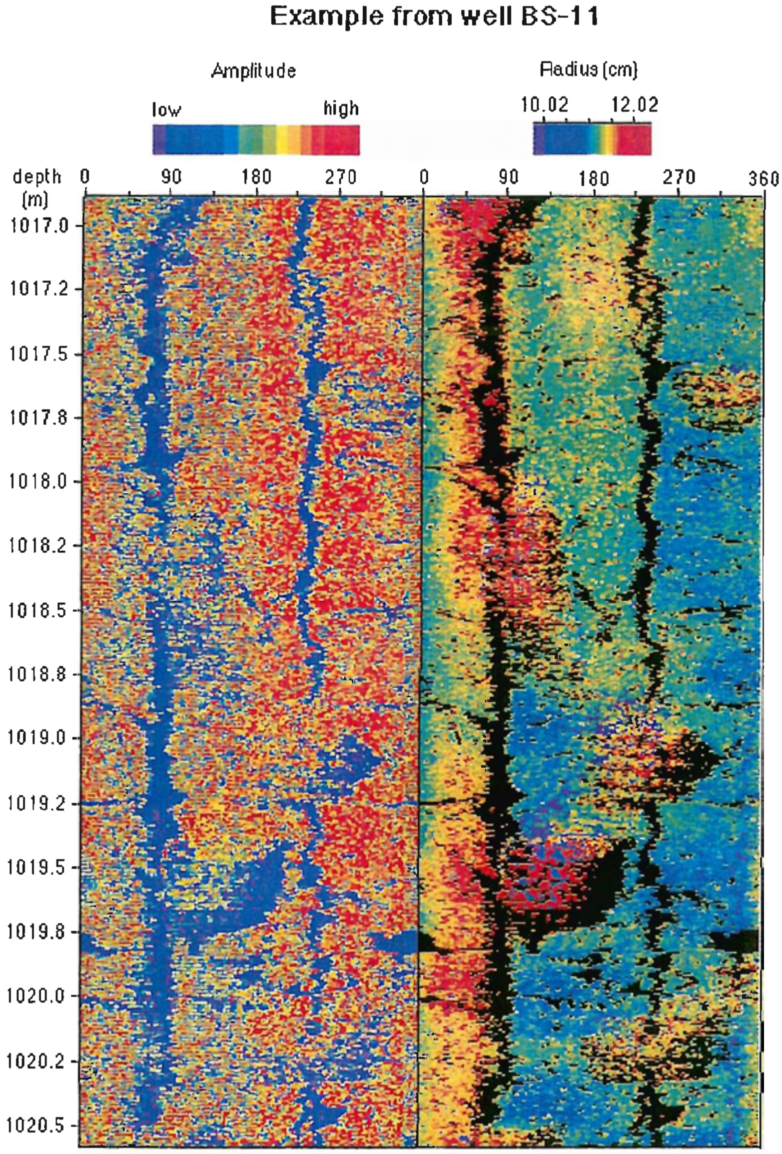

Figure 23. *Example for drilling induced vertical fractures observed in borehole BS-11. The data are displayed as described in Figure 22. The fractures appear as narrow vertical stripes of low reflection amplitude, much narrower than breakouts. Values for the radius calculated from travel time are missing for these stripes due to low amplitudes.*

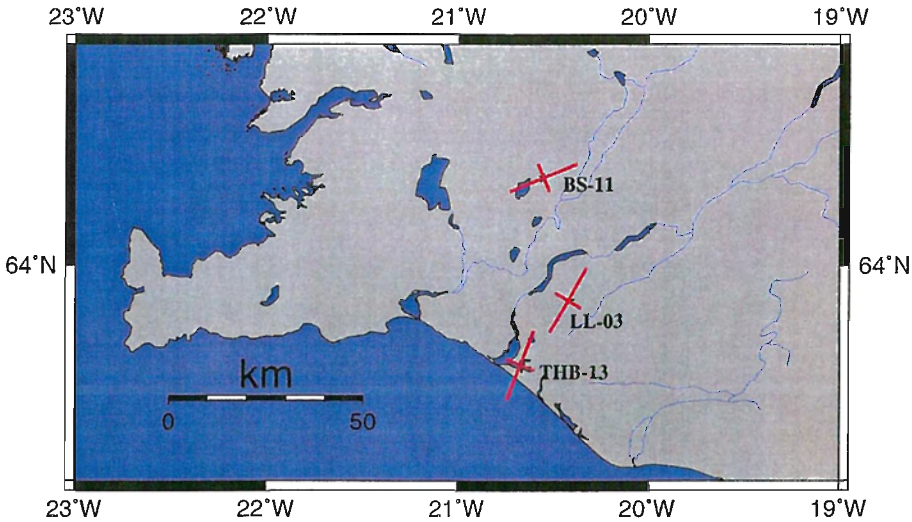

Figure 24. *Stress orientations found in boreholes in the South Iceland seismic zone. Long red lines indicate the orientation of the larger, short ones that of the lower principle horizontal stress.*

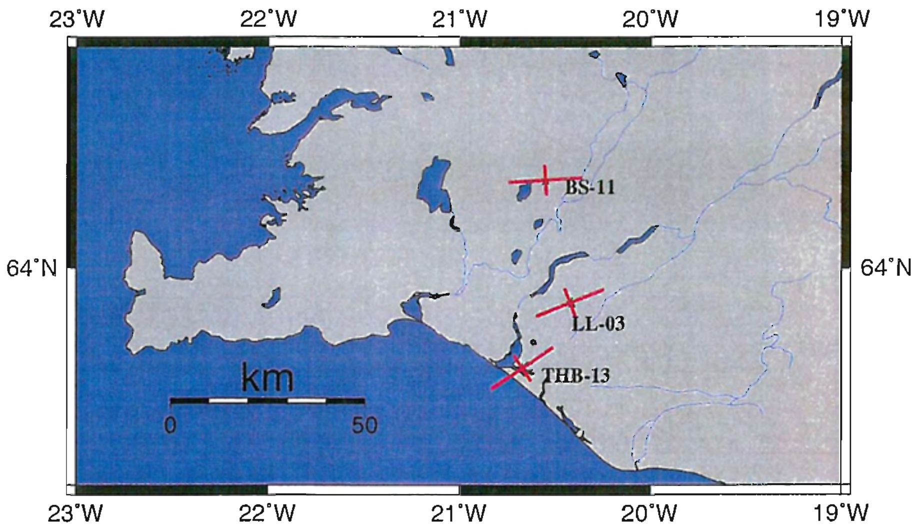

Figure 25. *Stress orientations calculated in Subpart 7B for borehole positions in and near the SISZ.*

Summary:
The results can be summarized as follows:

- The measurements at LL-03 for changes in P–wave velocity with the sonic log, for porosity changes with the neutron-neutron log, and for resistivities with the latero log, 16", and 64" show good repeatability.

- The earthquakes in June 2000 happened two weeks before the end of PRENLAB-2 project. Therefore, the last logging campaign before the events took place 8 months before the events. No clear indication for changes before the events was found. This might be, because the time difference was too long or the signals were below the detection threshold of the tools used.

- Coseismic changes might be visible at about 465 m depth, where both the 16" and the 64" log show a decrease in resistivity. It would be interesting to check whether cracks can be found there and at the other feed-points (visible in the temperature logs) with a high resolution borehole televiewer.

- Non-vertical fractures found down to nearly 1100 m depth show the same dominant strike as those observed at the surface (see first annual PRENLAB-2 report). A dependence of fracture orientation upon depth or upon geographical latitude could not be found.

- The stress orientations found at all three locations are similar and agree with a left–lateral strike-slip regime. They are based on data that are assumed to originate from 1977, 1992 and 1997 and are not perpendicular to existing ruptures found in the SISZ and, therefore indicate, that the SISZ is not a weak fault, as postulated for the San Andreas fault. Instead, it appeared prepared for another earthquake. From a rock mechanics view the stress directions found at LL-03 and THB-13 correlate with N-S striking faults, as they are found in the SISZ. On the other hand the orientation of maximum horizontal principal stress found at BS-11 correlates with the model of an E-W striking strike-slip fault zone. A linear dependency of stress orientation on age, depth or geographical position (in-/outside the SISZ) of the boreholes could not be found. Stress orientations similar to ours were also found by Stefánsson et al. (1993) from fault plane solutions. This was confirmed by other groups in the framework of PRENLAB as by Bergerat and coworkers (Subproject 6), who found a mean orientation of σ_H of N56°E derived from 1916 fault plane solutions selected from 48669 earthquakes in the SISZ of the years 1995 to 1997 (Angelier et al. 2000). A NE–SW orientation of σ_H was also the result of investigations of Crampin and coworkers on shear-wave splitting due to stress anisotropy at four of six seismic stations in the SISZ (Crampin et al. 1999) (Subproject 3).

Participants:
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3.4.5 References

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