Veðurstofa Íslands
Report

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PRENLAB - first annual report
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Chapter 1

Summary by coordinator

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

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

Originally the support requested for this project from EC was 2.2 MECU, but only 500.000 ECU could be provided by EC to a revised project. The question was raised, of course, if it would be right to cut out significant parts of the project to be better able to make progress on other parts of it. It was, however, agreed that it was more worth to keep the multidisciplinary character of the project, so all the main projects were kept in. It was evident at the contractor meetings that this decision was correct. It showed to be possible to achieve funds from other sources, especially for building out the seismological system. Among others, Icelandic communities and civil defence funds, the Icelandic Government and the Icelandic Research Council could provide a significant contribution to extend the seismic acquisition system, the SIL system. Most of the contractors succeeded to obtain guarantees for being able to plan realistic projects falling within the objectives of the original application.

The subprojects have all shown progress close to what was planned. However, one task of the project is significantly delayed from what was planned. This is the program for reviving the radon program in South Iceland together with development of an improved liquid scintillation apparatus to measure the radon content of water. This is a minor part of subproject 4: Borehole monitoring of fluid-rock interaction. The reason for the delay is that additional funding which was counted on has not yet been provided. The total EC contribution to this task is 20.000 ECU. Efforts are still going on to obtain the necessary additional funding. Success is expected within short so it is still considered right to plan this project. Meanwhile development work and research has been carried through that will create a better basis for this task when it can get started.

It is of a great significance for the project how successfully the SIL acquisition system has been expanded from the 18 stations that were available for the project at the time of application, to the 33 stations that are now in the permanent network. This adds considerably to the database which is available for the project. Another addition of a similar type is that 29 broad-band seismic stations are operated temporarily in Iceland during the period of the PRENLAB project. This is a part of the Iceland Hotspot Project which is run in cooperation between the University of Durham, in Princeton University, and the Icelandic Meteorological Office. The Hotspot network was installed during summer 1996 and will be operated until summer 1998. Geographically the Iceland Hotspot stations are complementary to the permanent SIL network, so it is of a great advance for the PRENLAB project to have access to these data.

Among results of a great significance for earthquake prediction research, the following can be mentioned:

- It has been demonstrated in several studies involving work of seismologists, geologists and geophysicists that it is possible on basis of microearthquakes to map subsurface faults with a great accuracy. A good agreement is between such studies within the project based on microearthquakes and the results of studying the faults on the surface when these are exposed. The same is true for the inversion of stresses inferred from microearthquakes that these coincide generally very well with what can be expected, based on paleostress studies of the geologists in this project, and have a relevance to the first results gained from the borehole experiment.

- Among significant new results that can be reported is that changes of shear-wave splitting at one of the SIL stations in the South Iceland seismic zone indicate stress changes with time that most probably can be attributed the intrusion of lava into the crust in the preparatory stage of the Vatnajökull eruption that started on September 30, 1996. The seismic station is 160 km away from the fissure intrusion. This indicates that it may be possible to predict increased probability for triggering of earthquakes based on monitoring of stress changes from outside the fault zone. It is also to be pointed out that one of the main pillars for using Iceland as a test area for earthquake prediction was that it would be possible to monitor stress or strain changes caused by measurable pulsations of the Iceland plume. These results have a consequence in general for understanding how stresses are transmitted in the crust anywhere.

- A result of a great significance is that it has been shown that it is possible to use satellite radar interferometry for measuring stable plate motion during a period of a couple of years in the favourable conditions that prevail in Iceland. This is of enormous significance for constructing a dynamical model of stress build-up in an earthquake area.

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

The results already obtained within the PRENLAB project have been demonstrated very thoroughly, as mentioned above, at the XXI EGS General Assembly in The Hague, May 6–10, 1996 and at the XXV ESC General Assembly in Reykjavík, September 9–14, 1996. These conferences gave a good opportunity to demonstrate obtained results within the project and to have them discussed among European geoscientists. Some parts of the project have also been demonstrated at some other meetings and conferences. Papers, which are based on the research within the project have already been published or submitted as can be seen in the publications lists in Chapters 3 and 4.

All the subprojects of PRENLAB were demonstrated at the ninth biennial EUG (European Union of Geosciences) meeting in Strasbourg, March 23–27, 1997, especially in Union Symposium 16, "Mitigating geological hazards (risks)", where 10 oral presentations were directly linked to PRENLAB. A significant presentation of PRENLAB results is also to be expected at the XXVII IASPEI (International Association of Seismology and Physics of the Earth's Interior) General Assembly in Thessaloniki, August 18-28, 1997.

A PRENLAB contractor meeting was held on March 25 in Strasbourg, coinciding with the ninth biennial EUG meeting. In August there is planned a contractor meeting coinciding with the IASPEI Assembly.

Chapter 2

Main achievements as reported by the responsible institutions

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

IMOR.DG coordinates the project and is responsible for subproject 1, "Real–time evaluation of earthquake–related–processes and development of database". The coordinator and contractor is Ragnar Stefánsson. IMOR.DG is responsible for a significant extension of the seismic network available for the project and for operating it. It has done extensive work in refining and standardizing the earthquake databases as well as related databases on slow changes, where continuous borehole strainmeter and gravimeter measurements are most significant. It serves the other subprojects with data from these databases. It is also responsible for projects in mapping of active faults, in studying seismicity patterns, in enhancing the alert system in Iceland, for installing and testing new algorithms for data acquisition and for enhanching the automatic evaluation processes. It cooperates closely with all the other subprojects, and through its coordination all the subprojects are well linked together.

Work has been carried out on all the tasks according to the time schedule of the workprogramme, although the needs of other partners for parts of a new and refined database are ahead of the intensive work going on with refining it.

2.2 UUPP.DGEO: Uppsala University, Department of Geophysics

UUPP.DGEO is responsible for subproject 2, "Development of methods using microearthquakes for monitoring crustal instability". The contractor is Reynir Bödvarsson. Task 1, Methods for subcrustal mapping of faults, Task 3, Methods for monitoring the local rock stress tensor and Task 6, Development of methods for acquisition of continuous GPS data through the SIL system, have all been in progress according to the planned time schedule. Task 2, Methods for monitoring the crustal wave velocities, and Task 5, Methods for statistical analysis of the space/time distribution of microearthquakes and earthquakes, are delayed by 2–4 months compared to the schedule. The main reason for this is that it was considered right to wait for finishing the ongoing refinement of the SIL database before starting these tasks. However, significant preparatory work has been carried out for Task 2, and more work than scheduled has been concentrated on Task 4, Methods for monitoring stable/unstable fault movements, which is a few months ahead of schedule of the workprogramme. Thus the work on subproject 2 is as a whole satisfactorily on schedule.

In all tasks the closest cooperator is IMOR.DG, except in Task 6 where the main cooperator is NVI. A special cooperation is in preparation with UEDIN.DGG in studying shear–wave splitting in a borehole experiment in northern Iceland.

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

UEDIN.DGG is responsible for subproject 3: "Monitoring stress changes before earthquakes using seismic shear–wave splitting". The contractor is Stuart Crampin. UEDIN.DGG cooperates closely with IMOR.DG. Other significant cooperators are UUPP.DGEO and GFZ.DR.DBL which will contribute by providing data from borehole experiments.

The tasks are within the workprogramme schedule.

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

GFZ.DR.DBL is responsible for subproject 4 as a whole: "Borehole monitoring of fluid–rock interaction". Subproject 4 is divided into subpart A, managed by contractor Frank Roth of GFZ.DR.DBL and subpart B, managed by associated contractor Páll Einarsson of UICE.DG (see 2.8).

All the tasks of subpart A, Geophysical loggings, have been carried out within the scheduled time frame.

Subpart B, which is a minor part of subproject 4, is behind the time schedule. The reason is that it has not been possible obtain additional funding as expected and needed. The EC funding for subpart B was planned to be used for Task 1 of the subpart, i.e. to build an improved LSC apparatus to measure radon content of water and gas samples. This work is at a final stage but has not been finalized yet as it has not been possible to get funds as expected for carrying out Task 2 of the subpart, i.e. to revive the radon sampling program in South Iceland. It is being worked on to obtain the necessary funds, and it can be expected that Task 2 of this subpart will be 9 months delayed, i.e. that it will start in month 14 instead of month 5.

Other partners that cooperate closely with GFZ.DR.DBL are IMOR.DG and UBLG.DF.

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

CNRS.DTP is responsible for subproject 5 as a whole: "Active deformation determined from GPS and SAR". The subproject is divided into two subparts, A and B.

Subpart A, SAR interferometry, is managed by contractor Kurt Feigl of CNRS.DTP in close cooperation with Freysteinn Sigmundsson of NVI (see 2.6). It is on schedule.

Subpart B, GPS geodesy, is managed by associated contractor Freysteinn Sigmundsson of NVI (see 2.6), cooperating with Reynir Bödvarsson of UUPP.DGEO (see 2.2). The work has been on schedule, however, continuous monitoring is not yet operative because of unsolved technical problems. This means that Task 2 of subpart B is partly delayed, i.e. a part which relies on continuous GPS monitoring. However, other subtasks relying on other deformation measurements were started in month 4 of the project and have been finalized with a publication.

2.6 NVI: Nordic Volcanological Institute

NVI is responsible for subproject 6: "Formation and development of seismogenic faults and fault populations". Subproject 6 is divided into subpart A, Paleostresses, managed by associated contractor Francoise Bergerat of CNRS.TT (see 2.9) and subpart B, Field and theoretical studies of faults and fault populations, managed by contractor Ágúst Gudmundsson of NVI. In carrying out the tasks NVI also cooperates closely with UBLG.DF.

The progress of both subparts is on schedule.

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

UBLG.DF is responsible for subproject 7: "Theoretical analysis of faulting and earthquake processes". This subproject is divided in two subparts, A and B.

Subpart A, Crust-mantle rheology in Iceland and Mid-Atlantic Ridge from studies of post-seismic rebound, is managed by contractor Maurizio Bonafede of UBLG.DF. Subpart A is well within the time schedule of the workprogramme.

Subpart B, Modelling of the earthquake related space-time behaviour of the stress field in the fault system of southern Iceland, is managed by associated contractor Frank Roth of GFZ.DR.DBL (see 2.4). UBLG.DF also works closely with NVI in carrying out the tasks.

All parts of subpart B started on schedule, i.e. in March 1996, except Task 4 which will start in May 1997. The tasks have not been finalized on schedule due to problems in hiring a co-worker. This problem was solved in January 1997, and work is progressing fast now and will be finalized within the project period.

2.8 UICE.DG: University of Iceland, Science Institute

Associated contractor Páll Einarsson (see 2.4).

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

Associated contractor Francoise Bergerat (see 2.6).

Summary of scientific achievements by subprojects and tasks

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

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Einar Kjartansson was especially hired as a researcher for the project from March 1, 1996, and has been working on it full time from the very beginning. The other researchers mentioned are staff members of the Department of Geophysics. They have carried out 48 man months of work for the project during the first year, paid by IMOR.DG.

3.1.1 Task 1: Database, development and service

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

3.1.1.1 Task 1.1: Data collection

A very significant achievement within Task 1 is the increase of number of operating seismic stations. In the original application to EC, 12 SIL type seismic stations were requested. The cutting of the application did not permit any new stations according to our own evaluation. However, it showed to be possible to arrange funds from other sources to build 15 new permanent SIL stations. These stations are as other permanent stations of the SIL network available for the PRENLAB project and of great significance for it. However, they do not fully complement what was asked for in the original application as they are not all at sites most preferable for the project.

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

From summer 1996 to summer 1998, 29 extra digital broad-band stations are operated continuously at remote places not covered by the SIL system, mainly for collecting teleseismic data. This is a part of the Iceland Hotspot project, lead by Gillian Foulger, University of Durham. Among other participants are Princeton University, with Jason Morgan and Guust Nolet, and Bruce Julian of the U.S. Geological Survey, besides IMOR.DG. The waveform information from these stations will be included into the SIL evaluation processes, especially as concerns the local seismic activity. This is a very significant addition to the data that we according to the original plan can approach for the PRENLAB project. As the Hotspot Project stations are operated at sites where we have only few SIL stations they can provide us with a much more general overview about the stress conditions in the country as a whole, than would be possible with the SIL system only. Figure 1 shows the locations of the seismic stations operated in Iceland during the period of the later part of the PRENLAB project.

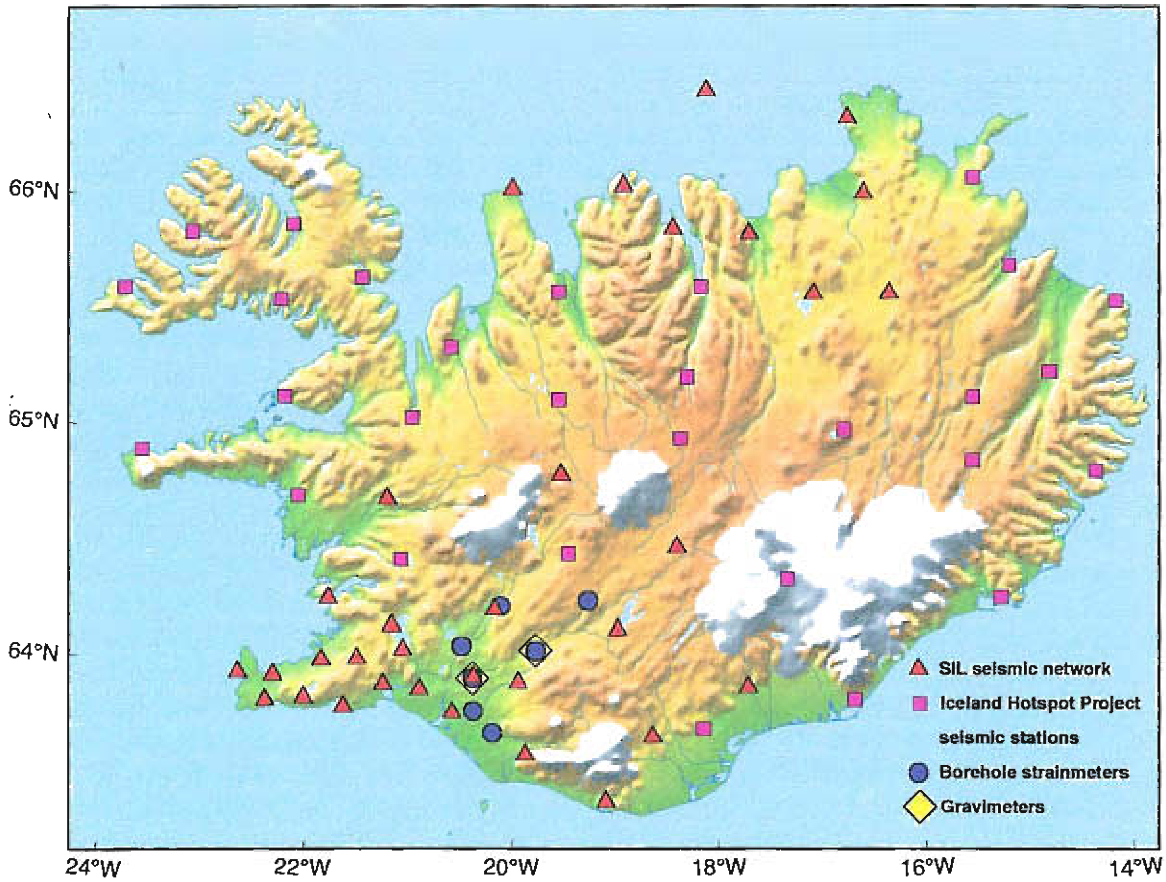

Figure 1: *Seismic station networks, strainmeters and gravimeters in Iceland in 1997.*

3.1.1.2 Task 1.2: The database access

A refined and easily accessible database for SIL data is under construction. Since 1991, 50.000 earthquakes have been recorded by the SIL system. The data were automatically evaluated and manually corrected.

Facilities have been developed to store all the data on–line on hard disks. Seismogram data is stored using packed binary format where only the number of bits that is required to store sample to sample variation is stored.

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

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

The existing database has shown to have faults which made it difficult to use by many scientists which needed evaluated data. It is therefore necessary to reevaluate much of the data before storing them in a new, refined database. The reevaluation is currently being performed and now the reevaluated database is available since 1995. The work with reevaluating the earlier years will be carried out during the next four weeks.

In spite of the necessary reevaluation, data from the SIL database have been provided to the various projects of PRENLAB as requested.

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

Spatial changes in seismicity have been studied in an area along the Reykjanes Peninsula, the South Iceland Lowland and into the eastern volcanic zone.

Work has been carried out for refined estimation of magnitudes and locations of historcial earthquakes.

Much work has been carried out in interpreting data from volumetric borehole strainmeters. Premonitory and coseismic changes, volumetric strain, and foreshocks, of the matnitude 5.8 earthquake at Vatnafjöll, near the eastern end of the South Iceland seismic zone, have been studied with results that indicate fluid intrusion coinciding with foreshocks and the main shock.

A long-term overview (since 1979) of the 7 volumetric strainmeters in Iceland is being worked out. Methods have been developed for cleaning the strainmeter record of weather influences.

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

The seismicity of the volcanic eruption in Vatnajökull, which started at the end of September 1996, was studied as concerns hypocenters and mechanism of the earthquakes which were linked to the eruption. Much effort was put in saving data on this remarkable eruption from the seismic networks, both earthquake data as well as data on volcanic tremor. Vatnajökull is directly above the Iceland mantle plume and changes of the plume activity greatly affect the seismicity along all of the plate boundary in Iceland.

Although the SIL system is a seismic data acquisition system, that is primarily designed for automatic acquisition and evaluation of data from local microearthquakes, it can also be used for collecting teleseismic and regional data for deep structure studies. It broadens the scientific use of the network and has made it easier to extend the network to a large part of the plate boundary in Iceland. The SIL station software has now been modified allowing for selection of waveform data additionally at 20 and 4 samples per second. This makes it economically possible to save long-time periods of seismological data from the SIL stations. We have developed an automatic procedure to select and store teleseismic data in the SIL system based on USGS/NEIC information on teleseismic events in the whole world which are measurable in Iceland. From USGS/NEIC we receive E-mail messages with a single-line information on earthquakes they have determined, the so-called "E" type messages. A selection program reads the messages and selects events that fulfill certain criteria of magnitude and epicentral distance. The program uses the iaspei91 model to compute the first arrival time at each station. The teleseismic body wave data are fetched with a sampling rate of 20 samples (in some cases 100 samples) per second and the surface wave data with sampling rate of 4 samples per second from the 1-3 days long ringbuffer of the SIL site stations.

Work has been carried out for studying and refining the alert thresholds for the SIL related alert system in Iceland.

An alert detector monitoring large amplitudes, background noise (tremor) and directivity of the microseisms has been tuned for the 1 Hz sensors of the system, using Hekla tremor from 1991 as test set. Implementation and tuning of a bandpass filter is needed for broad-band sensors.

A real–time filter has recently been introduced into the on–line process of the system, to be tuned for detecting signals and harmonic tremor, which cannot be detected through the automatic event detection of the SIL system. The continuous seismic signal at the SIL site stations is bandpass filtered at 0.5–1 Hz, 1–2 Hz and 2–4 Hz and the 1 minute mean amplitude is scanned and sent to the SIL center, where the interpretation of characteristics of the tremor is carried out and linked to the alert system. Visual presentation of this data gives an useful indication of the multiplicity of activity in real–time.

The extension of the SIL system into the highlands of Iceland has lead to many problems in the automatic detection and analysis. The SIL system was developed for use in the seismic zones. Monitoring in the highlands reveals in many ways new problems. Much work has been carried out to lower the detection threshold for earthquakes in the volcanic Central Iceland. The new real–time filter mentioned above will be used for this purpose together with tuning of parameters.

Work has been carried out on recent high seismic activity near the Hengill triple junction in SW–Iceland, i.e. spatial and temporal varations of activity have been studied and migration within the area. Fault plane solutions of more than 20.000 earthquakes have been studied in the area. Work has been carried out on detailed mapping of seismically active faults in the Tjörnes fracture zone, based on multievent hypocenter locations and on fault plane solutions. This has been done in cooperation with the NVI.

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

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

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

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

Cooperative partners: UUPP.DGEO, NVI

Work has been going on in using all useful seismological data for mapping active earthquake faults in the Tjörnes fracture zone at the north coast of Iceland (Figure 2). The method used is multievent method based on cross-correlating similar signals at the the same seismic station. Provided the time accuracy of the seismic data of the SIL system, close to 1 millisecond, active faults can be mapped with accuracy of the order of 10 meters. Fault plane solutions based on spectral amplitudes of P and S waves are then used as a part of the mapping to reveal the sense of the fault motion. Several special fault mapping efforts have been carried out related to ongoing earthquake sequences in other parts of the country, so gradually information on fault arrangement in different parts along the plate boundary is being collected.

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

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

Work has been carried out on recent high seismic activity near the Hengill triple junction in SW–Iceland, spatial and temporal varations of activity have been studied and migration within the area. Fault plane solutions of more than 20.000 earthquakes have been studied in the area (Figure 3).

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

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

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

Work is going on for introducing ACIS into the automatic procedures of the SIL system. ACIS is an acronym for "Reducing manual checking by Automatic Correlation of Incoming Signals". As has been shown in the work on multievent analysis for detailed mapping of faults most seismic events correlate well with each other within some areas. Based on this a new approximation has been started for the automatic operation of the SIL network in Iceland. A geographically indexed database is being created where different classes of earthquakes are stored. As new earthquakes are recorded by the network, the system automatically looks for similar waveforms in the database, and if found, takes the onset and the first motion direction picks from there. If no existing entry in the database correlates with the new event, the event is checked interactively by the network operators. This approach will improve the accuracy of the automatic analysis and reduce the need of work for interactive checking of the data without loss of useful signals.

Preliminary testing has demonstrated that the approach described here is possible. It is expected that the first version of the algorithm will be ready for testing within the SIL system in July 1997.

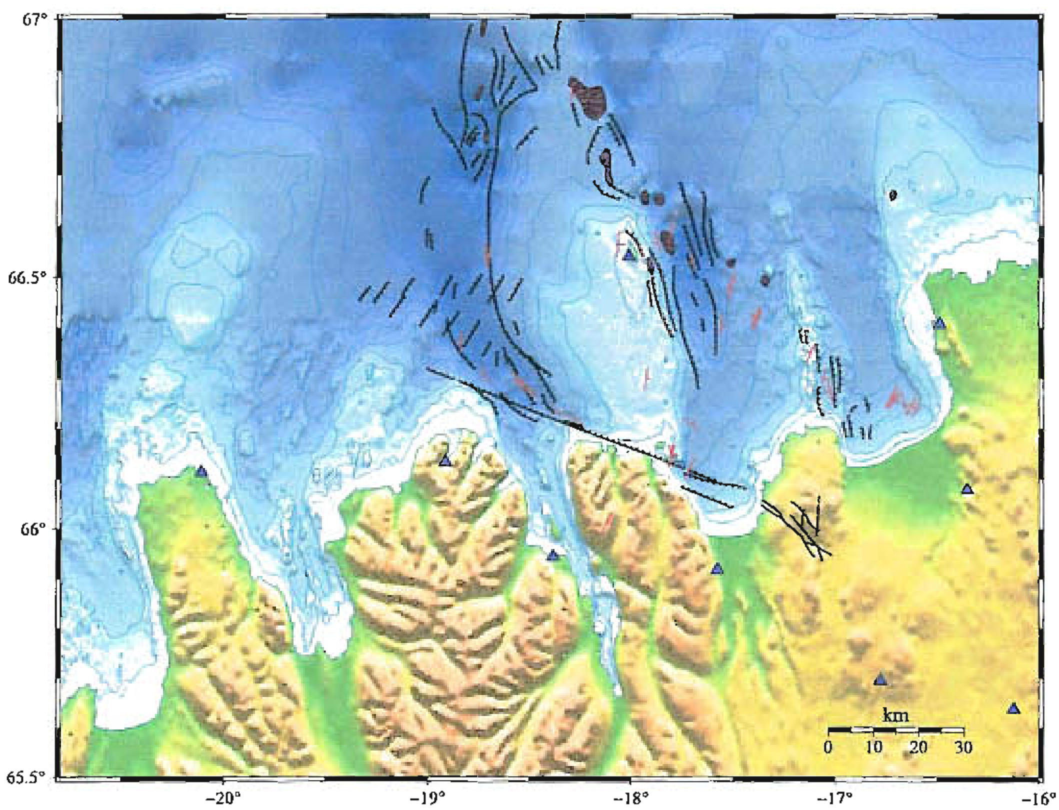

Figure 2: *Mapped faults within the Tjörnes fracture zone off the north coast of Iceland. Black lines indicate faults mapped with conventional reflection seismic methods or by direct observations on-land. Red lines are 35 active fault segments mapped using accurate relative locations of microearthquakes recorded by the SIL network. Seismic stations are denoted by triangles. Dark patches are sites of recent volcanism. The depth contour interval is 100 m.*

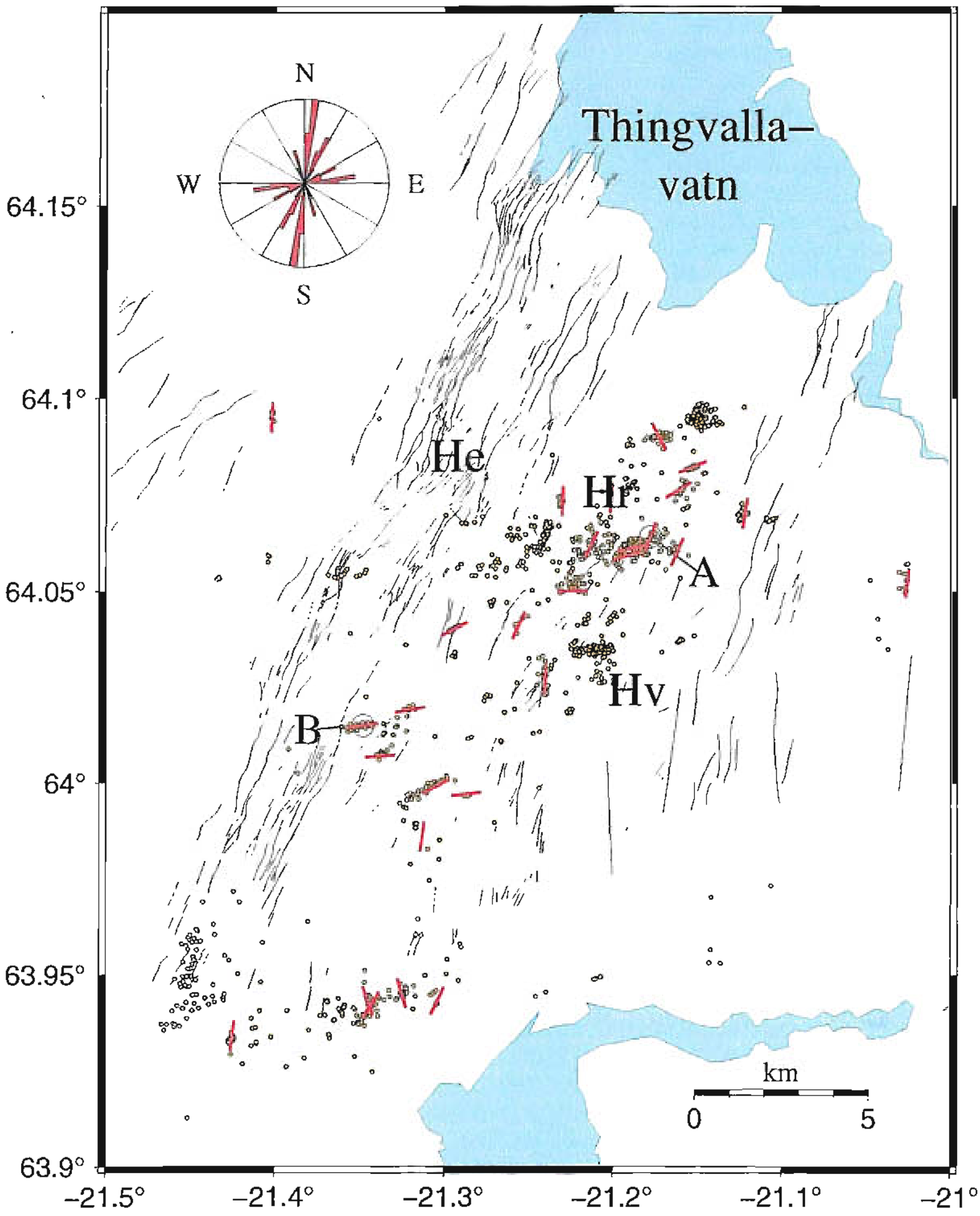

Figure 3: *Earthquakes in the Hengill volcanic area, SW–Iceland. The red lines show the location and orientation of fault planes estimated from the relative location of earthquakes. The black lines are mapped surface faults, yellow circles are relocated earthquakes. The inset rose diagram shows the orientation of the 28 faults mapped using accurate relative locations of earthquakes.*

A new algorithm has been introduced into the alert procedure, which is a special noise monitor. Noise is monitored by real–time filtering of the digital data from the seismic stations in three specified frequency bands, i.e. 0.5–1.0 Hz, 1.0–2.0 Hz and 2.0–4.0 Hz. During the recent eruption in Vatnajökull these frequencies showed to be useful in discriminating noise of different origin. The lower frequencies are typical for harmonic volcanic tremor, while the highest frequency seems to be expressing noise created by very intensive activity of very small earthquakes, although these are not discriminated as such. Such an activity is more typical in the approaching of an eruption and may possibly be of significance in the introductionary phase of earthquakes. Much work remains to be done to analyze the noise and how it is related to other activities of the crustal forces. This noise monitoring is already now used to monitor volcanic acivity. The experience will also be a good basis for designing a new detector in the SIL system which will be aimed at detecting and automatically evaluating "slow earthquakes" (meaning small earthquakes with corner frequencies of the order of 1 Hz) which are often observed in Iceland.

3.1.5 Meetings and conferences

Ragnar Stefánsson attended the XXI EGS General Assembly in The Hague, May 6-10, 1996, and the PRENLAB contractor meeting which was held there. He also attended the XXV ESC General Assembly in Reykjavík, September 9–14, 1996 (president of the Local Organizing Committee), and one of the two PRENLAB contractor meetings held there. He was a convenor of the special EC seismic risk workshop which was held there including coordinators of other ongoing EC seismic risk projects. The following researchers at IMOR.DG attended the second contractor meeting in Reykjavík: Sigurdur Th. Rögnvaldsson, Páll Halldórsson, Kristján Ágústsson, Einar Kjartansson, Gunnar B. Guðmundsson and Steinunn S. Jakobsdóttir.

3.1.6 Publications

[1] Angelier, J., S.Th. Rögnvaldsson, F. Bergerat, Á. Guðmundsson, S. Jakobsdóttir & R. Stefánsson 1996. Earthquake focal mechanisms and recent faulting: a seismotectonic analysis in the Vördufell area, South Iceland seismic zone. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 199–204.

[2] Ágústsson, K. 1996a. Continuous strain measurements in SW-Iceland with focus on the 1987 Vatnafjöll earthquake and the 1991 Hekla eruption. Thesis for Fil.lic. degree, Uppsala University, 34 p.

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

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The SIL microearthquake system produces detailed results of automatic analysis of large number of microearthquakes. To be able to work efficiently with this kind of information a special interactive program had previously been created. During the PRENLAB project, this program has now been further developed and allows now the results from single event location, from multievent location, from fault plane solution, and from rock stress tensor inversion as input. The program can now be used for steering results from one analysis to another, for example can the relative locations give constraint on the fault plane orientation which can be used in the input for both fault plane solutions and rock stress tensor inversion. The development of this interactive software has also required modifications in all other software to facilitate the information flow between the different algorithms.

3.2.1 Task 1: Methods for subcrustal mapping of faults

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

The algorithm for absolute and relative location of microearthquakes has been implemented in the SIL system routine analysis. This software has been applied in a search of crustal faults both in the north (Tjörnes fracture zone) and in the SIL area. This work has been in cooperation with geologists and these faults found from the microearthquakes show a remarkable agreement with the fault information available from sea bottom and land surveys. These studies also indicate the power of the multievent location technique for discriminating the fault plane and the auxiliary plane. A paper will soon be submitted for publication. An example of the results using this algorithm is shown in Figure 2.

3.2.2 Task 2: Methods for monitoring the crustal wave velocities

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

Work on methods for monitoring changes in wave velocities are somewhat delayed because it is considered more effective to concentrate on this after the refined database has been completed. Some preliminary work has been carried out towards inversion for the 3–D velocity structure in the SIL area. The first results show an interesting velocity anomaly at the lower boundary of the brittle crust (Figure 4). This work is a basis for effective work on finishing Task 2.

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

Start: March 1996 (month 1)
Estimated end: September 1997 (month 19)
Responsible partner: UUPP.DGEO
Cooperative partner: IMOR.DG

Software for rock stress tensor inversion based solely on microearthquake information is under development. Stress tensor inversion based on only microearthquake information has a crucial point in the choice of fault plane (eliminating the auxiliary plane). This new software allows to base this choice on not only the fit to the stress tensor for the slip direction but also due to stability and (perhaps most promising) due to relative locations of closely spaced similar microearthquakes. This allows a stress tensor inversion completely based on direct information from the microearthquakes without adding restrictions based on surface geology. The state of the work is that the software is developed and implemented in the SIL system context. Tests with synthetic data and with real data from the SIL area has been performed.

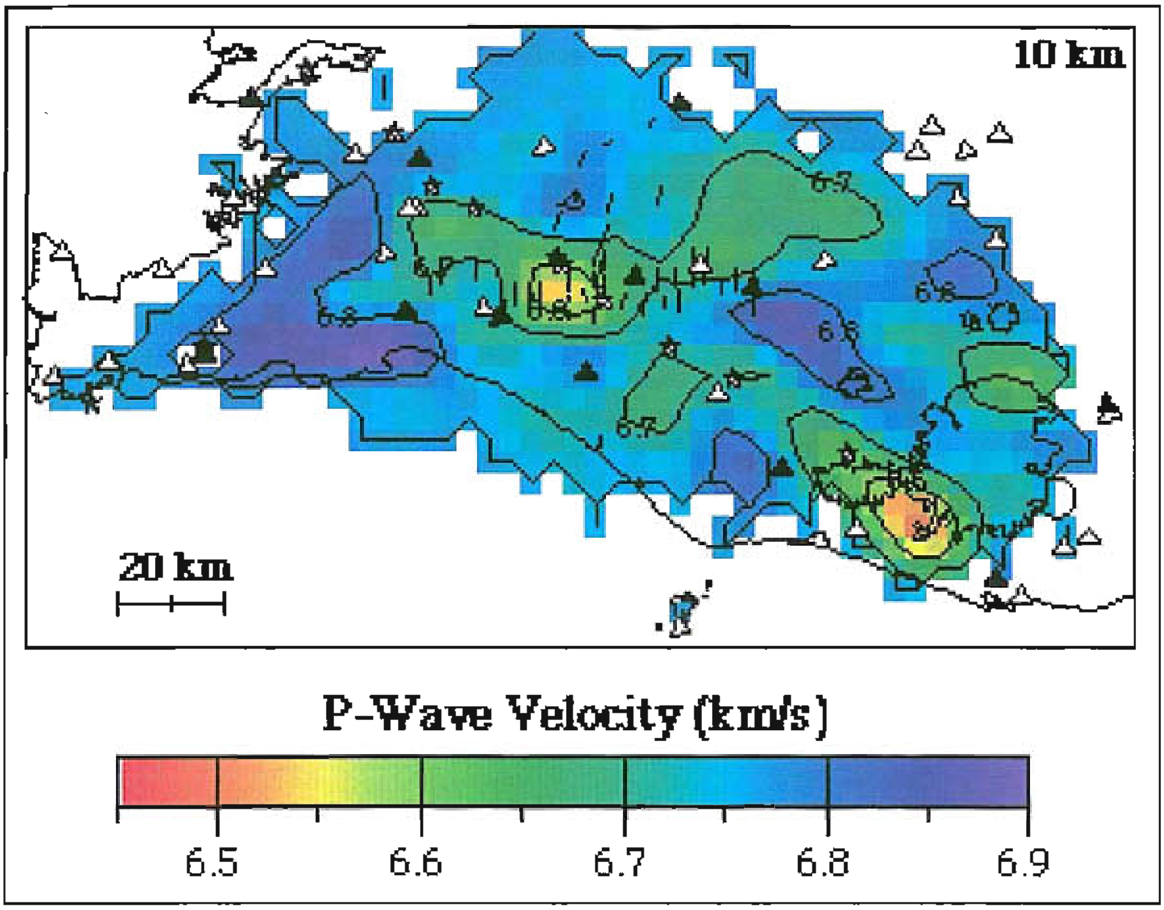

Figure 4: *3-D P wave velocity at 10 km depth in the crust beneath SW-Iceland estimated from local earthquake tomography.*

At present we are testing the algorithm and comparing the results with other algorithms. Preliminary results are shown in Figures 5 and 6.

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

Start: October 1996 (month 8)
Estimated end: February 1998 (month 24)
Responsible partner: UUPP.DGEO
Cooperative partner: IMOR.DG

This part of the project depends highly on the results from Task 1 and Task 3. This will thus be the last task to be finalized within the project. However, a thorough testing of the various algorithms used in the microearthquake analysis is being worked on. The first step was to test the automatic algorithm for the fault plane solution. This has been done by performing full waveform inversion for the moment tensors for a few selected earthquakes

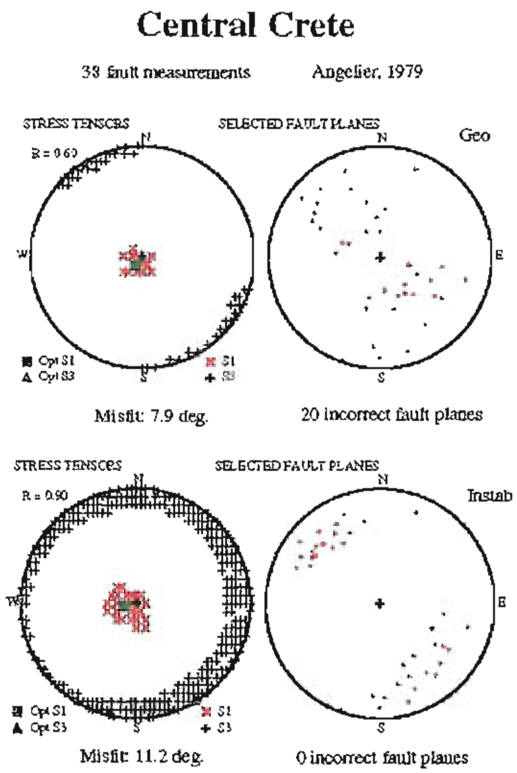

Figure 5: *Stress tensor inversion of microearthquake fault plane solutions is complicated by the fact that two possible fault planes are presented by the seismological fault plane solution. This problem does not exist for geological data. In order to investigate different ways of handling this the geological data presented by Angelier in 1979 was used to create a realistic set of microearthquake data but with known true fault plane. The four circles are equal area projections of the lower hemisphere. The left ones show the directions of maximum and minimum principal stresses (σ_1 and σ_3) for the stress tensors. The right ones show the orientations of the assumed fault planes (the direction of their normals). Two different ways of handling with the fault plane ambiguity of microearthquake data were tested. The upper two circles show the results when the choice of fault plane was based on the fit to Bott's criterion (the one with smallest deviation was accepted). The lower circles show the results when the plane with lowest stability (Mohr–Coulomb frictional model) was assumed to be the fault plane. In this later case all assumed fault planes were correct while the upper purely geometrical choice took the auxiliary plane for 20 of the 38 events. Although the stress tensor directions are very similar the size of the intermediate principal stress differs. In addition it is obvious that the purely geometrical approach gives very optimistic confidence regions. In conclusion this dataset indicates the value of including stability considerations into the stress tensor inversion in presence of auxiliary planes.*

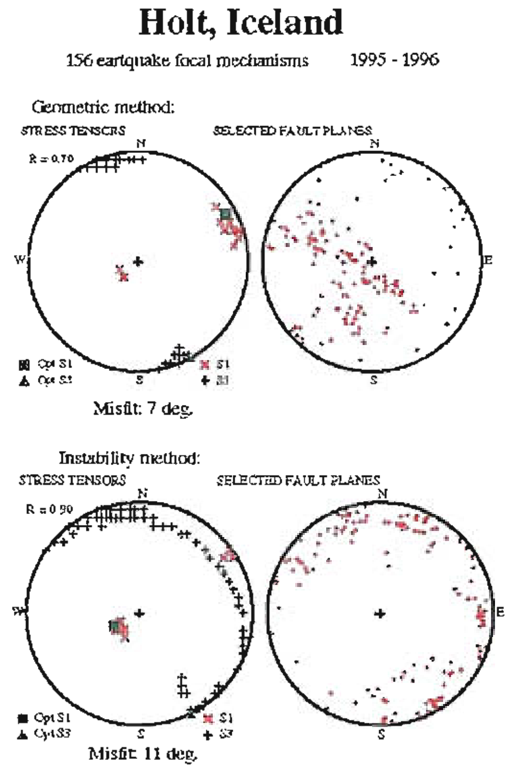

Figure 6: *An example of applications of the two methods of Figure 5 to real microearthquake data. Both methods gives two quite different optima with maximum principal direction either vertical or horizontal. The main difference is again in the uncertainty and in the choice of fault planes. The purely geometrical method chooses a large number of sub–horizontal planes although the optimum stress tensor indicates strike–slip stress conditions.*

in the SIL area. The results show a very good agreement with the automatic fault plane solutions produced by the SIL system. This paper will be submitted for publication during 1996 or early 1997. Work on this task was started earlier than planned because Tasks 2 and 5 are delayed due to the delay of the refined SIL database. Further work on this task is planned through out the project period.

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

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

Work on this task will commence soon, i.e. when the refined SIL database is available.

3.2.6 Task 6: Development of a method for acquisition of continuous GPS data through the SIL system

Start: May 1996 (month 3)
Estimated end: May 1997 (month 15)
Responsible partners: UUPP.DGEO, NVI
Cooperative partner: IMOR.DG

The software for transferring GPS data to the center in Reykjavík has been completed. We have had difficulties in getting information about software and/or software protocols for the Trimble 4000 GPS instruments. We have been trying to use DOS software from Trimble running under a DOS emulator for Interactive Unix, which is the operating system used at the stations. This has not succeeded as yet. So there is no continuous GPS data recording as by now. The plan now is to install Solaris operating system on the computers at the selected sites to be able to run the Trimble software. The SIL Utility Software has been compiled for Solaris. As soon as the IMOR.DG can install Solaris on this sites the operation can be started.

3.2.7 Publications

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[2] Bödvarsson, R., S.Th. Rögnvaldsson & R. Slunga 1996. Waveform correlation as a tool for automatic phase picking. In: Abstracts from the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. Icelandic Meteorological Office, Ministry for the Environment, University of Iceland.
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3.3 Subproject 3: Monitoring stress changes before earthquakes using seismic shear–wave splitting

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In June 1996 (month 4), Helen J. Rowlands, who had just completed her Ph.D. thesis on shear–wave splitting above microearthquakes, was hired as a researcher to work part–time on PRENLAB subproject 3.

3.3.1 Task 1: Identify optimal stations and search for precursors

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

Work on this task began in June 1996 (month 4) with the appointment of a researcher. This task is ongoing throughout this first year.

The World Wide Web is being used to access seismic data from the SIL seismic network. Seismicity maps (Figure 7) demonstrate that there are a number of stations sited over sufficient seismicity for analysis of shear–wave splitting to be viable. Shear–wave splitting is observed (Figure 8), but sometimes displays unusually large time-delays which may be caused by high temperatures and/or high pore-fluid pressures both of which may well be present in the upper crust in the Iceland.

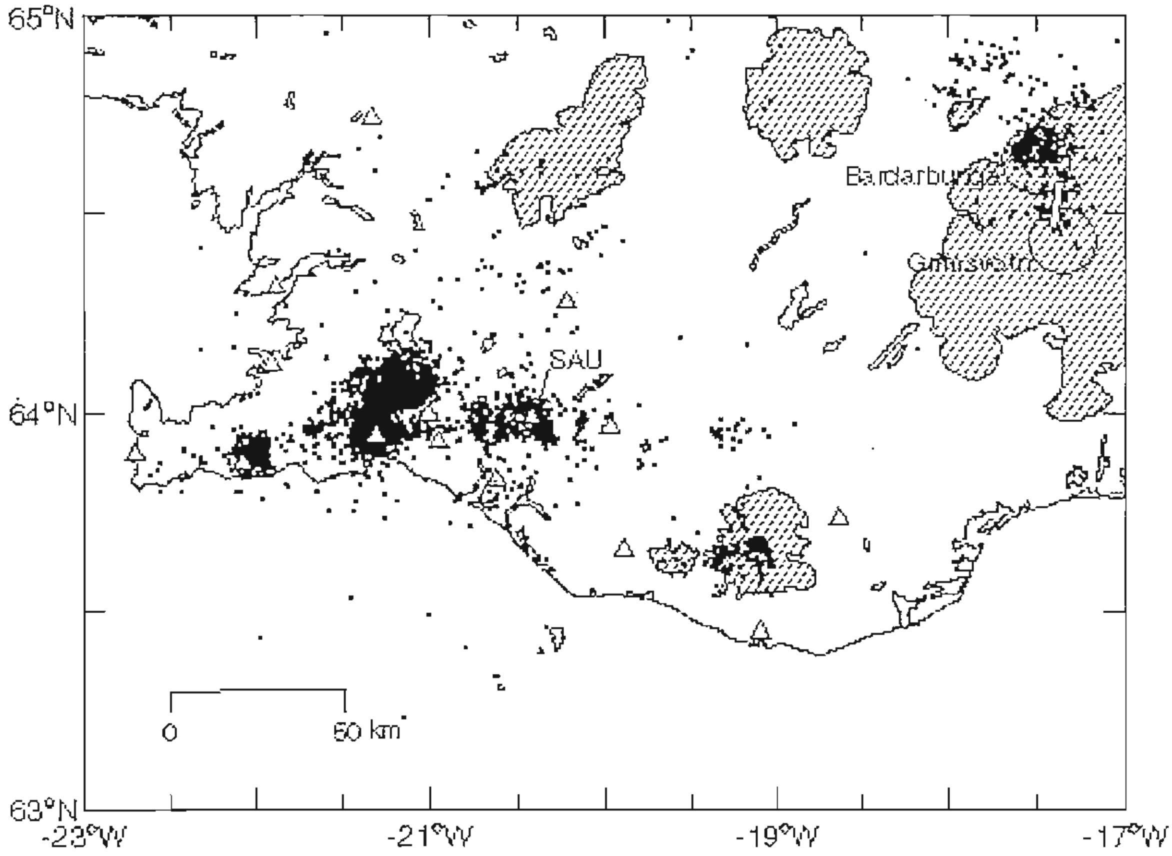

Figure 7: *Map showing seismic station SAU, volcanoes Bárdarbunga and Grímsvötn, and epicenters of earthquakes for 210 days from May 1, 1996. Triangles are seismic stations, ice fields are shaded, and open bar marks approximate location of fissure eruption.*

The remarkable observations are that the first 200 days of the first SIL seismic station we examined SAU showed variations in shear–wave splitting similar to those observed before and after earthquakes. Such behaviour can be interpreted (and numerically modelled) as the effects of increasing stress on the stress–aligned intergranular microcracks present in almost all rocks. These variations at SAU were reported at the internal PRENLAB meeting in Reykjavík, September 10, 1996, but since this was the first data we had analyzed from SIL, we were not too confident of the interpretation. In fact, SAU is about 160 km WSW of the eruption on September 30, 1996, beneath the Vatnajökull ice cap (Figure 7). Figure 9 shows the different behaviour of shear–wave splitting between ray path directions 0°–15° and 15°–45° to stress directions (the 15°–45° directions are sensitive to increasing stress). It is suggested that the changes in shear–wave splitting at SAU were the result of increasing pressure as magma was injected into the lower crust for some five months before the eventual eruption. A paper for submission to *Geophys. Res. Lett.* (Crampin et al. 1997) is being prepared.

The observed variations at SAU are a demonstration that shear–wave splitting is a sensi-

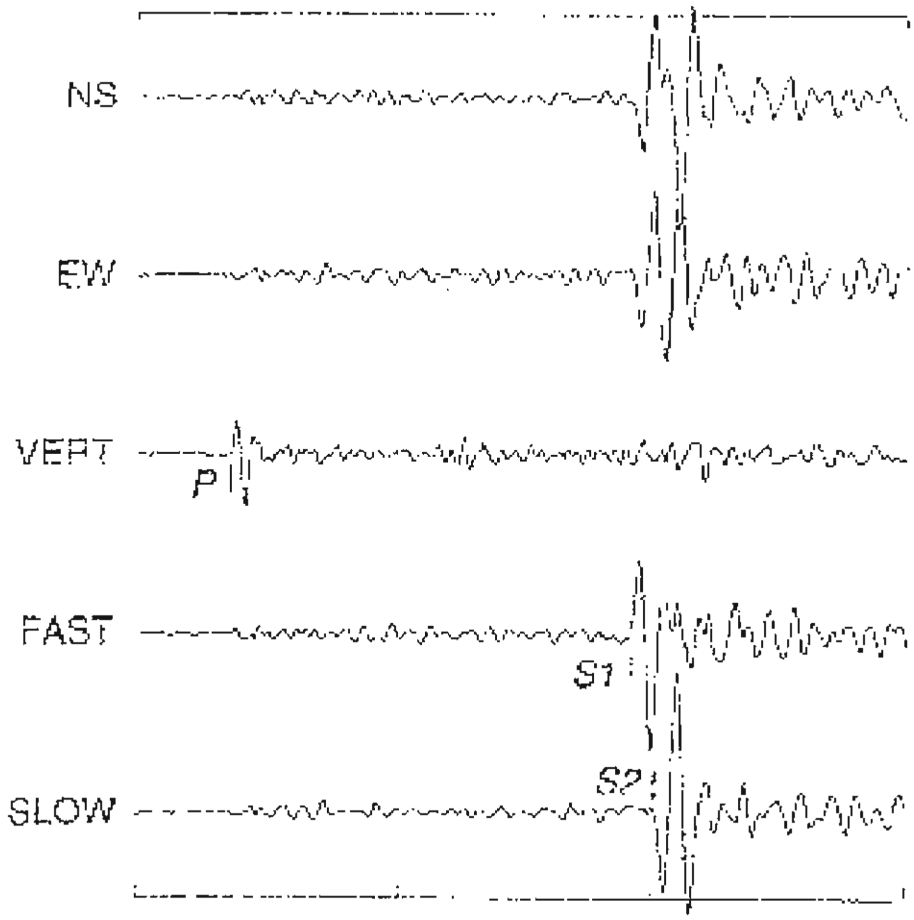

Figure 8: *Three-component seismograms of an earthquake (at 07:28:30.4, June 10, 1996) at SAU with time marks are every second. Upper traces are N–S, E–W, and vertical components. The lower traces are horizontal components rotated to the faster (N225° E) and slower (N315° E) shear-wave polarizations show time-delays beteen split shear-waves.*

tive monitor of current stress changes, and does not depend on the complicated interactions in earthquake preparation zones. It is very encouraging to see the effect of changes so early in the project.

- They confirm that shear–wave splitting has the potential for monitoring the detailed stress behaviour in Iceland.
- They confirm that Iceland is an active natural laboratory for research on earthquake source zones and volcanic manifestations.
- They suggest a number of new projects, to improve stress–monitoring of the crust beneath Iceland.

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[1] Crampin, S., H.J. Rowlands & R. Stefánsson 1996. Monitoring stress during magma injection. *Geophys. Res. Lett.*, submitted.

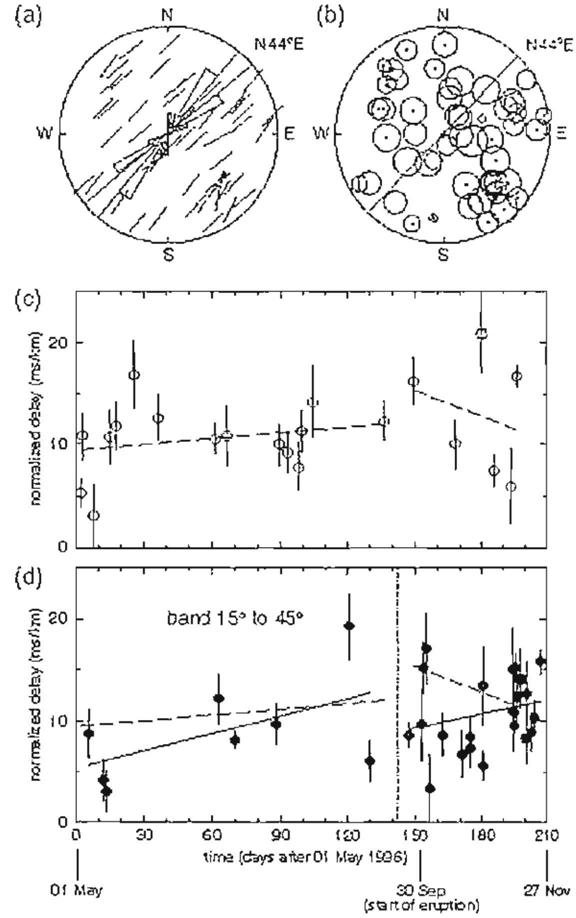

Figure 9: *Variations of shear-wave splitting at SAU for 210 days from May 1, 1996. Polar equal-area maps out to 45° of (a) shear-wave polarizations, with rose diagram indicating average direction, and (b) circles scaled to normalized time-delays (ms/km), where central dots indicate ray paths in the 15° to 45° bands. Variation with time of normalized time-delays for (c) ray paths in bands with incidence 0° to 15° to the crack face (sensitive to crack density), and for (d) ray paths in bands with incidence 15° to 45° to the crack face (sensitive to aspect-ratio). Lines are least-squares fits before and after the eruption. Dashed lines in (d) repeat lines in (c). Error bars are approximate.*

3.3.2 Task 2: Station/EQ relationship

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

Further research into the precursory sequence we have observed at SAU and more thorough investigations at other stations.

3.3.3 Task 3: Developing routine techniques

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

We will begin to develop routine techniques that can be used for real-time monitoring of splitting parameters in Iceland.

3.3.4 Task 4: Identify optimum areas

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

The work of Tasks 1, 2 and 3 will allow the identification of suitable areas for deployment of more closely spaced SIL stations, for more effective studies of precursory changes.

3.3.5 Meetings and conferences

PRENLAB contractor meetings:

> Reykjavík, September 10 and 12, 1996. Attended by Stuart Crampin.
> Strasbourg, March 25, 1997. Attended by Stuart Crampin and Helen J. Rowlands.

Symposia with presentations with direct or indirect references to PRENLAB work:

> XXV ESC General Assembly, Reykjavík, September 9–14, 1996. Stuart Crampin, 2 papers.
> Earthquake Research in Ankara, September 30–October 5, 1996. Stuart Crampin, 2 papers.
> Assessment of schemes for earthquake prediction, Geological Society, London, November 7–8, 1996. Stuart Crampin, 1 paper.
> Ninth biennial EUG meeting, Strasbourg, March 23-27, 1996. Stuart Crampin 1 paper, Helen J. Rowlands 1 paper.

3.3.6 Publications

[1] Crampin, S., H.J. Rowlands & R. Stefánsson 1996. Monitoring stress during magma injection. *Geophys. Res. Lett.*, submitted.

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[9] Crampin, S. 1996. Earthquake prediction and earthquake forecasting. In: Abstracts from Earthquake Research in Turkey: State of the Art, September 30–October 5, 1996, Ankara.

[10] Crampin, S. & S.V. Zatsepin 1996c. Opportunities for earthquake forecasting. In: Abstracts from Earthquake Research in Turkey: State of the Art, September 30–October 5, 1996, Ankara.

[11] Crampin, S. & S.V. Zatsepin 1996d. Forecasting earthquakes with APE. In: Abstracts from the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. Icelandic Meteorological Office, Ministry for the Environment, University of Iceland.

[12] Zatsepin, S.V. & S. Crampin 1996. Modelling rockmass deformation with APE: a mechanism for monitoring earthquake preparation zones with seismic shear-waves. In: Abstracts from the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. Icelandic Meteorological Office, Ministry for the Environment, University of Iceland.

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[14] Crampin, S. & S.V. Zatsepin 1997d. Forecasting earthquakes. In: Abstracts from the ninth biennial EUG meeting, March 23–27, 1997, Strasbourg.

[15] Rowlands, H.J., S. Crampin & R. Stefánsson 1997. Forecasting eruptions. In: Abstracts from the ninth biennial EUG meeting, March 23–27, 1997, Strasbourg.

3.4 Subproject 4: Borehole monitoring of fluid–rock interaction

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3.4.1 Subproject 4A: Geophysical loggings

Contractor:

Frank Roth

Subcontractor:

Valgardur Stefánsson

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

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

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

This is achieved by repeated logging with tools as:

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

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

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

During winter and spring 1996, the BCS, DIL and neutron tools were checked for azimuthal isotropy in their sensitivity, as it cannot be guaranteed that the tools follow the same spiral path through the well in each log run.

3.4.1.1 Task 1: Check of borehole conditions

Start: April 1996 (month 2)
End: June 1996 (month 4)
Responsible partner: GFZ.DR.DBL

Between April and June, OS checked the condition of the borehole selected for repeated logging – at first this was well NG–01 –, organized and supervised cleaning of the drillhole, and also arranged the opportunity to log in other wells on Iceland.
The data of the selected borehole are:

Borehole:	LL–03 at Nefsholt, South Iceland Lowland, inside the South Iceland seismic zone, provided from OS
Drilled:	1977
Position:	63.92°N, 20.41°W
Depth:	1108 m (originally drilled down to 1309 m)
Casing:	0–28 m, 12.5" diameter
Uncased:	28–1108 m, 8.5" diameter
Used section:	80–1108 m, i.e. 1028 m with basaltic lava flows and interbedded hyloclast (tuff)
Mud density:	1.0 kg/dm^3 (water)
Max. temperature:	105°C

3.4.1.2 Task 2: Basic measurements, choise of future logging interval (300–600 m)

Start: July 1996 (month 5)
End: October 1996 (month 8)
Responsible partner: GFZ.DR.DBL

Two field campaigns took place in July 1996, a third in October 1996. Moreover, additional logs could be run by us in July 1996 in 5 other boreholes on Iceland to add new information to previous results on the regional stress field. The following table and Figure 10 give an overview on the logging activities:

Name:	Location:	Max. depth:	Logged depth interval:	Tools used:
NG-01	Ólafsvellir (inside SISZ)	1070 m	180–1070 m	FED, GR, 3-arm-caliper, 16"- and 64"-resistivity, SP
HS-36	Reykjavík	980 m	330–980 m	BHTV, BCS, GR
LPN-10	Laugaland near Akureyri, North Iceland	890 m	80–880 m	BHTV, BCS, DIL, GR
LJ-08	Sydra Laugaland near Akureyri	2740 m	120–1890 m 120–1330 m	FED, BCS, DIL, GR BHTV
TN-02	Ytri-Tjarnir near Akureyri	1370 m	260–1370 m	BCS, GR
LL-03	Nefsholt (inside SISZ, site of repeated logging)	1309 m	80–1100 m	BHVT, BCS, DIL, GR, neutron–neutron, X–Y–caliper, SP, 16"- and 64"-resistivity

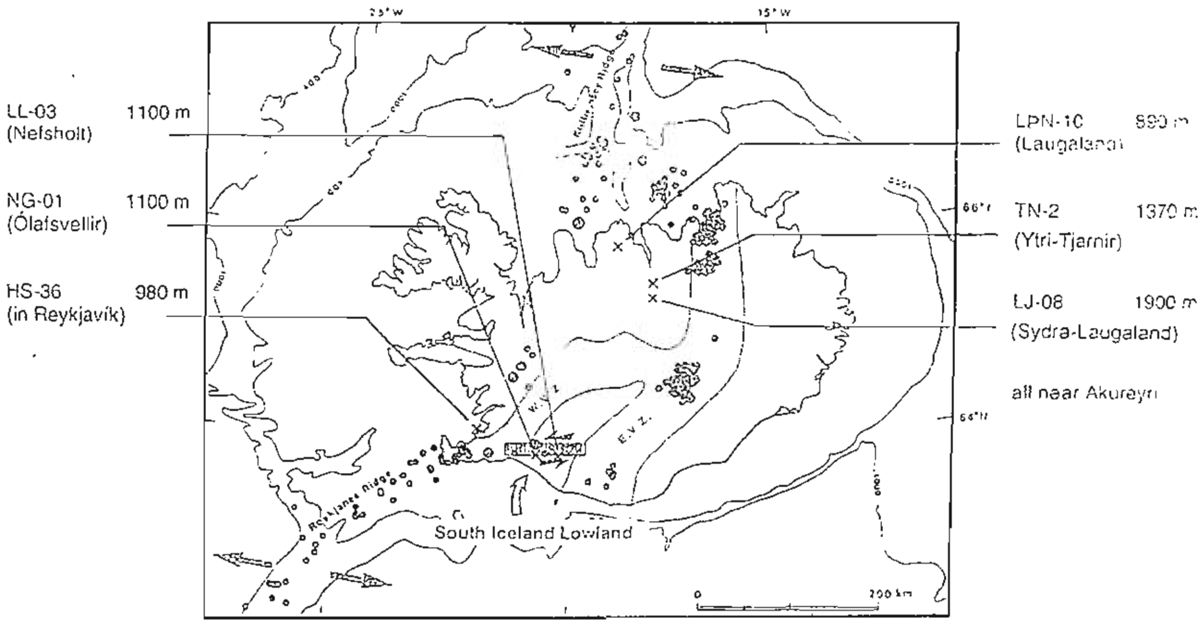

Figure 10: *Iceland, the Mid-Atlantic Ridge and the western and eastern volcanic zones. The hatched area denotes the South Iceland seismic zone, dots indicate earthquakes, crosses give the position of the boreholes where logging was performed. Left and right of the figure, names of the boreholes and maximum logging depth are displayed.*

Remarks: GR indicates gamma–ray–log, SP stands for spontaneous potential. As borehole NG–01 partly collapsed between log runs, the hole was abandoned and well LL–03 was chosen for repeated logging. For technical reasons, no FED run was possible in LL–03, no BHTV run was possible in LJ–08 below 1330 m depth. Due to the limited availability of a crane, no BHTV or FED run were possible in TN–02. The deepest parts of wells LJ–08 and LL–03 were not accessible anymore.

3.4.1.3 Task 3: Check for changes

Start: July 1996 (month 5)
End: October 1996 (month 8)
Responsible partner: GFZ.DR.DBL

See Task 2.

3.4.1.4 Task 4: Check for changes

Start: September 1997 (month 17)
End: September 1997 (month 17)

Responsible partner: GFZ.DR.DBL

Task 4 are to follow in 1997.

3.4.1.5 Task 5: Evaluation of measuring results

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

The processing of the data has begun, especially since January, when K. Henneberg, a very qualified scientist could be hired for the project. All logs add up to about 46 km logged intervals. This is due to the number of holes, the number of tools used, the number of repetitions of logs in LL–03 and the fact that in LL–03 several logs of the same kind were performed immediately one after the other. The latter is done to get information on the scattering of data in short time periods during which no changes due to tectonic processes are expected to have occurred.

The preprocessing of the data, especially merging of segments and depth matching, is done for all data. All BHTV data were converted and are being plotted.

Boreholes drilled vertically into isotropic rock – in a stress–regime with one principal stress acting vertically – are expected to show breakouts in the direction of the least principal horizontal stress, if the tangential compressional stress exceeds the strength of the rock. This is due to the concentration of circumferential stress around the borehole at an azimuth of 90 degrees to the direction of the maximum horizontal compressive stress. The most important of our data to get information about the orientation of the axes of principal stresses are those from televiewer logs. Televiewer logs run directly one after the other show very little scattering of data and thus a good repeatability.

Wellbore breakouts were found in LL–03 and LJ–08 at least. In NG–01, there are sections with cavities, where the large diameter indicates a breakout, but the small diameter does not have bitsize. This has to be checked more carefully to decide whether these cavities may be considered as breakouts induced by anisotropy in tectonic stresses.

Data examples of the televiewer logs run in boreholes LL–03 and LJ–08 in July are shown in Figure 11 and Figure 12. The left parts represent the amplitude of the signal reflected from the borehole wall in arbitrary units ranging from low (dark blue) to high (red) values. The right columns show travel times of the ultrasonic waves converted into the radius of the borehole in centimeters. In both presentations, the borehole wall is unwrapped from north over east to north.

In well LL–03 a series of breakouts occurs in the depth interval between 955 m and 985 m, the main breakout directions being N40°E and 220°E (Figure 13). Some further breakouts are observable between 780 m and 870 m depth as well as around a depth of 1060 m. These breakouts occurred in approximately the same direction as those shown in the data example.

In well LJ–08 breakouts have been found at an azimuth of N110°E (complementary at 290°E) but could only be observed over a depth interval of about 6 m.

Following the theory of breakout–inititation, the results imply an azimuth of the maximum horizontal compressive stress of about 130°E in the South Iceland seismic zone (LL–03)

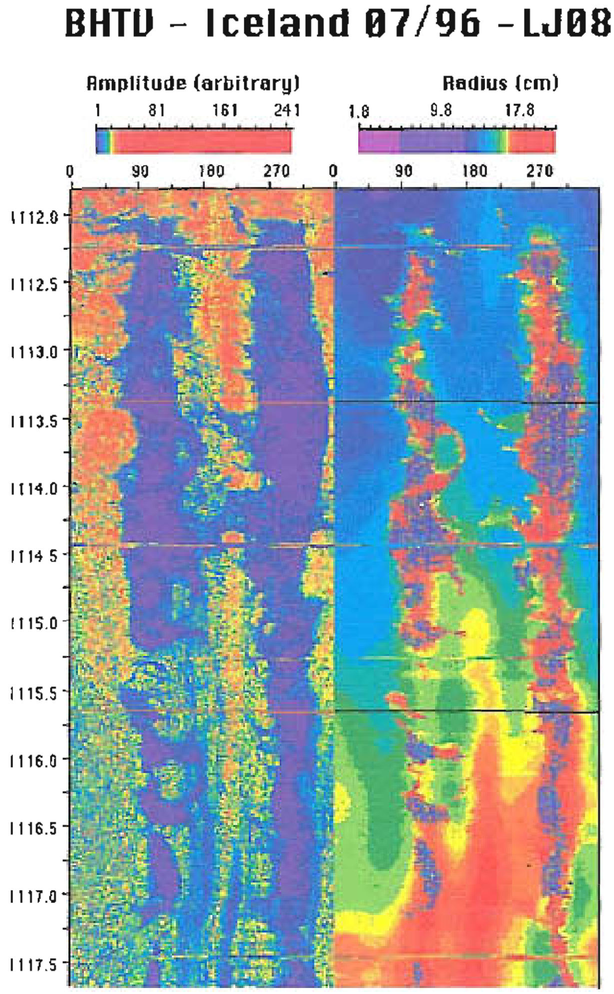

Figure 11: *Televiewer logs run in borehole LJ-08.*

and an azimuth of about 200°E for the location of well LJ-08 (Tjarnir) in the northern part of Iceland west of the axial rift zone. Both breakout-deduced orientations of the maximum horizontal compressive stress seem to be in contrast to the stress field obtained from focal mechanisms as well as to the gross tectonic setting of these areas. This requires a detailed study of the complicated regional stress fields which are influenced by rifting and the fracture zones connecting the ridge to the eastern volcanic zone.

An obvious change of breakout direction or shape between the logging campaigns performed in July an October 1996 could not be observed so far. This might be due to the short time interval between the campaigns as well as to the lack of a strong tectonic event in this area within these three months. This emphasizes the necessity of further measurements which are planned for this year.

Processing of other logging data (BCS, DIL, FED and neutron-log) are going on. It should be finished by the end of July, after which further logging campaigns will take place.

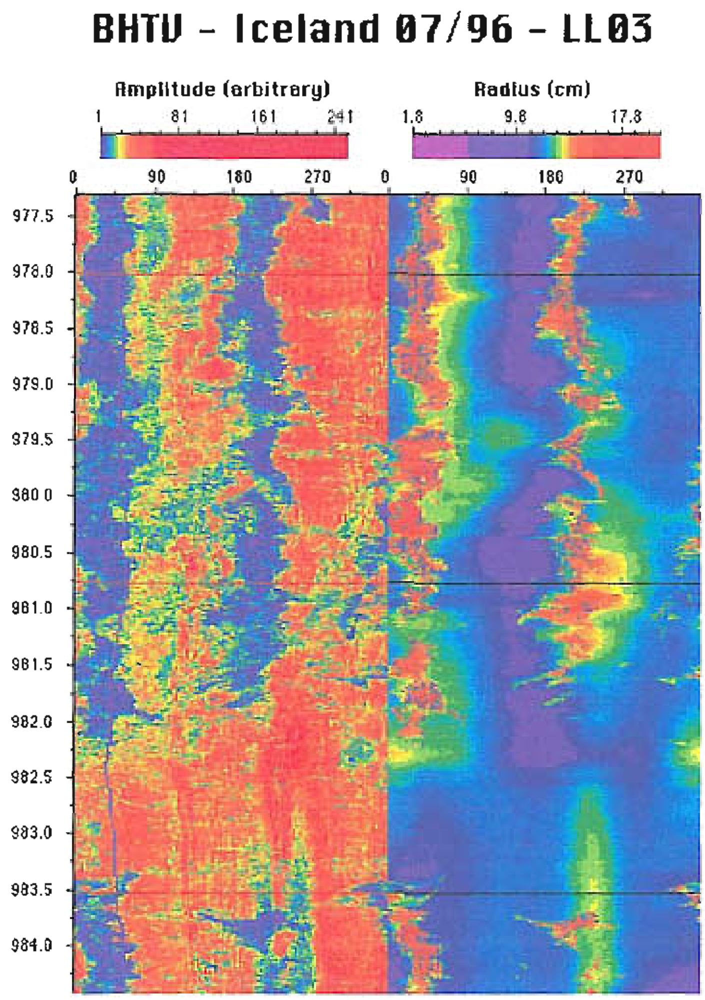

Figure 12: *Televiewer logs run in borehole LL-03.*

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

3.4.1.6 Publications

[1] Roth, F. 1997. Vorstellung des Projektes zu Wiederholungsmessungen in einer Bohrung im Südisländischen Seismizitätsgebiet. Special issue on borehole geophysics of Deutsche Geophysikalische Gesellschaft, submitted.

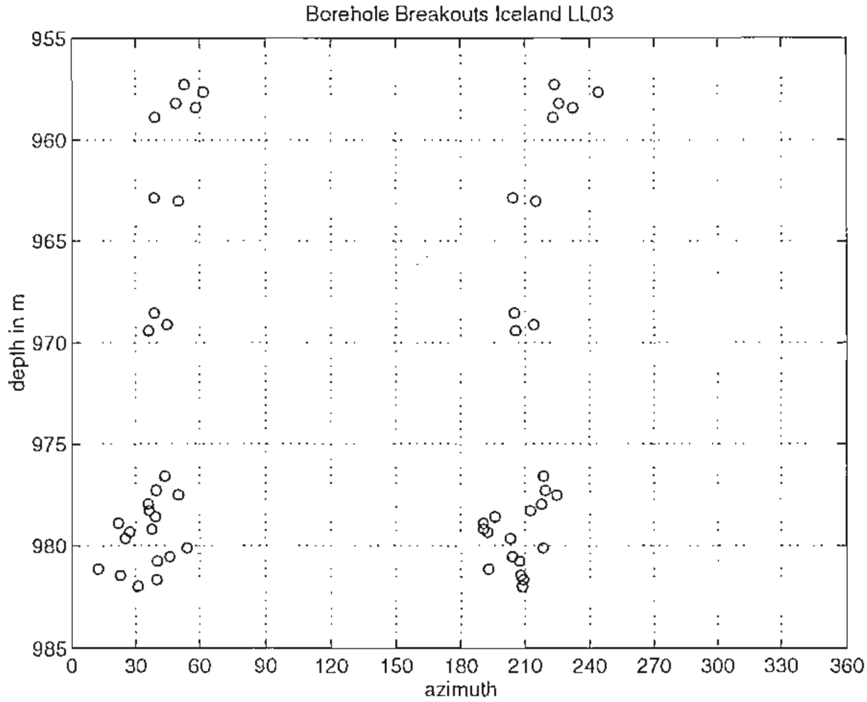

Figure 13: *Azimuths of the picked breakouts in well LL-03.*

3.4.1.7 Meetings

Meetings of Valgardur Stefánsson with Frank Roth took place in April and September 1996 in Reykjavík, and in September 1996 in Potsdam.

Meetings of Páll Einarsson with Valgardur Stefánsson and Frank Roth took place in April and September 1996 in Reykjavík.

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

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

Start: March 1996 (month 1)
End: April 1997 (month 14)
Responsible partner: UICE.DG

This task is at a final stage, and can be finalized within a month when funds have been secured for using it, i.e. for Task 2.

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

Start: April 1997 (month 14)
End: Februar 1998 (month 24)
Responsible partner: UICE.DG

The start of Task 2 has been delayed, it is hoped that it can get started in beginning of May, i.e. 9 months later than planned.

Additional sources of funding were needed to reach these goals. However, conditions changed after the signature of the contract, so the expected additional funds were not available. Attempts to obtain these additional funds are in a final stage and it is hoped that realization of Task 1 and Task 2 can start within a month. No EC funds have been spent on these tasks so far. Effort has been made, however, to strengthen the foundation of the radon project. This work has concentrated on two issues:

- Investigate further the different technical problems regarding the proposed Liquid Scintillation Counting apparatus. This development has been reported at conferences and in a recent book on weak radioactivity by Páll Theodórsson (1996b).
- Investigate the 17 years long radon time series from the South Iceland seismic zone. The results have been reported at conferences by Páll Einarsson and Sigurjón Jónsson.

The main results are as follows:

- Of all anomalies that could be expected from the magnitude-distance selection criterion, 24% were actually detected.
- 35% of all measured anomalies are related in time to seismicity.
- 80% of earthquake related anomalies are positive.
- If a positive anomaly is detected, there is 38% probability of an earthquake following it.
- Anomalies were detected before 30 events out of 98 possible events. There is thus 31% probability of a measured anomaly before an earthquake, that fulfills the magnitude-distance criterion.
- For most of the events the associated radon anomaly was detected at one station only. Five events were preceded by anomalies detected at two stations, one event at three stations, and one event at five stations.
- The sampling sites are not equally sensitive. The sensitivity is related to the local geological formations. The statistics can be improved considerably by eliminating stations with low sensitivity.

- Radon anomalies were detected that seem to be related to eruptions of the neighbouring Hekla volcano. Eight anomalies were found, five of which occurred prior to the eruptions.

3.4.2.3 Publications

[1] Jónsson, S. & P. Einarsson 1994a. Radon anomalies and earthquakes in South Iceland. In: Abstracts from the poster display at the annual conference of the Icelandic Geoscience Society, Reykjavík, April 21, 1994. In Icelandic.
[2] Jónsson, S. & P. Einarsson 1994b. Radon anomalies and earthquakes in South Iceland. In: Abstracts from the poster display at a public meeting in the South Iceland seismic zone, Selfoss, April 30, 1994, Icelandic Civil Defence. In Icelandic.
[3] Jónsson, S. & P. Einarsson 1994c. Radon anomalies and earthquakes in South Iceland. In: Abstracts from the poster display at the European School of Climatology and Natural Hazards, Mitigation of Volcanic Hazards, Vulcano, Italy, June 12–18, 1994.
[4] Jónsson, S. & P. Einarsson 1995. Radon anomalies and earthquakes in the South Iceland seismic zone 1977–1993. In: Abstracts from the XXI IUGG General Assembly, Boulder, Colorado, July 2–14, 1995.
[5] Jónsson, S. & P. Einarsson 1996. Radon anomalies and earthquakes in the South Iceland seismic zone 1977–1993. In: B. Thorkelsson (editor), *Seismology in Europe.* Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, Reykjavík, 247–252.
[6] Theodórsson, P. 1996a. Improved automatic radon monitoring in ground water. In: B. Thorkelsson (editor), *Seismology in Europe.* Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, Reykjavík, 253–257.
[7] Theodórsson, P. 1996b. Measurement of weak radioactivity. World Scientific Publishing Co., Singapore, 333 p.

3.5 Subproject 5: Active deformation determined from GPS and SAR

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

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

3.5.1 Subpart 5A: SAR interferometry

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

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

Kurt L. Feigl, Sigurjón Jónsson, Páll Einarsson and Helene Vadon

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

3.5.2 Subpart 5B: GPS geodesy

3.5.2.1 Task 1: Installation

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

Freysteinn Sigmundsson and Reynir Bödvarsson

The GPS geodesy project is still in its first phase, the planned installation of 3 GPS receivers in a semi-continuous mode in the South Iceland seismic zone has not been completed. Automatic GPS data collection with the 3 available Trimble 4000 SST instruments has been tested, and work has been done to automate the data analysis. Although continuous GPS has not been realized yet, an interpretation of older GPS measurments in the Hengill area has shed light on the 1994-1995 swarm of earthquakes there. A paper on the subject has been submitted to JGR, and these new results were presented at the EGS General Assembly in The Hague in May 1996.

The semi-continuous GPS measurements are still in its first phase, the planned installation of 3 GPS receivers in a semi-continuous mode in the South Iceland seismic zone has not been completed. Automatic GPS data collection with the 3 available Trimble 4000 SST instruments has been tested, and work has been done to automate the data analysis. We plan to initiate the measurements shortly.

3.5.2.2 Task 2: Deformation rates

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

Freysteinn Sigmundsson and Páll Einarsson

Since July 1994 an unusually persistent swarm of earthquakes ($M \leq 4.0$) has been in progress at the Hengill triple junction, SW–Iceland. Activity is clustered around the center of the Hrómundartindur volcanic system. Geodetic measurements indicate a few cm uplift and expansion of the area, consistent with a pressure source at 6.5 ± 3 km depth beneath the center of the volcanic system. The system is within the stress field of the South Iceland transform zone, and majority of the recorded earthquakes represent strike-slip faulting on subvertical planes. We show that the secondary effects of a pressure source, modelled as a point source in an elastic halfspace, include horizontal shear that perturbs the regional stress. Near the surface, shear stress is enhanced in quadrants around the direction of maximum regional horizontal stress, and diminished in quadrants around the direction of minimum regional stress. The recorded earthquakes show spatial correlation with areas of enhanced shear. The maximum amount of shear near the surface caused by the expanding pressure source exceeds 1 millistrain, sufficient to trigger earthquakes if the crust in the area was previously close to failure.

3.5.2.3 Publications

[1] Vadon, H. & F. Sigmundsson 1997. Crustal deformation from 1992 to 1995 at the Mid-Atlantic Ridge, SW-Iceland, mapped by satellite radar interferometry. *Science* 275, 193–197.

[2] Sigmundsson, F., P. Einarsson, S.Th. Rögnvaldsson, G.R. Foulger, K.M. Hodgkinson & G. Thorbergsson 1996. 1994–1995 seismicity and deformation at the Hengill triple junction, Iceland: triggering of earthquakes by a small magma injection in a zone of horizontal shear stress. *J. Geophys. Res.*, in review.

[3] Vadon, H. & F. Sigmundsson 1996. Plate movements and volcano deformation from satellite radar interferometry: 1992–1995 crustal deformation at the Mid-Atlantic Ridge, SW-Iceland. In: Abstracts from the AGU 1996 fall meeting, San Francisco, December 15–19, 1996.

[4] Sigmundsson, F. & H. Vadon 1996. Oblique spreading at the Mid-Atlantic Ridge, SW-Iceland: 3D crustal velocity field inferred from satellite radar interferometry and geologic evidence. In: Abstracts from the AGU 1996 fall meeting, San Francisco, December 15–19, 1996.

[5] Sigmundsson, F. 1996. Inversion of geodetic data from Hengill triple junction, Iceland: rift subsidence and volcano inflation. In: *Annales Geophysicae*. Abstracts from the XXI EGS General Assembly, The Hague, May 6–10, 1996, Supplement I to vol. 14.

[6] Sigmundsson, F., P. Einarsson, S.Th. Rögnvaldsson, G. Foulger & G. Thorbergsson 1996. 1994–1995 earthquake swarm at Hengill triple junction, Iceland: Triggering of earthquakes by an inflating magma chamber in a zone of horizontal shear stress? In: *Annales Geophysicae*. Abstracts from the XXI EGS General Assembly, The Hague, May 6–10, 1996, Supplement I to vol. 14.

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

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

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

Thierry Villemin also has student working on the project, but no salary from the project has been paid to that student.

According to this overview, all the tasks are on schedule.

3.6.1 Subproject 6A: Paleostresses

3.6.1.1 Task 1: Determine the paleostress tensor

Start: July 1996 (month 5)
Expected end: September 1997 (month 19)
Responsible partner: CNRS.TT
Cooperative partners: NVI, IMOR.DG

Francoise Bergerat and Jacques Angelier

The paleostress tensors for many localities in the South Iceland seismic zone have been made, using fault–slip datasets. Preliminary studies of the paleostress field of the whole SISZ have already started. Work on Tjörnes fracture zone (TFZ) will be carried out mainly next summer, but some paleostress tensors for this zone have already been calculated. This task is in collaboration with Ágúst Gudmundsson and Sigurður Th. Rögnvaldsson and is on schedule.

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

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

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

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

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

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

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

Field studies have been carried out in September 1996 in the SISZ in order to collect fault slip data measurements. The collection has been made in some selected sites in late Tertiary and Pleistocene lavas and hyaloclastites and in postglacial lavas. The areas investigated were the Skardsfjall, Hestfjall and Búrfell mountains, the Grímsnes area and the canyons of Stóra Laxá and Stóra Mástunga. The measurements are now being analyzed in terms of stress tensors. The study will be completed in the next few months by analysis of focal mechanisms of earthquakes in the same areas.

3.6.1.1.3 *Stress tensor determination from focal mechanisms: development of new methodology*

New methods, especially aiming at solving the problem of the choice between nodal planes for each datum within a set of focal mechanisms of earthquakes, are in preparation. Such a methodology will be of particular interest in the SISZ, where large numbers of data are available, as well as accurate relocations of earthquakes by IMOR.DG.

The techniques being presently prepared give more weight to analytical resolution of the system of equations involved in the inverse problem, relative to the numerical procedures. As a preliminary case study, the Vördufell analysis mentioned above provides a good example for methodological evaluation, in addition to its intrinsic seismotectonic interest.

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

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

Francoise Bergerat and Jacques Angelier

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

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

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

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

N030° and N100°. The tilt of the blocks was used to estimate the stretching accommodated by the block rotations.

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

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

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

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

3.6.1.3 Future prospects

In 1997, the selected areas of the SISZ will be studied in detail both in the field and for focal mechanisms of earthquakes. Some preliminary studies in the Tjörnes fracture zone will also be carried out (paleostress analyses, focal mechanisms of earthquakes).

3.6.1.4 Publications

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[2] Bergerat F., J. Angelier, O. Dauteuil & T. Villemin 1996. Present-day tension–shear

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[3] Angelier, J., S.Th. Rögnvaldsson, F. Bergerat, Á. Guðmundsson, S. Jakobsdóttir & R. Stefánsson 1996. Earthquake focal mechanisms and recent faulting: a seismotectonic analysis in the Vördufell area, South Iceland seismic zone. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 199–204.

[4] Angelier J., F. Bergerat, O. Dauteuil & T. Villemin 1996. Tension-shear relationships in extensional fissure swarms, axial rift of northeastern Iceland: morphological evidences. *J. Struct. Geology*, in press.

[5] Angelier J., S.Th. Rögnvaldsson, F. Bergerat & Á. Gudmundsson 1997. Earthquake focal mechanisms and regional stress: the seismotectonic behaviour of the South Iceland seismic zone revealed by the Vördufell earthquake activity. In: Abstracts from the ninth biennial EUG meeting, March 23–27, 1997, Strasbourg.

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

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

Start: July 1996 (month 5)
Expected end: February 1998 (month 24)
Responsible partner: NVI
Cooperative partners: IMOR DG, UUPP.DGEO

Field inspection of the faults in the SISZ was made in the summer of 1996. Detailed mapping of individual seismogenic faults in the Holocene lavas of the SISZ has already resulted in detailed maps of the Leirubakki–Svínhagi fault; other faults are currently being mapped. This work, which now includes considerations of fluid pressure effects and the relation of seismogenic faults to geothermal systems, is made in collaboration with Helgi Torfason, Icelandic Energy Authority.

Some maps of the TFZ have already been made. The most detailed work, however, will be made next summer (1997) in collaboration with Thierry Villemin (see Task 5). This task is on schedule.

3.6.2.1.1 *The South Iceland seismic zone*

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

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

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

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

Work on the SISZ is in close collaboration with Jacques Angelier, Françoise Bergerat, Sigurdur Th. Rögnvaldsson and Helgi Torfason. A manuscript on the origin and tectonic evolution of the South Iceland seismic zone is near to being completed.

3.6.2.1.2 *The Tjörnes fracture zone*

Work is in progress on combining field and numerical studies with seismic studies from the extension of the SIL network in this area. A manuscript is in preparation, entitled: Seismotectonic analysis of the Tjörnes fracture zone, an active transform fault in North Iceland. The purpose of this paper is to combine a detailed seismic analysis by Sigurdur Th. Rögnvaldsson and Ragnar Slunga with on-land field studies of the faults in the Tjörnes fracture zone. Our conclusion is that many of the strike–slip faults in the Grímsey fault, as well as those associated with the Dalvík "lineament" are northerly trending sinistral faults rather than westerly trending dextral faults. We are working on numerical (boundary element) models with a view of explaining the current stress field in this area.

3.6.2.1.3 *Effects of fluid pressure on fault development*

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

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

3.6.2.2 Task 2: Boundary-element models of the faults

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

This work has alredy started and is carried out in collaboration with Maurizio Bonafede and Maria Elina Belardinelli, who use analytical methods. So far the work has focussed on the well-defined faults in the Holocene part of the SISZ. The work is on schedule.

3.6.2.2.1 *Analytical and numerical studies on fault populations*

Fault populations develop in space and time. Both analytical and numerical studies are important in order to be able to predict the evolution of fault populations, in particular those in the South Iceland seismic zone and in the Tjörnes fracture zone. Part of this work uses data from other fault areas in Iceland, such as the Borgarfjördur area where strike-slip faults are common. This work is made in collaboration with Maurizio Bonafede and Maria Elina Belardinelli.

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

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

General models have already been made and give very interesting results, particularly on the migration of seismicity in these zones. This work is in collaboration with Olivier Dauteuil, Jacques Angelier, Françoise Bergerat, Thierry Villemin and Sigurdur Th. Rögnvaldsson. This work is on schedule.

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

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

Olivier Dauteuil has already made analog models of transform faults in general and published recently in JGR. Dauteuil is now applying these models to the SISZ and the TFZ. This task is on schedule.

3.6.2.5 Task 5: Detailed tectonic map of the TFZ

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

Detailed tectonic map of TFZ. This work has already started and the main part will be made in the summer of 1997 in collaboration with Águst Gudmundsson and Freysteinn Sigmundsson. This work is on schedule.

3.6.2.5.1 *The Tjörnes fracture zone*
Part of the work on the Tjörnes fracture zone is made in collaboration with Thierry Villemin, particularly on the on–land parts of the Húsavík–Flatey fault. A detailed GPS network, set up by the NVI in 1994, was expanded in collaboration with Villemin in 1995. One objective of this work is to correlate the seismicity on the Húsavík–Flatey fault with the on–land slip of the fault, as measured by the GPS network. A paper was presented at the ninth biennial EUG meeting in Strasbourg on some of the results of this work.

3.6.2.6 Publications

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[2] Gudmundsson, Á. 1996b. Stress fields controlling strike–slip faulting in Iceland. *Physics and Chemistry of the Earth*, in press.
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Tensile fracturing in the earth's crust. Programme with abstracts. University College, London, Department of Geological Sciences, September 1996.
[5] Gudmundsson, Á., F. Bergerat, & J. Angelier 1997. Strike-slip faults in the central part of the South Iceland seismic zone. In: Abstracts from the ninth biennial EUG meeting, March 23–27, 1997, Strasbourg.
[6] Gudmundsson, Á. 1997. Origin and tectonic evolution of the South Iceland seismic zone. In preparation.
[7] Gudmundsson, Á. 1996e. Mid-ocean ridge processes in Iceland. In: *Annales Geophysicae*. Abstracts from the XXI EGS General Assembly, The Hague, May 6–10, 1996, Supplement I to vol. 14.
[8] Rögnvaldsson, S., Á. Gudmundsson & R. Slunga, 1997. Seismotectonic analysis of the Tjörnes fracture zone, an active transform fault in North Iceland. In preparation.
[9] Gudmundsson, Á. 1996f. Formation and development of fractures, with application to fluid flow in solid rocks. Lectures at the University of Bergen, October 1996.

3.7 Subproject 7: Theoretical analysis of faulting and earthquake processes

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

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Maria Elina Belardinelli is working 30% of her time in the project since March 1, 1996.
Maurizio Bonafede is working 20% of his time on the project since March 1, 1996.
Antonio Piersanti is working 30% of his time in the project since March 1, 1996.
Giorgio Spada is working 30% of his time in the project since March 1, 1996.

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

Start: March 1996 (month 1)
End: November 1996 (month 9)
Responsible partner: UBLG.DF
Cooperative partner: NVI

Maurizio Bonafede, Maria Elina Belardinelli and Ágúst Gudmundsson

The appearance of tension gashes at the earth surface, following an earthquake, can provide constraints on the regional stress field which produced the earthquake. Such fissures can be often observed when the seismic fault does not reach the surface and are called secondary earthquake fractures. This study is applied to the South Iceland seismic zone, located between the Reykjanes Ridge and the eastern volcanic zone, in South Iceland. This zone is characterized by N and NE trending arrays of en–enchelon tension fractures which are the most prominent surface features. The arrays are globally oriented in the direction of dextral

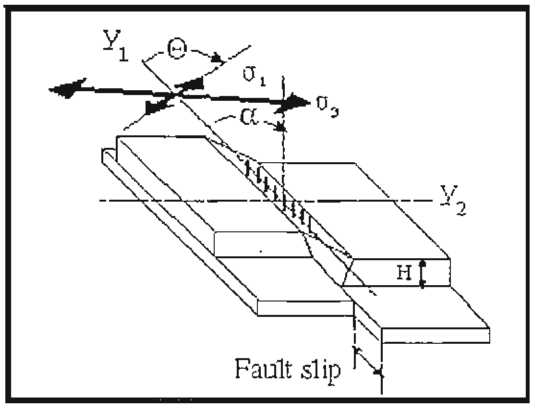

Figure 14:

strike–slip faults, buried under Holocene lava flows, but the orientations (α) of individual fissures generally deviate 10°–20° from the strike direction (Figure 14).

In order to understand the relationships between fissure arrays and the stress field producing them, the earthquake–induced stress field is computed by means of a dislocation model in a layered half-space and is superposed onto a regional stress field with principal axes σ_1 and σ_2 (Figure 15a).

The angle between the seismic fault and individual fissures cannot be less than 22.5°, if the latter open as pure tensile cracks, whatever the orientation (θ) of the regional stress field (Figure 15b). Fissure angles less than 22.5° can be explained if the fissures break at depth as shear cracks, with strike direction α' dictated by the Coulomb–Navier criterion (Figure 15c), and open in mixed tensile mode from the surface down to a few tens of meters, where the tensile stress produced by the earthquake overcomes the lithostatic pressure (Figure 16). Accordingly, the presence of open fissures striking a few degrees away from the direction inferred for the fault strike can be employed to draw inferences on the frictional regime prevailing in the brittle seismogenic layer and on the orientation and intensity of the regional stress field.

Compared to anticipated milestones in work program, the previous report is a contribution to Task 1. A more detailed description of the stress induced by strike–slip earthquakes in the near-field has been obtained employing crack models in which the stress drop on the fault is assigned instead of the slip vector. The inclusion of variable stress drop, compatible with frictional laws, surface layering and tectonic loading will be obtained in the next few months.

Preliminary results were presented at the Reykjavík meeting, further advancements have been presented at the GNGTS meeting in Rome, and at the ninth biennial EUG meeting in Strasbourg in March 1997. A paper is in preparation.

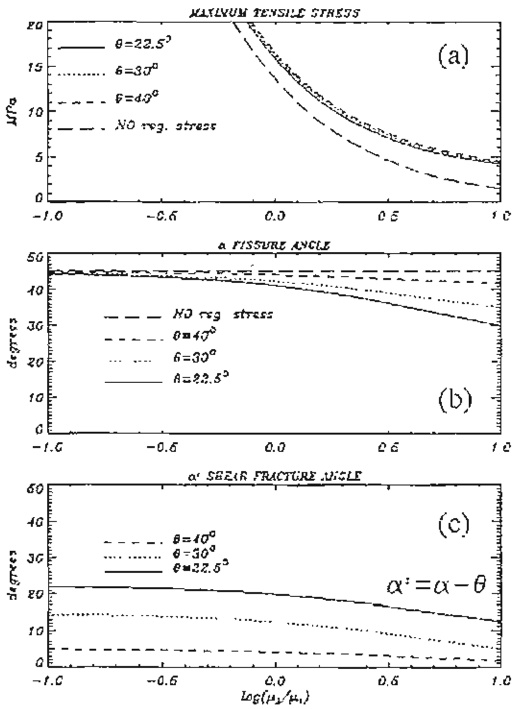

Figure 15:

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

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

Maurizio Bonafede, Antonio Piersanti and Giorgio Spada

In order to study the post–seismic rebound following large lithospheric earthquakes we have built a spherical, self-gravitating earth model with viscoelastic rheology (Piersanti et al. 1997). This model, which allows to compute coseismic and postseismic displacements associated to lithosperic earthquakes, is now employed to predict horizontal and vertical rates of deformations in Iceland. The results are compared with geodetic data in order to better constrain the rheological structure of the upper mantle beneath Iceland. Although motions associated with rift dynamics and postglacial adjustment are expected to contribute in a dominant way to present–day velocities in this area, new insights are expected from the application of our postseismic rebound model to Iceland. The solutions and algorithms developed under Task 2 are meant as working tools for finalizing Tasks 3 and 5.

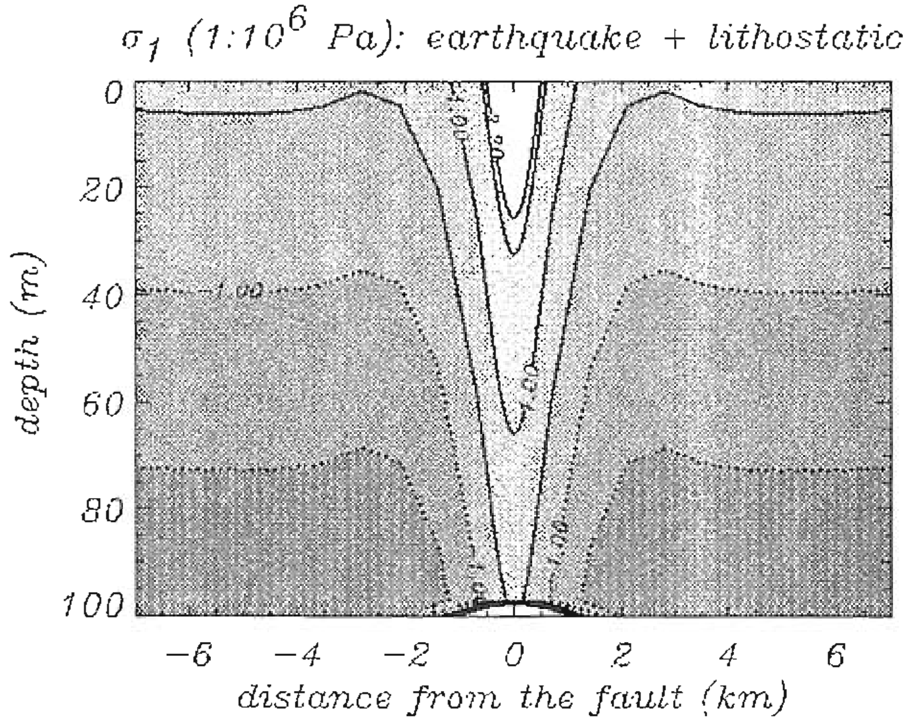

Figure 16:

References:

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

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

Andrea Antonioli, Maurizio Bonafede, Antonio Piersanti and Giorgio Spada

We have compared two different approaches to the study of post-seismic deformations. In the first one, we have considered a flat earth model forced by a vertical strike–slip fault embedded in an elastic lithosphere (Nur and Mavko 1974). In the second one, we have solved the same problem in spherical geometry, taking advantage of the results by Piersanti et al. (1997) (see 3.7.1.2). In both cases, we have computed the coseismic displacements and the delayed post-seismic displacements associated with the viscoelastic relaxation of a

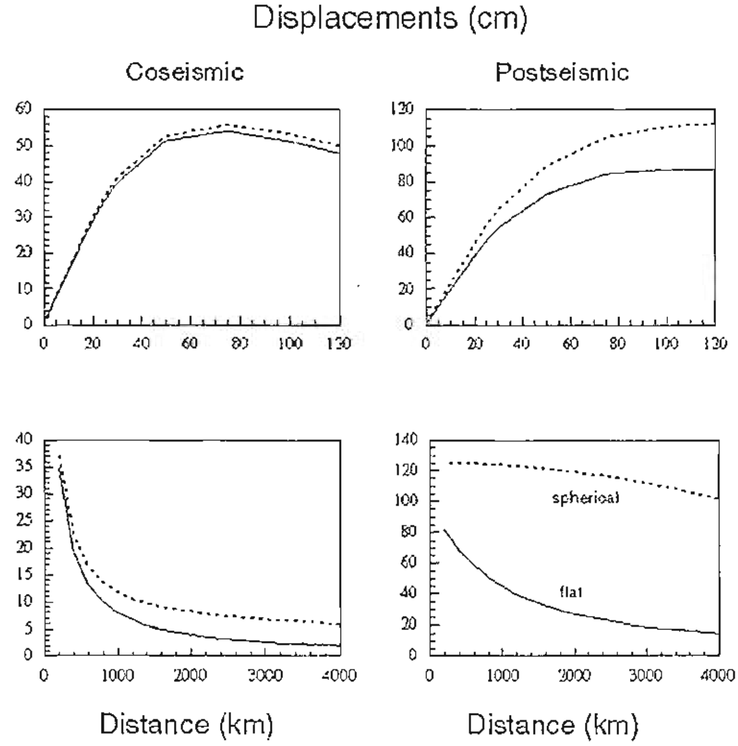

Figure 17:

uniform mantle.

In Figure 17 we compare coseismic (left) and postseismic (right) horizontal displacements computed according to the spherical model (dashed lines) with those predicted on the basis of the flat one (solid lines). The two top panels refer to moderate source-observer distances (i.e., 0<d<120 km), whereas the far-field responses are portrayed in the bottom panels, with 120<d<4000 km. In this case study we have employed a vertical strike-slip fault source of width W=50 km, which breaks the lithosphere-mantle boundary, located at a depth of 100 km. As expected, there is a close agreement between the two models in the coseismic regime for moderate source-observer distances (0<d<120 km, top left panel). In the postseismic regime (top, right) the spherical model predicts a displacement which sensibly differs from the one obtained by means of a flat model. Differences between spherical and flat models are particularly large in the far field (bottom panels).

An analysis similar to that performed in Figure 17 has also been carried out on the stress fields induced by a strike-slip earthquake. Significant corrections to both the time-evolution and the spatial pattern of the stress field have been found even at distances from the ridge much less than the radius of the earth. We have observed that stresses due to lithospheric earthquakes in a spherical earth decay slowly with increasing distance from the fault, in contrast with predictions based on flat models. We have also computed the time-evolution of the stress field for earth models including a realistic viscosity profile. We have found that mantle relaxation acts to increase the amount of stress in the lithosphere associated to a large earthquake. The spatio-temporal pattern of postseismic stress diffusion has been found to be strongly direction-dependent. The relaxation time which characterizes stress diffusion at large distances from the epicenter is mainly governed by the rheology of the asthenosphere.

The results of this study have been presented at the 1996 GNGTS meeting in Rome. They are contained in the dissertation by A. Antonioli 1995: Deformazione post-sismica globale: confronto fra modelli piani e sferici ed analisi del campo si sforzi generato da grandi eventi sismici, Thesis, University of Bologna, 82 p. Further results on the stress field were presented at the ninth biennial EUG meeting in Strasbourg (Antonioli, A., A. Piersanti, G. Spada & M. Bonafede 1997: Time-dependent stress field associated with rift dynamics, abstract). A paper entitled "Post-seismic deformations: a comparison between spherical and flat earth models and stress diffusion following large earthquakes" has been submitted to Geophysical Journal International.

References:

[1] Nur, A. & G. Mavko 1974. Postseismic viscoelastic rebound. *Science* 183, 204-206.

3.7.1.4 Task 4: Modelling of a spreading ridge

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

Andrea Antonioli, Maurizio Bonafede, Antonio Piersanti and Giorgio Spada

By means of a viscoelastic model we have computed the deformations associated with the dynamics of a spreading ridge in a spherical, rheologically stratified earth. The purpose is to apply this model to a study of the tectonics of the Iceland Ridge. The method of solution is based on a quasi-analytical spectral approach to the general equations which govern the deformations of a spherical earth due to seismic sources.

Figures 18 and 19 illustrate the results obtained by means of the technique outlined above. In this case study, we have employed a simple earth model which includes a 100 km thick elastic lithosphere, a uniform mantle with Maxwell rheology, and a fluid inviscid core. The source of deformation consists of a 200 km long tensile fault buried at a depth of 50 km. The response of the earth to this finite fault has been retrieved by summation of the effects of n=51 point sources, each characterized by a Burger's vector b=15 m and by an Heaviside time-history. The more realistic case of a slowly opening tensile fault can be dealt in a simple way. Figure 18 portrays the coseismic surface displacement u (in cm) observed at a given distance from the fault along different azimuths α (namely, $0°$, $45°$ and $90°$ from top to bottom). The surface displacement is decomposed along the spherical unit vectors r, θ, and ϕ (dash-dotted, solid, and dotted curves, respectively).

To appreciate the effects of mantle relaxation upon surface observables, we show in Figure 19 the long-term response of the earth to the same excitation source considered in Figure 18. The time-scales governing the transition from coseismic to postseismic displacements depends essentially from the viscosity stratification of the mantle. For an upper mantle characterized by a relatively low viscosity (such as the mantle beneath Iceland) these time-scales

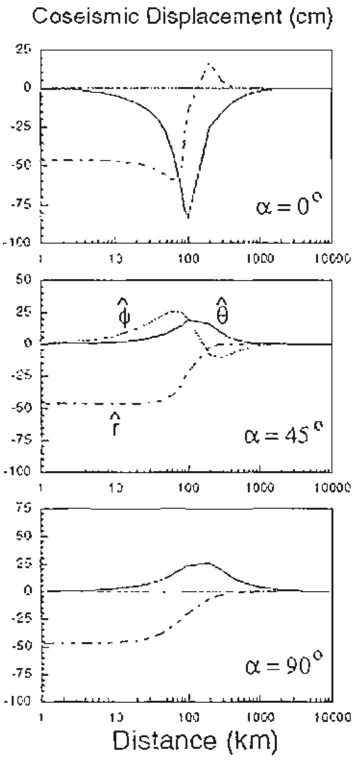

Figure 18:

amount to a few years (Piersanti et al. 1997, see 3.7.1.2). A comparison between Figures 18 and 19 indicates that relatively large amounts of relaxation may affect all of the components of the displacement field. In particular, we observe amplifications of a factor of 2 for the θ and r components of displacements along α=90° (bottom panels). Another interesting feature of Figure 19 is the large spatial scale of the region experiencing horizontal motions in the postseismic regime.

We have developed the capability to model a spreading ridge in a stratified earth with Maxwell rheology. Our approach allows for a realistic description of the time–dependent surface deformation associated with the opening of a rift according to an arbitrary time–history. A particular attention is being devoted to the study of the stress field due to the rift dynamics and on its potential impact on earthquake triggering at any distance from the ridge axis. Comparisons with available analytical solutions valid for a homogeneous half–space model have allowed to appreciate the effects of mantle layering on the induced displacement field. In particular, we have found that the subsidence observed along the ridge axis during episodes of magma upwelling can be accounted for.

Preliminary results on this topic have been presented at the 1996 GNGTS meeting in Rome, final results were presented at the ninth beinnial EUG meeting in Strasbourg (Antonioli, A., A. Piersanti, G. Spada, and M. Bonafede 1997: Time-dependent stress field associated with rift dynamics, abstract). A paper is in preparation.

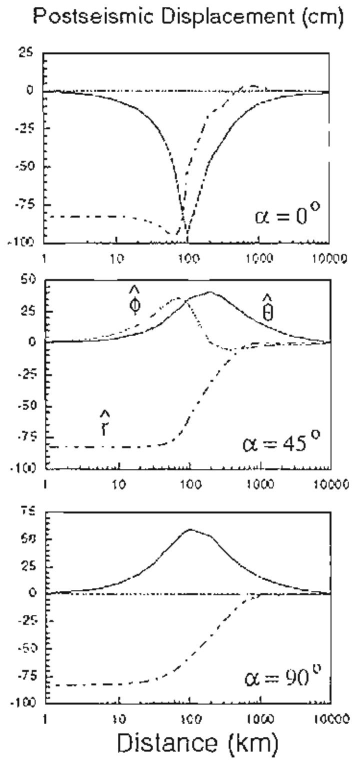

Figure 19:

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

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

Andrea Antonioli, Maurizio Bonafede, Antonio Piersanti and Giorgio Spada

The episodic uprise of magma along the Iceland rift is expected to induce time-dependent stress accumulation in the surrounding regions, which may be associated to seismic activity along transform faults. In turn, seismic activity may affect significantly the evolution of Mid-Atlantic Ridge. In order to model these complex interacting processes, we will employ the earth model described above (Tasks 2 and 4), which allows to compute the deformation and stress fields associated with major earthquakes and the time-dependent opening of the Iceland rift. As planned, Task 5 can not be finalized within the project, though preliminary results will be obtained.

3.7.1.6 Meetings and conferences

XXI EGS General Assembly, The Hague, The Netherlands, May 6–10, 1996.
XXV ESC General Assembly, Reykjavík, Iceland, September 9–14, 1996.
Institut de Physique du Globe, Paris, September 30, 1996 (meeting of Maurizio Bonafede, Ágúst Gudmundsson, Jacques Angelier and Françoise Bergerat).

3.7.1.7 Publications

[1] Piersanti, A., G. Spada & R. Sabadini 1997. Global postseismic rebound of a viscoelastic earth: theory for finite faults and application to the 1964 Alaska earthquake. *J. Geophys. Res.* 102, 477–492.
[2] Belardinalli, M.E. & M. Bonafede 1997. Near-field stress evolution after a strike-slip earthquake in a layered viscoelastic halfspace. *Phys. and Chem. of the Earth*, in press.
[3] Antonioli, A., A. Piersanti & G. Spada 1997. Post-seismic deformations: a comparison between spherical and flat earth models and stress diffusion following large earthquakes. *Geophys. J. Int.*, submitted.
[4] Bonafede, M. & S. Danesi 1997. Near-field modifications of stress induced by dyke injection at shallow depth. *Geophys. J. Int.*, submitted.
[5] Belardinelli M.E. & M. Bonafede 1996a. Near-field stress evolution after a strike-slip earthquake in a layered viscoelastic half space. In: Abstracts from the XXI EGS General Assembly, The Hague, May 6–10, 1996.
[6] Bonafede, M., S. Danesi & M. Olivieri 1996. Modelling surface topography of rift zones in terms of crack theory. In: Abstracts from the XXI EGS General Assembly, The Hague, May 6–10, 1996.
[7] Belardinelli M.E. & M. Bonafede 1996b. Stress fields and tensile fractures in a transform domain. In: Abstracts from the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. Icelandic Meteorological Office, Ministry for the Environment, University of Iceland.
[8] Bonafede, M. & S. Danesi 1996. Campo di sforzi e meccanismi di fagliazione indotti dalla intrusione di un dicco in prossimita' della superficie. In: Abstracts from the 15th GNGTS Annual Meeting, Rome, November 11–13, 1996.
[9] Belardinelli, M.E., M. Bonafede & Á. Gudmundsson 1996. Orientamento delle fessure superficiali create da un terremoto trascorrente. In: Abstracts from the 15th GNGTS Annual Meeting, Rome, November 11–13, 1996.
[10] Antonioli, A., A. Piersanti, G. Spada & R. Sabadini 1996. Studio su scala globale del campo di sforzi prodotto dai grandi terremoti. In: Abstracts from the 15th GNGTS Annual Meeting, Rome, November 11–13, 1996.
[11] Piersanti, A., A. Antonioli, M. Cocco & C. Nostro 1996. Global post-seismic deformation: stress field changes. In: Abstracts from the AGU 1996 fall meeting, San Francisco, December 15–19, 1996.
[12] Antonioli, A., A. Piersanti, G. Spada & M. Bonafede 1997. Time-dependent stress field associated with rift dynamics. In: Abstracts from the ninth biennial EUG meeting, March 23–27, 1997, Strasbourg.
[13] Belardinelli, M.E., M. Bonafede & Á. Gudmundsson 1997. Orientation of secondary

earthquake fractures. In: Abstracts from the ninth biennial EUG meeting, March 23–27, 1997, Strasbourg.

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

In the framework of the EC project "Earthquake Prediction Research in a Natural Laboratory", a model study was begun to obtain forward models of the stress field and stress changes in the South Iceland seismic zone.

This proposal has the target to model the space–time development of the stress field using data on strain and stress changes from the other experiments and from databases.

In detail, this aims at the modelling of:

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

With the funding available, the following models are addressed:

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

Start: March 1996 (month 1)
Expected end: October 1997 (month 20)
Responsible partner: GFS.DR.DBL
Cooperative partner: IMOR.DG

See Task 2.

3.7.2.2 Task 2: Comparison with the seismic moment release

Start: March 1996 (month 1)
Expected end: October 1997 (month 20)
Responsible partner: GFS.DR.DBL
Cooperative partner: IMOR.DG

As a first step in carrying out Task 1 and Task 2, the existing software was checked and transferred into the new Fortran-90 standard. Then the programs were tuned for faster performance and extended to allow calculation of six instead of five layers to account for detailed knowledge of velocity depth profiles.

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

Data are gathered on strong (historical) earthquakes on Iceland and its surroundings.

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

Start: March 1996 (month 1)
Expected end: October 1997 (month 20)
Responsible partner: GFZ.DR.DBC

At the moment, two models are prepared: (1) a scheme comprising the main ridge parts on Iceland and the North Atlantic Ridge to the North and to the South of the island and (2) a model of the South Iceland seismic zone and the adjacent part of the eastern volcanic zone, including both faults and the load due to Katla and Hekla volcanoes. Due to the fact, that no co-worker could be hired up to now, work is behind schedule. This will change with a new geophysicist who began work in January in subproject 4. Thus, the associated contractor - the only one working in this subproject - will have more time to concentrate on this work.

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

Expected start: May 1997 (month 15)
Expected end: January 1998 (month 23)

3.7.2.5 Publications

[1] Roth, F. 1996a. Surface deformation due to a source below several soft sedimentary layers. In: *Annales Geophysicae*. Abstracts from the XXI EGS General Assembly, The Hague, May 6–10, 1996, Supplement I to vol. 14.
[2] Roth, F. 1996b. Deformation pattern of displacement source below several layers. In: Abstracts from the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. Icelandic Meteorological Office, Ministry for the Environment, University of Iceland.

3.7.2.6 Meetings and conferences

Meetings between Maurizio Bonafede and co-workers with Frank Roth took place in May in The Hague and in September in Reykjavík.

3.7.2.7 Methods

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

The objectives of these investigations are:

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

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

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

3.7.2.8 Modelling tools

The associated contractor provides computer programs to calculate:

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

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

Papers directly associated with PRENLAB

4.1 Subproject 1

[1] Angelier, J., S.Th. Rögnvaldsson, F. Bergerat, Á. Guðmundsson, S. Jakobsdóttir & R. Stefánsson 1996. Earthquake focal mechanisms and recent faulting: a seismotectonic analysis in the Vördufell area, South Iceland seismic zone. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 199–204.

[2] Ágústsson, K., A. Linde & R. Stefánsson 1996. The 1987 Vatnafjöll earthquake South Iceland viewed by strainmeters: information on source processes from associated deformation. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 175–180.

[3] Böðvarsson, R., S.Th. Rögnvaldsson, S. Jakobsdóttir, R. Slunga & R. Stefánsson 1996. The SIL data acquisition and monitoring system. *Seism. Res. Lett.* 67, 35–46.

[4] Crampin, S., H.J. Rowlands & R. Stefánsson 1996. Monitoring stress during magma injection. *Geophys. Res. Lett.*, submitted.

[5] Rögnvaldsson, S.Th., G. Guðmundsson, K. Ágústsson, S. Jakobsdóttir & R. Stefánsson 1996: Recent seismicity near the Hengill triple-junction, SW-Iceland. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 461–466.

[6] Rögnvaldsson, S.Th., G. Guðmundsson, K. Ágústsson, S. Jakobsdóttir, R. Slunga & R. Stefánsson 1997. Seismicity in the Hengill volcanic area, SW-Iceland. *Volcanology and Seismology*, submitted.

[7] Stefánsson, R. 1996. Towards earthquake prediction in Iceland. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 3–8.

[8] Stefánsson, R., R. Bödvarsson & G. Guðmundsson 1996. Iceland plume tectonics. Some speculations and facts. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 505–511.

4.2 Subproject 2

[1] Bödvarsson, R., S.Th. Rögnvaldsson, S. Jakobsdóttir, R. Slunga & R. Stefánsson 1996. The SIL data acquisition and monitoring system. *Seism. Res. Lett.* 67, 35–46.

[2] Stefánsson, R., R. Bödvarsson, & G. Gudmundsson 1996. Iceland plume tectonics. Some speculations and facts. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers pre-

sented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 505-511.

4.3 Subproject 3

[1] Crampin, S., H.J. Rowlands & R. Stefánsson 1996. Monitoring stress during magma injection. *Geophys. Res. Lett.*, submitted.

4.4 Subproject 4

[1] Roth, F. 1997. Vorstellung des Projektes zu Wiederholungsmessungen in einer Bohrung im Südisländischen Seismizitätsgebiet. Special issue on borehole geophysics of Deutsche Geophysikalische Gesellschaft, submitted.

[2] Jónsson, S. & P. Einarsson 1996. Radon anomalies and earthquakes in the South Iceland seismic zone 1977–1993. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, Reykjavík, 247-252.

[3] Theodórsson, P. 1996. Improved automatic radon monitoring in ground water. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, Reykjavík, 253–257.

4.5 Subproject 5

[1] Sigmundsson, F., P. Einarsson, S.Th. Rögnvaldsson, G.R. Foulger, K.M. Hodgkinson & G. Thorbergsson 1996. 1994–1995 seismicity and deformation at the Hengill triple junction. Iceland: triggering of earthquakes by a small magma injection in a zone of horizontal shear stress. *J. Geophys. Res.*, in review.

[2] Vadon, H. & F. Sigmundsson 1997. Crustal deformation from 1992 to 1995 at the Mid-Atlantic Ridge, SW-Iceland, mapped by satellite radar interferometry. *Science* 275, 193–197.

4.6 Subproject 6

[1] Angelier J., F. Bergerat, O. Dauteuil & T. Villemin 1996. Tension–shear relationships in extensional fissure swarms, axial rift of northeastern Iceland: morphological evidences. *J. Struct. Geology*, in press.

[2] Angelier, J., S.Th. Rögnvaldsson, F. Bergerat, Á. Guðmundsson, S. Jakobsdóttir & R. Stefánsson 1996. Earthquake focal mechanisms and recent faulting: a seismotectonic analysis in the Vördufell area, South Iceland seismic zone. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 199–204.

[3] Gudmundsson, Á. 1996a. Geometry, displacements and driving stresses of seismogenic

faults in Iceland. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X. Reykjavík, 193–198.
[4] Gudmundsson, Á. 1996b. Stress fields controlling strike-slip faulting in Iceland. *Physics and Chemistry of the Earth*, in press.

4.7 Subproject 7

[1] Antonioli, A., A. Piersanti & G. Spada 1997. Post-seismic deformations: a comparison between spherical and flat earth models and stress diffusion following large earthquakes. *Geophys. J. Int.*, submitted.
[2] Belardinelli, M.E. & M. Bonafede 1997. Near-field stress evolution after a strike-slip earthquake in a layered viscoelastic halfspace. *Phys. and Chem. of the Earth*, in press.
[3] Bonafede, M. & S. Danesi 1997. Near-field modifications of stress induced by dyke injection at shallow depth. *Geophys. J. Int.* submitted.
[4] Piersanti, A., G. Spada & R. Sabadini 1997. Global postseismic rebound of a viscoelastic earth: theory for finite faults and application to the 1964 Alaska earthquake. *J. Geophys. Res.* 102, 477–492.