PRENLAB 1

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Chapter 1

Summary by coordinator

The PRENLAB project started in March 1996. A start-up workshop was held in Hague, May 7, 1996, coinciding with the EGS (European Geophysical Society) conference 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 geophysisists of Europe.

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

It was evident at the meetings in September 1996 that the decision to keep the multidisciplinary character of the project was right. It had of course been a question if would be right to cut out significant parts of the project to be better able to make progress on other parts of it. Originally the requested support for the project was 2.2 MECU, but only 500.000 ECU could be provided from EC to the revised PRENLAB project. The experience has shown that the decision to keep the multidisciplinary character was right. It showed to be possible to achieve funds from other sources, especially for building out the seismic system. Icelandic communities and civil defence funds, the state of Iceland and the Icelandic Research foundation could provide a significant contribution to extend the seismic acquisition system, the SIL system. Most of the contractors succeded to obtain garantees for being able to plan realistic projects falling within the objectives of the original application. The subprojects have all showed progress close to what was planned.

One task of the project is significantly delayed from what was planned. This is 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 that it was successful to extend the SIL acquisition system from the 18 stations that were awailable for the project when it was applied for to the 32 stations that are now in the permanent SIL network. This adds considerably

to the database which is awailable for the project. Another addition of a similar type is that approximately 30 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 University of Durham in Britain, Princeton University in USA and the Icelandic Meteorological Office. The Hotspot network was installed during the summer of 1996 and will be operated untill the summer of 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 eartquake prediction research following can be mentioned:

1. It has been demonstrated in several studies involving work of seismologists, geologists and geophysisists 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, as well as what is inferred from the borehole experiment.

2. Among significant new results that can be reported is that changes of shear wave splitting, at one of the SIL seismic 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 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 strainchanges caused by the measureable pulsations of the Iceland Plume. These results have a consequence in general for understanding how stresses are transmitted in the crust , anywhere.

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

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

The results already obtained within the PRENLAB project have been demonstrated very thoroughly, as said above, at The EGS conference in Hague, May 1996, at the ESC General Assembly in Iceland September 9–14, 1996. These conferences were 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 chapter 3, "Summary of scientific achievements, by subprojects and tasks".

All the subprojects of PRENLAB will be demonstrated at the EUG (European Union of Geosciences) conference in Strasbourg 23–27 of March, 1997, especially in Union symposium 16, "Mitigating geological hazards (risks)", where 10 oral presentation will be directly linked to PRENLAB. A significant presentation of PRENLAB results is also to be expected at the IASPEI (International association of seismology and physics of the earths interior) conference in Thessaloniki in August of 1997.

The next contractor meeting of PRENLAB is planned to be March 25 in Strasbourg, coinciding with the EUG conference. An ind August there is planned a contractor meeting in coinciding with the IASPEI conference.

Chapter 2

Main achievements as reported by the responsible institutions

2.0.1 IMOR.DG, Icelandic Meteorological Office, Department of Geophysics

Coordinates the project and is responsible for subproject 1. It 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 databeses as well as related databases on slow changes, most significant continuous measurements of boreholestrainmeters and gravimeters. It serves the other subprojects with data from these databases. It is responsible also for projects in mapping of active faults, in studying seismicity patterns and in enhanching the alert system in Iceland and for developing and installing new algorithms for dataacquisition and for enhanching the automatic evaluation processes. It cooperates with all the other subprojects.

Work has been carried out on all the tasks according to the time schedule of the workprogramme.

2.0.2 UUPP.DGEO, Uppsala University, Deprtment of Geophysics

Has been responsible for subproject 2, i.e. development of various methods for analysing microearthquakes. The tasks, task 1: Methods for subcrustal mapping of faults, task 3: Methods for monitoring the local rock stress tensor, task 6: methods for 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 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 considerd right to wait for finishing the ongoing refinement of the SIL database before starting these tasks. Instead more work has been concentrated on task 4: Methods for monitoring stable/unstable fault movements which is a few months before the schedule of the workprogramme.

In all tasks the closest cooperator is IMOR.DG, except in task 6 where the main cooperator is NVI.

2.0.3 UEDUIN.DGG, University of Edinburgh, Department of Geology and Geophysics

Has been responsible for subproject 3: Monitoring stress changes before earthquakes using seismic shear-wave splitting. It cooperates closely with IMOR.DG. Other significant coop-

erators are UUPP.DGEO and GFZ which will contribute by providing data from borehole experiments.

The tasks are within the workprogramme schedule.

2.0.4 GFZ.DR.DBL, Stiftung Geoforschungszentrum Potsdam, Disaster Research, Section 5.3 - Deep Borehole Logging

Is responsible for subproject 4 as a whole: Borehole monitoring of fluid rock interaction. Subproject 4 is devided into two parts, part A, managed by Frank Roth of the GFZ and part B, managed by Páll Einarsson, associated contractor UICE.DG, University of Iceland, Division of Geophysics.

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

The subpart B is behind the time schedule. The reason is that it has not been possible obtain additional funding as expected and needed. The EC funding was planned for task 1 of this subpart i.e. to build an improved LSC apparatus to measure radon content of water and gassamples. This work is in 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 this subpart will be 8 months delayed.

2.0.5 CNRS.DTP, Centre National de la Recherce Scientifique, UPR 0234 – Dynamique Terrestre et Planétaire

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

Subpart A: SAR interferometry is managed by Kurt Feigl of the CNRS.DTP in close cooperation with F. Sigmundsson of NVI. It is on schedule.

Subpart B is managed by F. Sigmundsson of NVI, with R. Böðvarsson of UUPP.DGEO. 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.

2.0.6 NVI, Nordic Volcanological Institute

Is responsible for subproject 6: Formation and development of seismogenic faults and fault populations. Subproject 6 is devided into subpart A: Paleostresses, managed by F. Bergerat, associated contractor, CNRS.TT and subpart B, managed by Á. Guðmundsson, NVI. The progress of both subparts is on schedule.

2.0.7 UBLG.DF, Universita degli Studi di Bologna, Dipartimento di Fisica "A. Righi"

Is responsible for subproject 7: Theoretical analysis of faulting and earthquake processes. This subproject is devided in two parts A and B.

Subpart A: Crust - mantle rheology in Iceland and Mid–Atlantic Ridge from studies of post–seismic rebound is managed by M. Bonafede, 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 Frank Roth, GFZ.DR.DBL. Subpart B is .....?

Chapter 3

Summary of scientific achievements by subprojects and tasks.

3.1 Subprojects 1 : Real–time evaluation of earthquake–related–processes and development of database, and coordination of the project

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((March 1 Dr. Einar Kjartansson was hired to the project and he has been working on it full time since that. We expect that 4 staff members of Department of Geophysics have been working full time since March 1 on the project))

3.1.1 Task 1: Database, development and service

Start: Month 1
End: 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 seismic stations of the SIL type 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 14 new permanent SIL stations. These stations are as other permanent stations of the the SIL network available for the PRENLAB project and of a 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 31 and will increase to 32 during the next weeks, if weather conditions will allow. The new stations are funded by Icelandic communities, hydrothermal and hydroelectrical power companies, civil security organizations, 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 The Icelandic Meteorological Office/The State of Iceland, which besides contributions to the initial costs garantees the operation cost of the system.

At the moment, and so it will be during the next two years there will be more than 30 extra digital broad band stations operated continuously at remote places not covered by the SIL system, mainly for collecting teleseismic data. This is a part of the Hot Spot project, lead by Gillian Foulger, Durham. Among other participants are Princeton University, with Jason Morgan and Guus Nolet and Bruce Julian of the Geological Survey, besides the Meteorological Office of Iceland. The wave form 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 Hot spot project stations are operated at sites where we have no or few SIL stations they can provide us with a much more general overview about the stress condition 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

3.1.1.2 Task 1.2 The database access

A refined and easily accessable 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 online 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 seperate tables. This information is incorporated into headers when data is 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 is 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 the the data is always readily accessible.

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

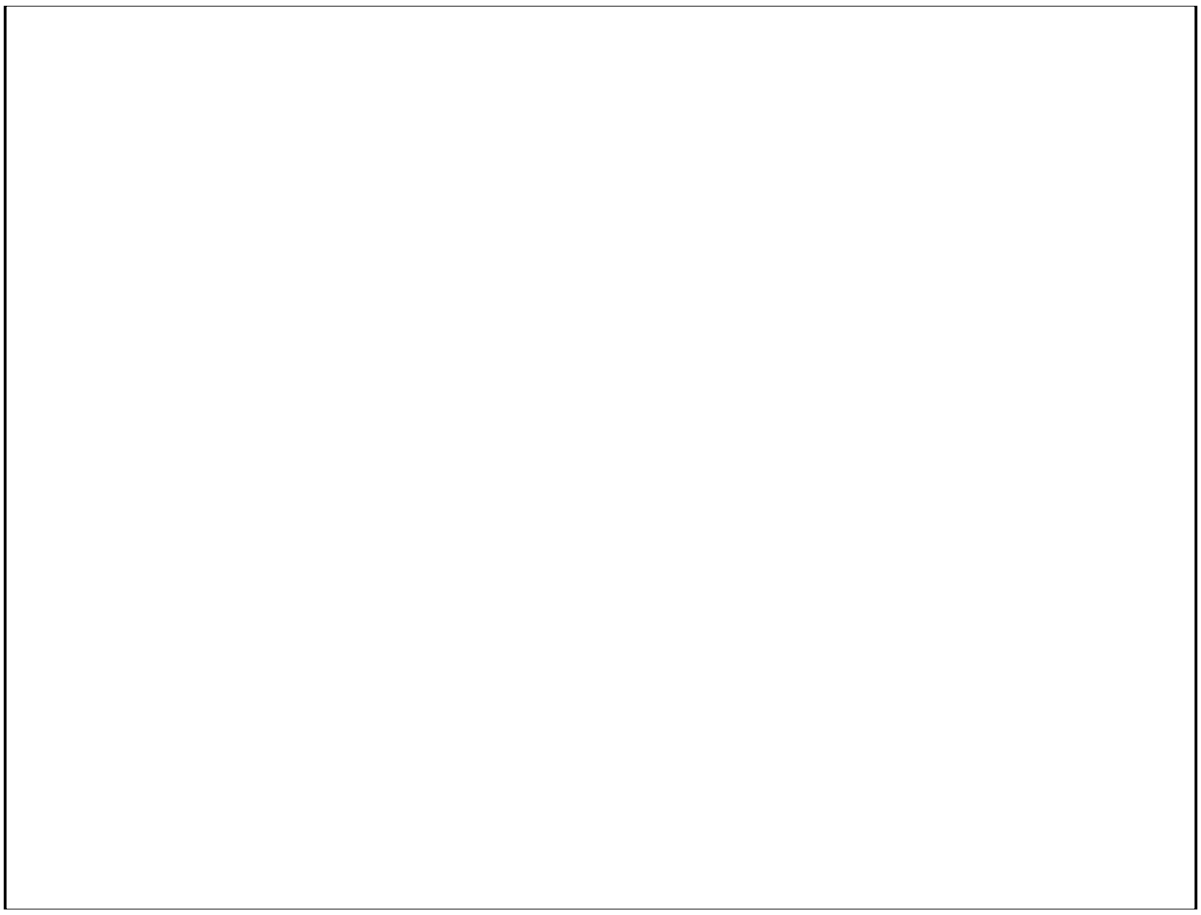

Figure 1: *Seismic station network in Iceland ???*

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 intepreting data from volumetric borehole strainmeters. Premonitory changes and coseismic changes, volumetric strain and earthquakes (foreshocks), of the 5.8 magnitude 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 oweview (since 1979) of the 7 Icelandic volumetric strainmeters is being worked out. Methods have been developed for cleaning the strainmeter record of weather influences.

The seismicity of volcano Katla 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.

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 measureable 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 seconds 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 1Hz 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 0.5-1Hz, 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 a 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 in 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 tripple 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. Work 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 Nordic Volcanological Institute.

Work has been carried out to find 3-D crustal Velocity structure in SW Iceland from local earthquake tomography in cooperation with Uppsala University

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

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

Start: month 1
End: month 24
Responsible partner: IMOR.DG
Cooperative partners: UUPP.DGEO, NVI

Work has been going on in using all useful seismological data for mapping actve earthquake faults in the Tjörnes fracture zone at the north coast of Iceland (Figure 2). The method used is multievent method based on crosscorrelating similar signals at the the same seismic station. Provided the time accuracy of the seismic data of the SIL syste, close to 1 ms, 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 e arthquake 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: month 4
End: month 24
Responsible partner: IMOR.DG
Cooperative partners: UUPP.DGEO, NVI

Work has been carried out on recent high seismic activity near the Hengill tripple 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).

Figure 3 Hengilsmynd, t.d. af momentútlausn.

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

Start: month 4
End: 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 surrounding. 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 multieventanalysis 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 data base 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 data base, and, if found, takes the onset and the first motion direction picks from there. If no existing entry in the data base 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 (Figure 4).

Figure 4 sýnir hvað staðsetning tekur miklum framförum við multievent.

Some tests have already been carried out to which demonstrate that the approach described here is possible. It is expected that the ACIS will be in rouine operation within the SIL system in June or July of 1997.

A new algoritms has been introduced into the alert procedures, which is a special noise-monitor. Noise is monitored real time filtering of the digital data from the seismic stations in 3 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 freuqency seems to be expressing noise created by very intensive activity of very small earthquakes, although these are not descriminated 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 analyse 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 frequency of the order of 1 Hz) which are often observed in Iceland.

3.1.5 Work arrangements

On March 1, 1996, Dr. Einar Kjartansson was hired to the project and has since worked full–time on PRENLAB Subproject 1. We expect that 4 staff members of Department of Geophysics have been working full–time since March 1 on the project.

3.1.6 Meetings and conferences

agnar til Strassbourg

3.1.7 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 Vordufell area, South Iceland seismic zone. In: Thorkelsson, B. (editor) *Seismology in Europe*. Papers presented at the XXV ESC General Assembly. ISBN 9979-60-235-X. Reykjavík, pp. 199–204
[2] Ágústsson, K.,1996. The 1987 Vatnafjöll earthquake south Iceland viewed by strainmeters: information on source processes from associated deformation. Abstracts for the 25th ESC General Assembly.
[3] Ágústsson, K., 1996. Continuous strain measurements in SW Iceland with focus on the 1987 Vatnafjöll earthquake and the 1991 Hekla eruption. Thesis for Fil. lic. degree Uppsala, 1966, pp 1-34.
[6] 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.
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Hér vantar: 2 abströkt á jarðfræðiráðstefnunni (ensk þýðing á nafninu í sviga dyrir aftan íslenska nafnið).

Sennilega mætti bæta fleiri greinum við, t.d. Crampin o.fl submitted to GRL o.s.frv.

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

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Reynir Böðvarsson is 40% founded by EC and Ragnar Slunga is 20% founded EC.

The SIL micro–earthquake system produces detailed results of automatic analysis of large number of micro–earthquakes. 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 multi-event 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 sub–crustal mapping of faults

Start: Month ?
End: Month ?
Responsible partner ?

The algorithm for absolute and relative location of micro–earthquakes 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 micro–earthquakes show a remarkable agreement with the fault information available from sea bottom and land surveys. These studies also indicate the power of the multi–event 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 the figure (Figure 3) below.

Some preliminary work has been carried out towards inversion for the 3-d velocity structure in the SIL area. velocity structure in the SIL area. The first results show an interesting velocity anomaly at the lower boundary of the brittle crust. See figure (Figure 4).

This task was finalized in July 1996.

3.2.2 Task 2: Methods for monitoring the crustal wave velocities

Start: Month ?
End: Month ?
Responsible partner ?

Nothing has been done on this yet. It will be more efficient to work on this when the SIL database is completed.

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

Start: Month ?
End: Month ?
Responsible partner ?

Software for rock stress tensor inversion based solely on micro–earthquake information is under development. Stress tensor inversion based on only micro–earthquake 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 micro–earthquakes. This allows a stress tensor inversion completely based on direct information from the micro–earthquakes 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. At present we are testing the algorithm and comparing the results with other algorithms. The two figures below show some results. 5 6

This task is progressing according to plans and will be finalized before September 1997.

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

Start: Month ?
End: Month ?
Responsible partner ?

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 micro–earthquake 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 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 the tasks 2 and task 5 are delayed due to lack of data. 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 micro–earthquakes and earthquakes

Start: Month ?
End: Month ?
Responsible partner ?

This task will be worked on when the SIL database is available.

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

Start: Month ?
End: Month ?
Responsible partner ?

The software for transferring GPS data to the center in Reykjavik 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 IMO can install Solaris on this sites the operation can be started.

3.2.7 Publications

Publications associated with the project:

[1]Böðvarsson, R., S.Th. Rögnvaldsson, S. Jakobsdóttir, R. Slunga & R. Stefánsson, 1996. The SIL data acquisition and monitoring system. *Seismological Research Letters*. pp 35–46.

[2]Böðvarsson, R., S.Th. Rögnvaldsson & R. Slunga, 1996. Waveform correlation as a tool for automatic phase picking. Abstracts of the XXV General Assembly of ESC, Reykjavík. p. 32.

[3]Guðmundsson, G. S. Jakobsdóttir & R. Böðvarsson, 1996. Automatic selection of teleseismic data in the SIL system. Abstracts for the 25th ESC General Assembly. B2.09, p. 34.

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

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[8]Shomali, Z. H. & Slunga, R., 1996. Determination of the mechanism and source parameters of earthquakes by using moment tensor inversion of earthquakes in the South Iceland Seismic Zone. Abstracts of the XXV General Assembly of ESC, Reykjavík. p. 75.

Publication plans:

Four articles are planned to be submitted for publication during 1997. One article on Stress Tensor inversion methods, one on the mapping of the Stress Tensors in Iceland, one article on Moment Tensor inversion for a few larger events in the SIL area and one article on the application of the relative location technique for real–time network operation.

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

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In June 1996 (month 4), Helen Rowlands, who had just completed her PhD thesis on shear–wave splitting above micro–earthquakes, 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: month 4
End: month 12
Responsible partner: UEDIN.DGEO
Cooperative partner: IMOR.DG

Work on this task began in month 4 with the appointment of a researcher. This task is on-going 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.

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, 10th September, 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 30th September, 1996, beneath the Vatnajökull ice cap, see 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, Rowlands & Stefánsson, 1997) is being prepared, and a preliminary draft is attached to this report.

The observed variations at SAU are a demonstration that shear–wave splitting is a sensitive 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, listed below, to improve stress–monitoring of the crust beneath Iceland.

3.3.2 Task 2: Station/EQ relationship

Start: month 13
End: 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 teqhniques

Start: month 13
End: 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: month 19
End: 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, 11 September, 1996. Attended by Stuart Crampin.
Strasbourg, 25 March, 1997. Attended by Stuart Crampin & Helen Rowlands.

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

European Seismological Commission, Reykjavík, 9–14 Sept., 1996. Stuart Crampin, 2 papers.
Earthquake Research in Turkey, Ankara, 30 Sept.–5 Oct., 1996. Stuart Crampin, 2 papers.
Assessment of schemes for earthquake prediction, Geological Society, London, 7-8 Nov., 1996. Stuart Crampin, 1 paper.
European Union of Geosciences, Strasbourg, 23-27 March, 1996. Stuart Crampin 1 paper, Helen Rowlands 1 paper.

3.3.6 Publications

Publication directly associated with project:

[1] Crampin, S., H. J. Rowlands & R. Stefánsson 1996. Monitoring stress during magma injection, *Geophys. Res. Lett.*, in preparation. (Attached in Annex)

Publications associated with project:

[1] Crampin, S. & S. V. Zatsepin 1996a. Forecasting earthquakes with APE, 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, 318–323.

[2] Crampin, S. & S. V. Zatsepin 1996b. Rocks, dead or alive?: Theory prompts new understanding of fluid-rock interaction and shear–wave splitting. *EOS*, 77, 281, 286.

[3] Crampin, S. 1997a. Going APE: Monitoring and modelling rock deformation with shear–wave splitting. *Proc. 4th Int. Symp. Rockbursts. Seism. Mines*, Kraków, in press.

[4] Crampin, S. & S. V. Zatsepin 1997a. Changes of strain before earthquakes: the possibility of routine monitoring of both long–term and short–term precursors, *J. Phys. Earth*, in press.

[5] Crampin, S. & S. V. Zatsepin 1997b. Modelling the compliance of crustal rock: II - response to temporal changes before earthquakes. *Geophys. J. Int.*, 129, in press. GV240

[6] Crampin, S. 1997b. Earthquake forecasting: a viable alternative to prediction. *Geophys. J. Int.*, submitted. GX016

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Associated Abstracts:

[8] Crampin, S. 1996. Earthquake prediction and earthquake forecasting (Abstract). Earthquake Research in Turkey: State of the Art, 30 Sept.–5 Oct., 1996, Ankara.

[9] Crampin, S. & S.V. Zatsepin 1996a. Opportunities for earthquake forecasting (Abstract), Earthquake Research in Turkey: State of the Art, 30 Sept.-5 Oct., 1996, Ankara.
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[11] Zatsepin, S.V. & S. Crampin, S. 1996. Modelling rockmass deformation with APE: a mechanism for monitoring earthquake preparation zones with seismic shear–waves (Abstract), XXV General Assembly, European Seismological Commission, 9 Sept., 1996, Reykjavík, Paper E3.06.
[12] Crampin, S. & S.V. Zatsepin 1997. The possibility of forecasting earthquakes (Abstract). Assessment of schemes for earthquake prediction, Geological Society, 7–8 Nov., 1996, London.
[13] Crampin, S. & S.V. Zatsepin, 1997. Forecasting earthquakes, Eur. Union. Geophys: 9, 23–27 March, 1996, Strasbourg.
[14] Rowlands, H.J., S. Crampin & R. Stefánsson 1997. Forecasting eruptions, Eur. Union. Geophys: 9, 23–27 March, 1996, Strasbourg.

3.4 Subproject 4: Borehole Monitoring of Fluid-Rock Interaction

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3.4.1 Subproject 4A: Geophysical loggings

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In the framework of the EU–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 seismological 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 geo–parameters 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) and
- borehole televiewer (BHTV).

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

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 borhole conditions

Start: month 2
End: month 4

Between April and June, OS checked the condition of the borehole selected for repeated logging – at first this was well NG–01 –, organised 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 Lowlands, 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)

Start: month 5
End: month 8

Two field campaigns took place in July 1996, a third in October '96.

Moreover, additional logs could be run by us in July '96 in 5 other boreholes on Iceland to add new information to previous results on the regional stress field.

The following table gives 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	Syðra 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

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: month 5
End: month 8

See task 2.

3.4.1.4 Task 4: Check for changes

Start: month 17
End: month 17

Task 4 are to follow in 1997

3.4.1.5 Task 5: Evaluation of measuring results

Start: month 5
End: month 24

The processing of the data has begun, especially since January, when Mrs. 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 the figures. 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 North 40 degrees East and 220 degrees East (see also the graphical presentation of the azimuths of the picked breakouts). 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 North 110 degrees East (complementary at 290 degrees East) 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 degree East in the South Iceland Seismic Zone (LL-03) and an azimuth of about 200 degree East 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.

A significant change of breakout direction or shape between the logging campaigns performed in July an October 1996 could not be observed. 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.

3 Figures

Processing of the 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.

Besides the Mrs. 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. Hermansson (OS), S. Mielitz (GFZ), J. Palmer (GFZ), H. Sigvaldason (OS), Ó. Sigurðsson (OS), B. Steingrímsson (OS) and M. Thoms (GFZ).

3.4.1.6 Publication

A report on the outline of the project was given at a German workshop on borehole geophysics and rock physics. An extended abstract of six pages on this presentation is submitted for publication in a special issue of the proceedings of the German Geophysical Society.

3.4.1.7 Meetings

Meetings of V. Stefánsson with F. Roth took place in April and September in Reykjavik and in September in Potsdam.

Meetings of P. Einarsson with V. Stefánsson and F. Roth took place in April and September in Reykjavík.

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

Associated contractor:

Páll Einarsson
Address ?

Subcontractor:

Fjölnemar h.f.
address ?

3.4.2.1 Task 1: Improved LSC apparatus

Start: ?
End: ?

???

3.4.2.2 Radon measurements revived

Start: ?
End: ?

???

3.5 Subproject 5: Active deformation determined from GPS and SAR

Contractor:

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Centre National de la Recherche Scientifique (CNRS), Toulouse, France

Associated contractor:

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Sigurjón Jónsson is working 50% in the project from March 1, 1996 to May 1, 1997. Founded 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: Anaysis of SAR images from the ERS–1 and ERS–2 satellites

Start: month 1
End: month 19
Responsible partner: CNRS

Researcher: Kurt 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/yr

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/yr, probably caused by compaction of a geothermal reservoir in response to it's utilization by a power plant. The deflation we infer is in good agreement with leveling 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/yr 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: month 1
End: month 16
Responsible partner: NVI
Cooperative partner: UUPP.DGEO

Freysteinn Sigmundsson, Reynir Böðvarsson

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 shead 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 meeting 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: month 6
End: month 24

Responsible partne: NVI
Cooperative partner:

Freysteinn Sigmundsson and Páll Einarsson

Since July 1994 an unusually persistent swarm of earthquakes (M $<$ 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 mstrain, 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 stellite radar interferometry. *Science*, 275, 193–197.
[2] Sigmundsson, F., P. Einarsson, S.Th. Rognvaldsson, 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. EOS Transactions American Geophysical Union, 77, AGU 1996 Fall Meeting abstracts.
[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. EOS Transactions American Geophysical Union, 77, AGU 1996 Fall Meeting abstracts.
[5] Sigmundsson, F. 1996. Inversion of geodetic data from Hengill triple junction, Iceland: Rift subsidence and volcano inflation. Paper presented at the 21th General Assembly of EGS in the Hague, May 1996, Annales Geophysicae, 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? Paper presented at the 21th General Assembly of EGS in the Hague, May 1996, Annales Geophysicae, Supplement I to vol. 14.

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

Contractor:

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ATHUGA ÞETTA

People hired for this subproject (6A and6B).

Agust 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 SISZ. Agust has also been starting a collaboration with Philip Meredith (Univ. College London, who is in the new application); that collaboration has involved some travel cost for Prof Meredith.

Francoise Bergerat and Jacques Angelier have a student working on the paleostress fields of the SISZ, but so far, I believe, that student has not been paid from the project.

Thirrey Villemin also has student working on the project, but very little if any 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
Expected end: September 1997
Researchers: Francoise Bergerat and Jacques Angelier

The paleostress tensors for many localities in the South Iceland Seismic Zone have been made, using fault-slip data sets. Preliminary studies of the paleostress field of the whole SISZ have already started. Work on 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 Guðmundsson 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 A. Gudmundsson and S. Th. Rögnvaldsson) A seismotectonic analysis was carried out in the Vörðufell 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 (Stefansson et al., 1993) with determinations of earthquakes mechanisms (Rognvaldsson and Slunga, 1993 and 1994; Slunga et al., 1995), a data set 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 data set. First, using the P- and T- dihedra method (Angelier and Mechler, 1977), 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, Angelier 1975 and 1984) and the direct inversion method (INVD, Angelier 1984 and 1990). 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 Vörðufell Mtn. 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 Vörðufell 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 A. Gudmundsson and S. Th. 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 Pleiostocene lavas and hyaloclastites and in postglacial lavas. The areas investigated were the Skardsfjall, Hestfjall and Burfell mountains, the Grimsnes area and the canyons of Stora Laxa and Stora Mastunga. The measurements are now being analysed 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 the Icelandic

Meteorological Office..

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

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

Start: July 1996
Expected end: February 1998
Researchers: Francoise Bergerat and Jacques Angelier

This task has involved collaboration with Thierry Villemin and Olivier Dauteuil. It has so far focused 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 Mofell area. (work carried out with O. Dauteuil and T. 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 localised into fissure swarms, 1 to 5 km wide. Major volcanic centers are present along swarm axes. We analysed the partitioning of extension into a major fissure swarm : the Krafla fissure swarm. The studied area was a 4,5 km2 area, near the Mofell Mtn, 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 data set was obtained from detailed mapping structures combining field measurements, SPOT satellite images and aerial photographs. Most faults and fissures trend N 010°-030°. The fissures width ranges from ten centimeters to two meters. The faults have a maximum vertical throw of 20 meters. The second data set 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 degrees), 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 analysed in compared to the fault network. The plunge values vary from 0.2°to 3°, with trend comprised between N 030°and N 100°. 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 Leirhnjukur area (work carried out with O. Dauteuil and T. 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 analysed 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 localised 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 analysed. 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 palaeodepths 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 metres 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 (paleo–stress analyses, focal mechanisms of earthquakes).

3.6.1.4 Publications

[1]Bergerat F., Angerlier J., Dauteuil O. et Villemin T. (1996). - Morphologie et déformation dans un rift océanique émergé : exemple du champ de fissures du Krafla (Nord-Est Islande). 16ème Réun. Sc. Terre, Orléans, 10-12 avril 1996, vol. résumés, p.20, 1 fig.
[2]Bergerat F., Angerlier J., Dauteuil O. et Villemin T. (1996) - Present-day tension-shear deformation and morphology in the Krafla fissure swarm, axial rift zone of northeastern Iceland. XXVe General Assembly of the European Seismol. Comm., Reykjavik, 9-14 september 1996, Abstracts volume, p. 53.
[3]Angerlier J., Rögnvaldsson S. Th., Bergerat F., Guðmundsson A., Jakobsdóttir S. et Stefánsson R. (1996) - Focal mechanisms of earthquakes and recent faulting : A seismotectonic analysis of the vordufell area, South Iceland Seismic Zone. XXVe General Assembly of the European Seismol. Comm., Reykjavik, 9-14 september 1996, Abstracts volume, p. 53 and Papers volume, P. 199-204, 2 fig., 4 tabl.
[4]Angerlier J., Bergerat F., Dauteuil O. et Villemin T. (1996). - Tension-shear relationships in extensional fissure swarms, axial rift of northeastern Iceland : morphological evidences.

Journ. Struct. Geology, in press.
[5]Angerlier J., Rögnvaldsson S. Th., Bergerat F. et Guðmundsson A. (1997). - Earthquake focal mechanisms and regional stress : the seismotectonic behaviour of the South Iceland Seismic zone revealed by the Vörðufell earthquake activity. Communication à l'E.U.G.IX, Strasbourg, 23-27 mars 1997.
[6]Bergerat F., Angerlier J., Guðmundsson A. et Rögnvaldsson S. Th. (1997) - Joint study of recent faulting and earthquake focal mechanisms in the South Iceland Seismic Zone : the Vörðufell area as a case example. Communication à l'E.U.G. IX, Strasbourg, 23-27 mars 1997.
[7]Dauteuil O., Angerlier J., Bergerat F., Ferber V., Verrier S. et Villemin T. (1997). - Deformation pattern and morphology in the northern Iceland rift. Communication à l'E.U.G. IX, Strasbourg, 23-27 mars 1997.
i[8]Guðmundsson A., Bergerat F. et Angerlier J. (1997). Strike-slip faults in the central part of the South Iceland Seismic Zone. Communication à l'E.U.G. IX, Strasbourg, 23-27 mars 1997.

3.6.2 Subproject 6B: Fault populations

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

Start: July 1996
Expected end: February 1998

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-Svinhagi 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, Orkustofnun, Reykjavik.

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 focused 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-Svinhagi seimogenic 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 echelong 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-Svinhagi fracture is location in the 9000-year-old Thorsarhraun lava flow. The age of the fracture itself is, however, not known. It is obviously less than 9000 year old, but may be only several hundred years old. At the southern end of the fracture, near the farm Svinhagi, hot water (15-20°) 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-Svinhagi 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-Svinhagi fault is unusually clear and conspicuous and must be explained by any model that attemts to account for the fracture pattern associated with the South Iceland Seismic Zone.

Work on the SISZ is in close collaboration with Jacques Angelier, Francoise Bergerat, Sigurdur Rögnvaldsson and Helgi Torfason. A manuscript on the Origin and tectonic evolution of the South Iceland Seimic 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 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 Grimsey fault, as well as those associated with the Dalvik "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 Phil Meredith, University College, London.

3.6.2.2 Task 2: Boundary-element models of the faults

Start: March 1996
Expected end: September 1997

This work has alredy started and is carried out in collaboration with Maurizio Bonafede and Maria Elina Beldarinelli, who use analytical methods. So far the work has focused 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 Belardinelly (Italy).

3.6.2.3 Task 3: Boundary–element study of the TFZ and the SISZ

Start: March 1996
Expected end: September 1997

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, Francoise Bergerat,Thierry Villemin and Sigurdur Th Rognvalsson. This work is on schedule.

3.6.2.4 Task 4: Make analogue models of the South Iceland seismic zone and the Tjörnes fracture zone

Start: March 1996
Expected end: February 1998

Olivier Dauteuil has already made analogue 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 TFZ

Start: July 1996
Expected end: December 1997

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 Agust 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 Husavik-Flatey Fault. A detailed GPS network, set up by the NVI in 1994, was expanded in collaboration with Thierry Villemin in 1995. One objective of this work is to correlate the seismicity on the Husavik-Flatey fault with the on-land slip of the fault, as measured by the GPS network. An abstract has already been submitted to the EUG 9 meeting in Strasbourg on some of the results of this work.

3.6.2.6 Publications

[1] Gudmundsson, A., 1996. Geometry, displacements and driving stresses of seismogenic faults in Iceland. *In Seismology in Europe,* Bardi Thorkelsson (ed), Reykjavik, pp. 193-198. (Also an Abstract)
[2] Gudmundsson, A., 1996. Stress fields controlling strike-slip faulting in Iceland. *Physics and Chemistry of the Earth* (in press).
[3] Gudmundsson, A., 1996. Stress field controlling strike-slip faulting in Iceland. General Assembly of EGS in the Hague, May 1996, *Annales Geophysicae*, Supplement I to vol. 14.
[4] Gudmundsson, A., 1996. Formation and development of tension fractures in a lava pile. *Tensile Fracturing in the Earth's Crust.* Programme with Abstracts. University College London, Department of Geological Sciences, September 1996.
[5] Gudmundsson, A., Bergerat, F. and Angelier, J., 1996. Strike-slip faults in the central part of the South Iceland Seismic Zone. *Abstract submitted to EUG 9*, Strasbourg 1997.
[6] Gudmundsson, A., 1996. Origin and tectonic evolution of the South Iceland Seismic Zone (MS in perparation).
[7] Gudmundsson, A., 1996. Mid-ocean ridge processes in Iceland. General Assembly of EGS in the Hague, May 1996, *Annales Geophysicae*, Supplement to vol. 14.
[8] Rögnvaldsson, S., Gudmundsson, A., and Slunga, R., 1996. Seismotectonic analysis of the Tjörnes Fracture Zone, an active transform fault in North Iceland (MS in perparation).
[9] Gudmundsson, A., 1996. 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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Andrea Antonioli is supported with a fellowship under contract ENV4-CT96-0252, start date: October 1st, 1996. He is working 100% of his time on the project.
Maria Elina Belardinelli is working 30% of her time in the project since March 1st, 1996.
Maurizio Bonafede is working 20% of his time on the project since March 1st, 1996.
Antonio Piersanti is working 30% of his time in the project since March 1st, 1996.
Giorgio Spada is working 30% of his time in the project since March 1st, 1996.

3.7.1 Milestones

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

Start: March 1996
End: November 1996
New issues to be addressed within phase 2.

Maurizio Bonafede, Maria Elina Belardinelli and Agust 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 North and North–East trending arrays of en–enchelon tension fractures which are the most prominent surface features. The arrays are globally oriented in the direction of dextral strike–slip faults, buried under Holocene lava flows, but the orientations (alpha) of individual fissures generally deviate 10–20 degrees from the strike direction (see Figure 11).

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 sigma1 and sigma2 (Figure 12.a).

The angle between the seismic fault and individual fissures cannot be less than 22.5 degrees, if the latter open as pure tensile cracks, whatever the orientation (theta) of the regional stress field (Figure 12.b). Fissure angles less than 22.5 degrees can be explained if the fissures break at depth as shear cracks, with strike direction alpha' dictated by the Coulomb–Navier criterion (Figure 12.c), 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 13). 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 Reykjavik meeting, further advancements

have been presented at the GNGTS meeting in Rome, and will be presented at the EUG9 meeting in Strasbourg. A paper is in preparation.

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

Start: March 1996
Expected end: February 1997

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. 1996]. 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.

References: A. Piersanti, G. Spada, and R. Sabadini, Global postseismic rebound of a viscoelastic Earth: Theory for finite faults and application to the 1964 Alaska earthquake, J. Geophys. Res., 102, 477–492, 1997.

3.7.3 Task 3: Comparison between global earth models, including sphericity and self–gravitation, and plane models

Start: March 1996
Expected end: Finished February 1997

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. [1996] (see reference to task no. 2). In both cases, we have computed the coseismic displacements and the delayed post–seismic displacements associated with the viscoelastic relaxation of a uniform mantle.

In Figure 14 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 14 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: 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 pp., 1995. Further results on the stress field will be presented at the EUG9 meeting in Strasbourg (Antonioli, A., A. Piersanti, G. Spada, and M. Bonafede, Time–Dependent Stress Field Associated with Rift Dynamics, EUG Abstract, submitted, 1996). 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: Nur, A., and G., Mavko, Postseismic viscoelastic rebound, Science, 183, 204–206, 1974.

3.7.4 Task 4: Modeling of a spreading ridge

Start: October 1996
Expected end: March 1997

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 15 and 16 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 Burgers 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 15 portrays the coseismic surface displacement u (in centimeters) observed at a given distance from the fault along different azimuths alpha (namely, 0, 45 and 90 degrees from top to bottom). The surface displacement is decomposed along the spherical unit vectors r, theta, and phi (dash–dotted, solid, and dotted curves, respectively).

To appreciate the effects of mantle relaxation upon surface observables, we show in Figure 16 the long–term response of the Earth to the same excitation source considered in Figure 15 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 amount to a few years [Piersanti et al., 1996]. A comparison between Figures 4.1 and 4.2 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 theta and r components of displacements along alfa = 90 degrees (bottom panels). Another interesting feature of Figure 16 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 episedes of magma upwelling can be accounted for.

Preliminary results on this topic have been presented at the 1996 GNGTS meeting

in Rome, final results will be presented at the EUG9 meeting in Strasbourg (Antonioli, A., A. Piersanti, G. Spada, and M. Bonafede, Time–Dependent Stress Field Associated with Rift Dynamics, EUG Abstract, submitted, 1996). A paper is in preparation.

3.7.5 Task 5: Modeling 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
Preliminary results by february 1998. To be completed within phase 2.

Andrea Antonioli, Maurizio Bonafede, Antonio Piersanti, 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 no. 2 e 4), which allows to compute the deformation and stress fields associated with major earthquakes and the time–dependent opening of the Iceland rift. Task 5 can not be finalized within Phase 1, though preliminary results might be available during Phase 1.

3.7.6 Meetings and conferences

XXI EGS General Assembly, The Hague, The Netherlands, May 6–10, 1996.
XXV ESC General Assembly, Reykjavik, 10th September, 1996.
Institut de Physique du Globe, Paris, September 30, 1996 (meeting of M. Bonafede, A. Gudmunsson, J. Angelier and F. Bergerat).

3.7.7 Publications

Publications associated with project:

[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 ahallow depth. *Geophys. J. Int.*, submitted.

Abstracts:

[1] Belardinelli M.E. & M. Bonafede 1996. Near–field stress evolution after a strike–slip earthquake in a layered viscoelastic half space. XXI EGS General Assembly, The Hague 6–10 may 1996.

[2] Bonafede, M., S. Danesi & M. Olivieri 1996. Modelling surface topography of rift zones in terms of crack theory. XXI EGS General Assembly, The Hague 6–10 may 1996.

[3] Belardinelli M.E. & M. Bonafede 1996. Stress fields and tensile fractures in a transform domain. XXV General Assembly of the European Seismological Commission, Reykjavik 9–14 september 1996.

[4] Bonafede, M. & S. Danesi 1996. Campo di sforzi e meccanismi di fagliazione indotti dalla intrusione di un dicco in prossimita' della superficie. 15–th GNGTS Annual Meeting, Rome, 11–13 november 1996.

[5] Belardinelli, M.E., M. Bonafede & A. Gudmundsson 1996. Orientamento delle fessure superficiali create da un terremoto trascorrente. 15–th GNGTS Annual Meeting, Rome, 11–13 november 1996.

[6] Antonioli, A., A. Piersanti, G. Spada & R. Sabadini 1996. Studio su scala globale del campo di sforzi prodotto dai grandi terremoti. 15–th GNGTS Annual Meeting, Rome, 11–13 november 1996.

[7] Piersanti, A., A. Antonioli, M. Cocco & C. Nostro 1996. Global Post–seismic Deformation: Stress Field Changes. (Poster), AGU 1996 Fall meeting, San Francisco, Dec. 15–19, 1996.

[8] Antonioli, A., A. Piersanti, G. Spada & M. Bonafede 1997. Time–Dependent stress field associated with rift dynamics. EUG 9, Strasbourg, 23–27 March, 1997.

[9] Belardinelli, M.E., M. Bonafede & A. Gudmundsson 1997. Orientation of secondary earthquake fractures, EUG 9, Strasbourg, 23–27 March, 1997.

3.7.8 Subproject 7.2 (3.8B): Modelling the earthquake related space–time behaviour of the stress field in the fault system of southern Iceland

In the framework of the EU–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 (SISZ).

The stress drop during earthquakes should be preceded by a stress accumulation before the event. Therefore, many methods in earthquake prediction research aim at the observation of stress changes:

- The determination of fault plane solutions of earthquakes,
- the monitoring of changes in the propagation of elastic waves,
- the measurements of displacements from which strain and stess changes can be calculated or
- the monitoring of electrical conductivity in the crust.

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 data bases.

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.

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. Further more, 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 North–South 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.

3.7.8.1 Methods

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.

3.7.8.2 Modelling Tools

The proposer 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.

With the funding available, the following models (Tasks) are addressed:

Task 1 calculation of the stress field due to motions on the main faults,
Task 2 comparison with the seismic moment release,
Task 3 stress build–up by these motions and stress release by the major earthquakes,
Task 4 forward modelling of the rheological parameters of the lithosphere/ asthenosphere in southern Iceland using data of postseismic deformations.

As a first step, 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 meetings of the European Geophysical Society and the European Seismological Commission.

For Tasks 1 and 2, data are gathered on strong (historical) earthquakes on Iceland and its surroundings.

Towards task 3, at the moment, to 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 the Katla, Hekla etc. volcanoes. Due to the fact, that no coworker 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 proposer - the only one working in this subproject - will have more time to concentrate on this work.

Tasks 1 to 3 should be finished by October '97.

Work on task 4 will start in fall 1997 and will last to January '98.

3.7.9 Publications

Report on first results were given in papers presented at EGS XXIst General Assembly, The Hague, 5/1996, paper SE4–020 and XXV General Assembly of the ESC, Reykjavik, 9/1996, paper SC–A2.21.

3.7.10 Meetings and conferences

Metings between M. Bonafede and coworkers with F. Roth took place in May in The Hague and in September in Reykjavi'k.

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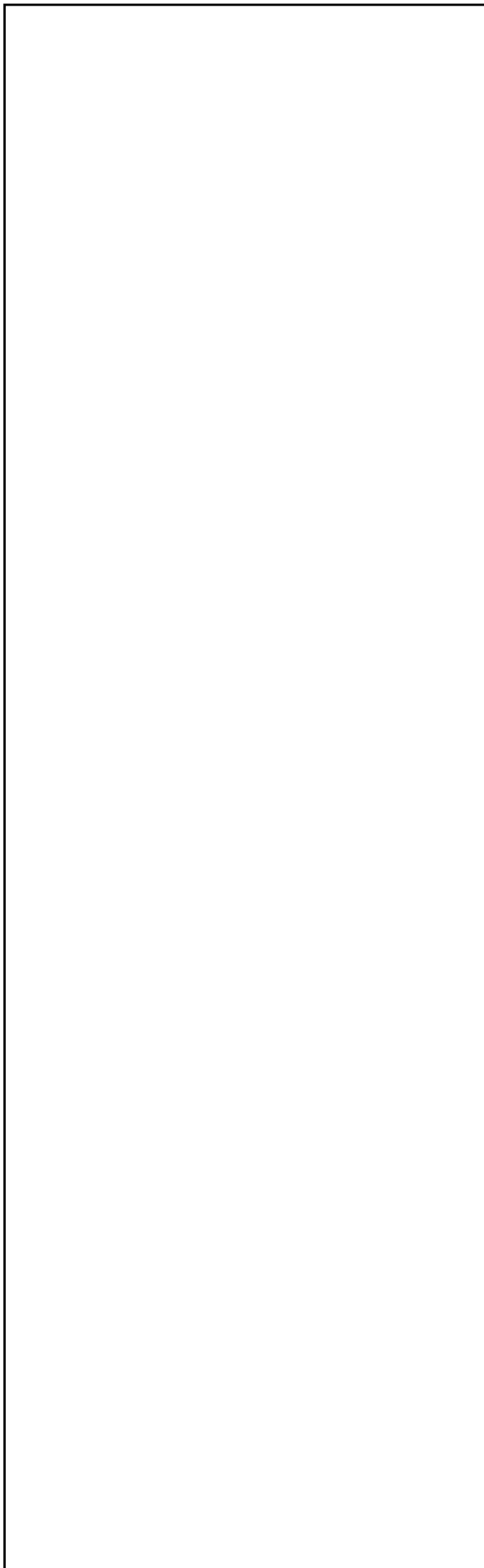

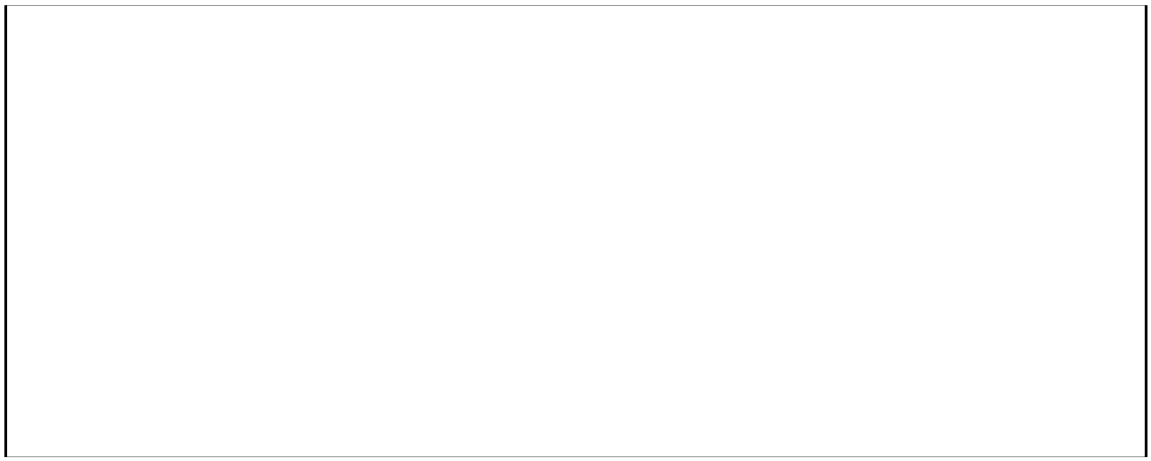

Figure 3: *Tjörnesmyndin hand Sigga*

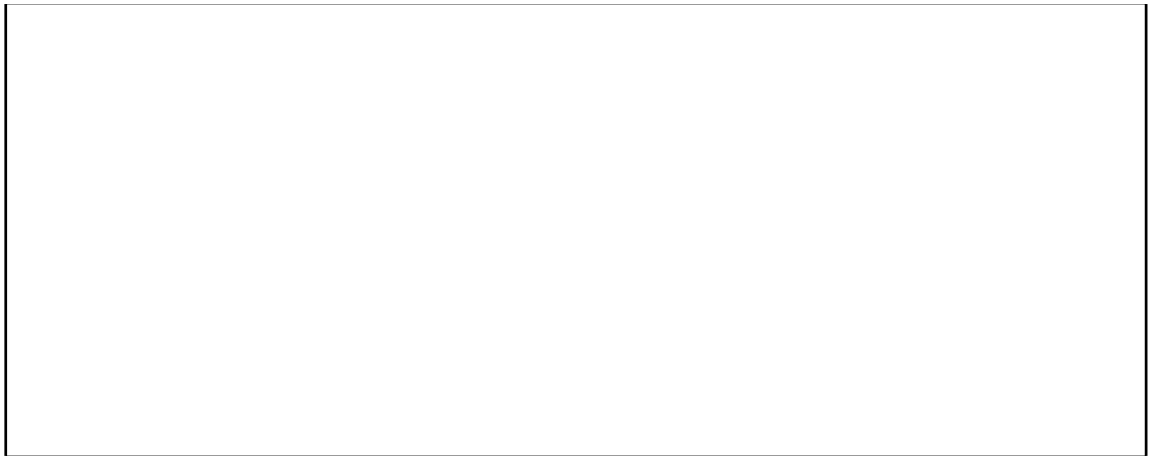

Figure 4:

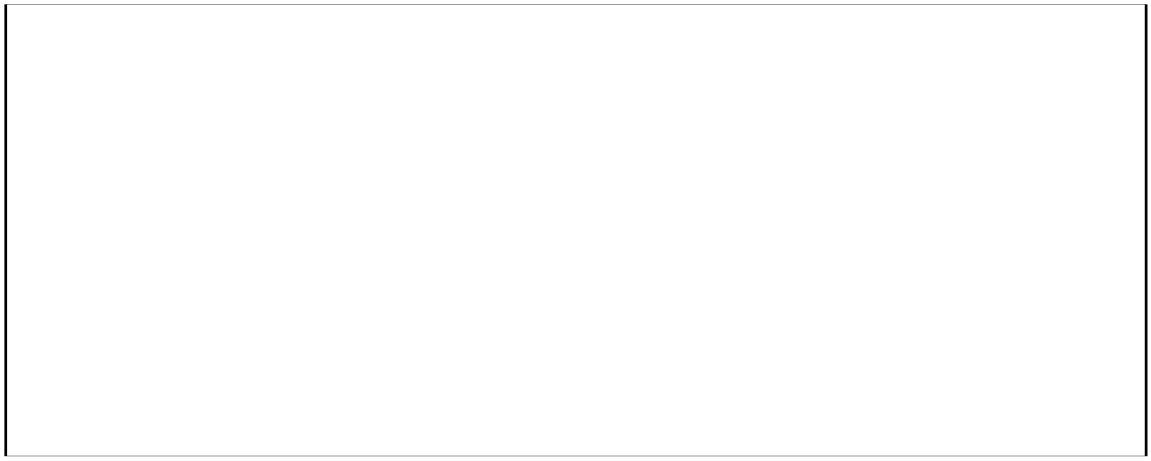

Figure 5: *Stress tensor inversion of microearthquake fault plane solutions is complicated by the fact that two possible fault planes are presented by the seismological fault plane solution. This problem does not exist for geological data. In order to investigate different ways of handling this the geological data presented by Angelier 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 (sigma1 and sigma3) 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 data set indicates the value of including stability considerations into the stress tensor inversion in presence of auxiliary planes.*

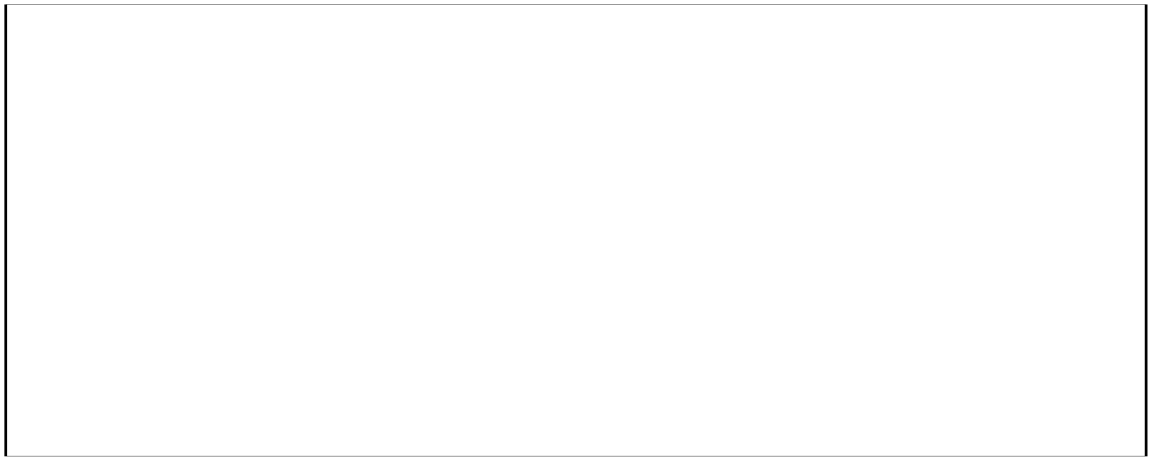

Figure 6: *This is an example of applications of the two methods of figure 1 to real microearthquake data. Both methods gives two quite different optima with maximum principal direction either vertical or horizontal. The main difference is again in the uncertainty and in the choice of fault planes. The purely geometrical method chooses a large number of sub–horizontal planes although the optimum stress tensor indicates strike slip stress conditions.*

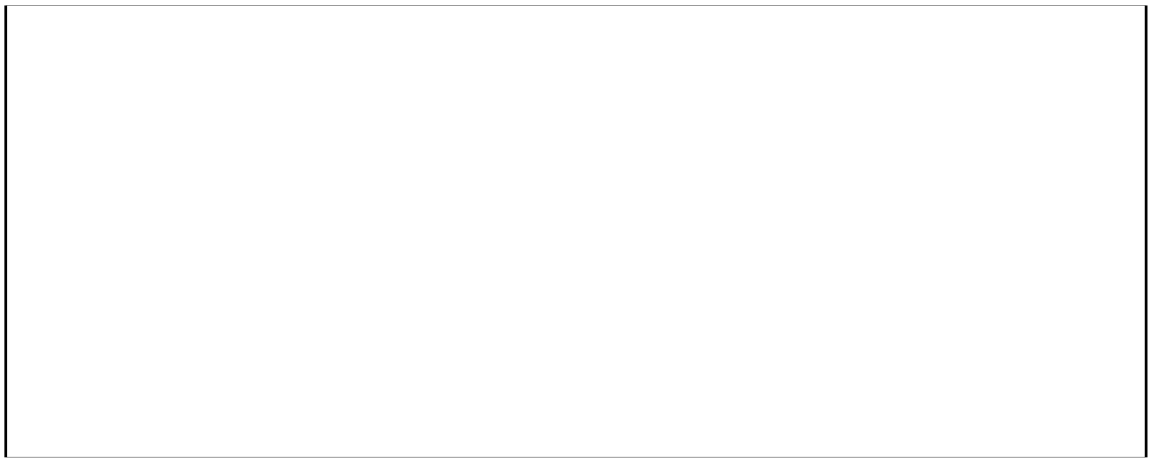

Figure 7: *Map showing seismic station SAU, volcanoes Bárdarbunga and Grímsvötn, and epicentres of earthquakes for 210 days from 1st May, 1996. Triangles are seismic stations, ice fields are shaded, and open bar marks approximate location of fissure eruption.*

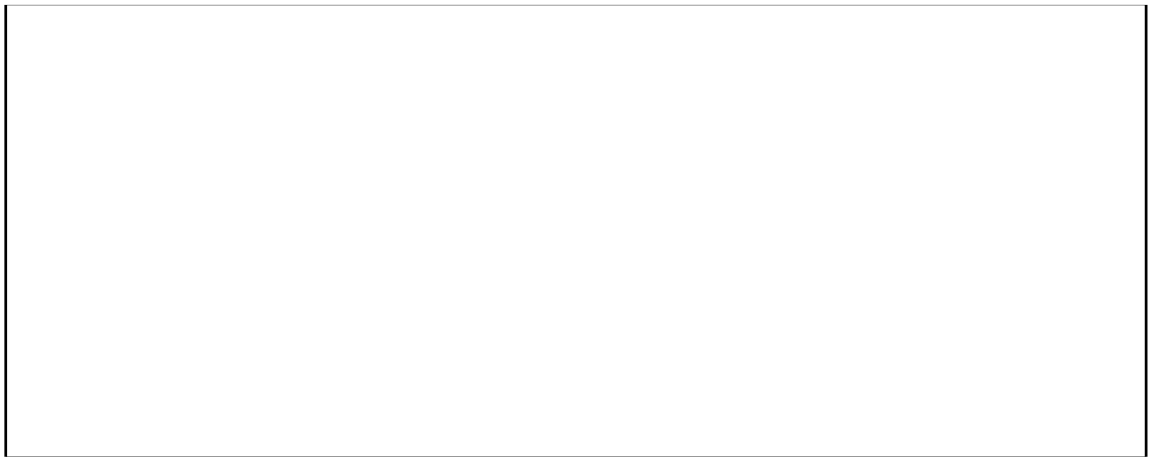

Figure 8: *Three–component seismograms of an earthquake (07h 28m 30.4s, 10th June, 1996) at SAU with time marks are every second. Upper traces are NS, EW, and Vertical components. The lower traces are horizontal components rotated to the faster (N225E) and slower (N315E) shear–wave polarizations show time–delays beteen split shear–waves.*

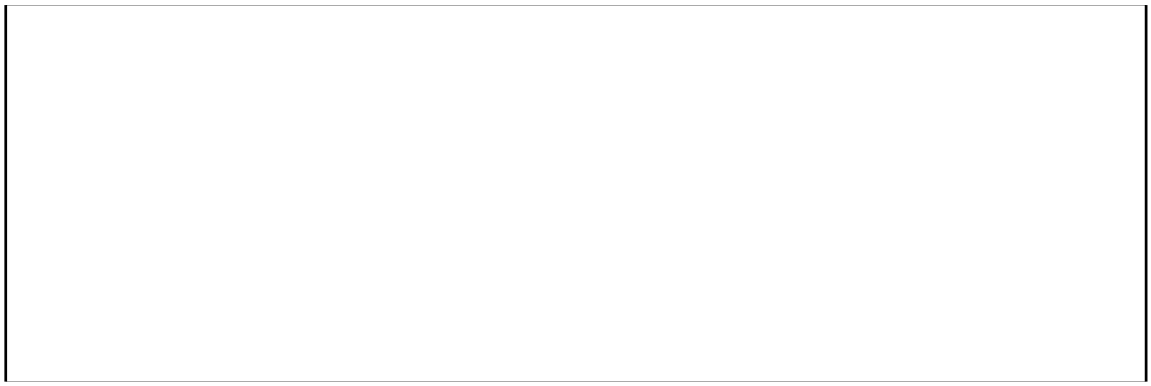

Figure 9: *Variations of shear–wave splitting at SAU for 210 days from 1st May, 1996. Polar equal–area maps out to 45° of (a) shear–wave polarizations, with rose diagram indicating average direction, and (b) circles scaled to normalized time-delays (ms/km), where central dots indicate ray paths in the 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.*

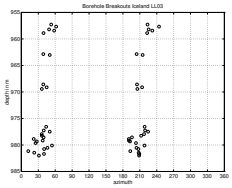

Figure 10: *Myndatexti*

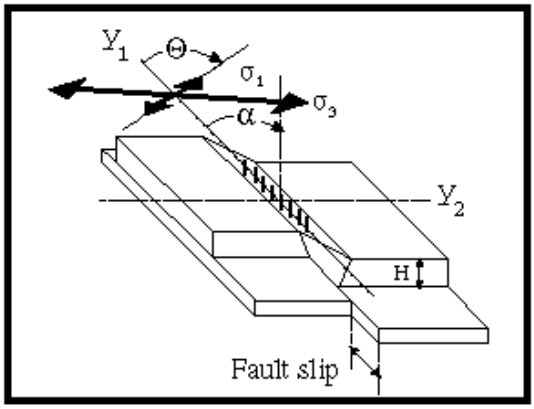

Figure 11:

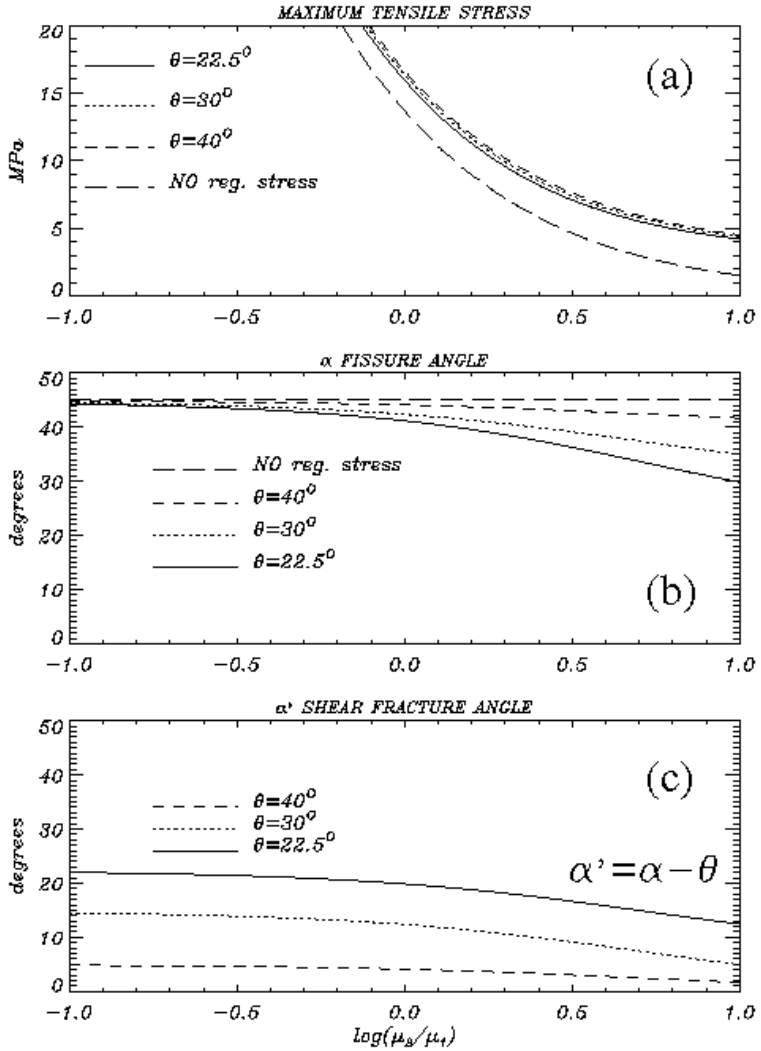
MAXIMUM TENSILE STRESS
MPa
θ=22.5°
θ=30°
θ=40°
NO reg. stress
(a)
α FISSURE ANGLE
degrees
NO reg. stress
θ=40°
θ=30°
θ=22.5°
(b)
α' SHEAR FRACTURE ANGLE
degrees
θ=40°
θ=30°
θ=22.5°
(c)
α'=α−θ
log(μs/μt)

Figure 12:

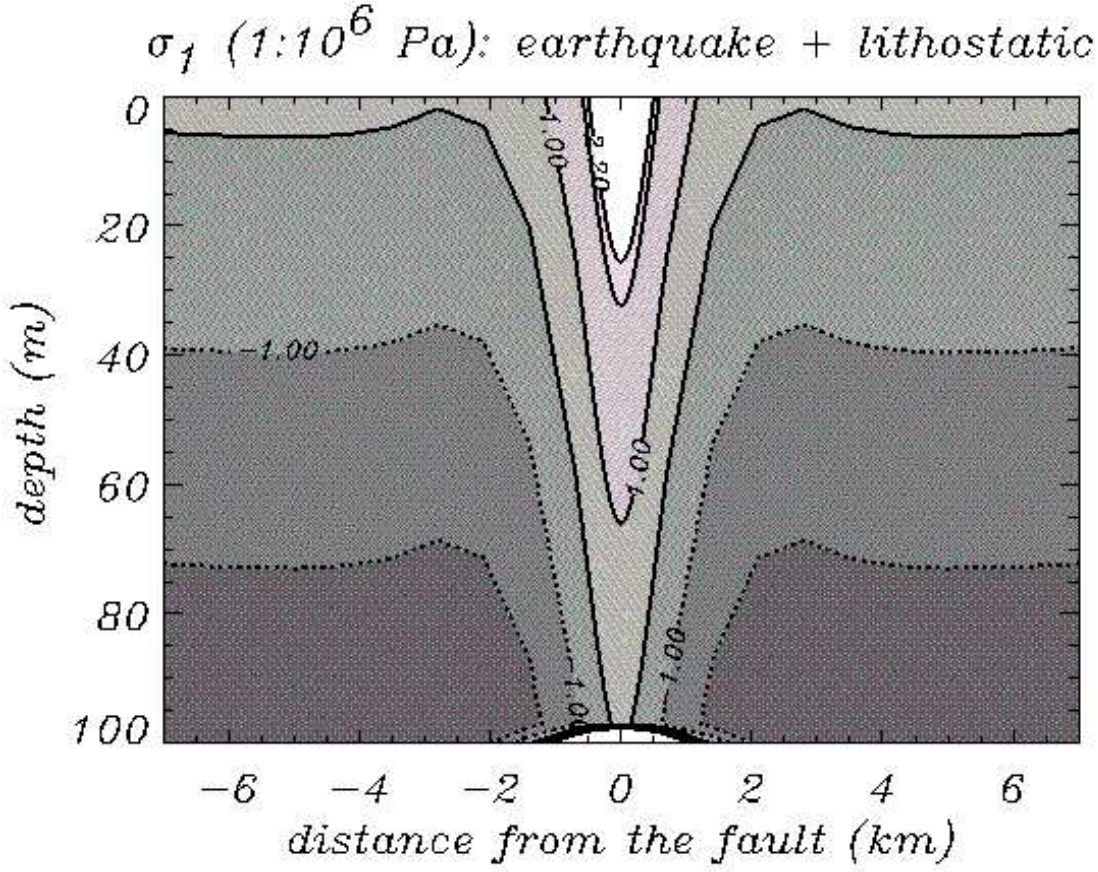
σ1 (1:10^6 Pa): earthquake + lithostatic
depth (m)
0
20
40
60
80
100
−6
−4
−2
0
2
4
6
distance from the fault (km)
-1.00
-2.00
-1.00
-1.00
-1.00

Figure 13:

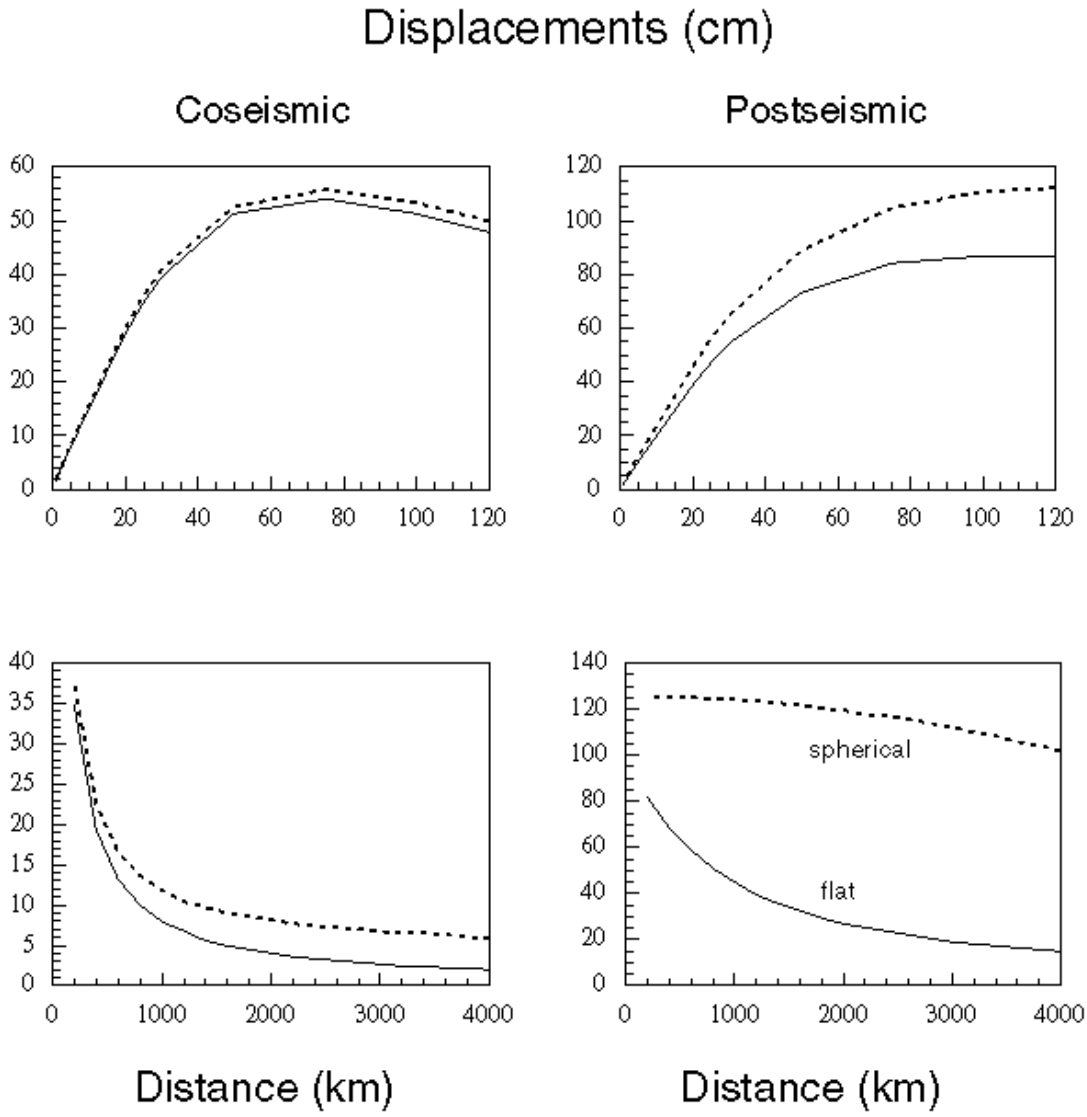
Displacements (cm)
Coseismic
Postseismic
spherical
flat
Distance (km)
Distance (km)

Figure 14:

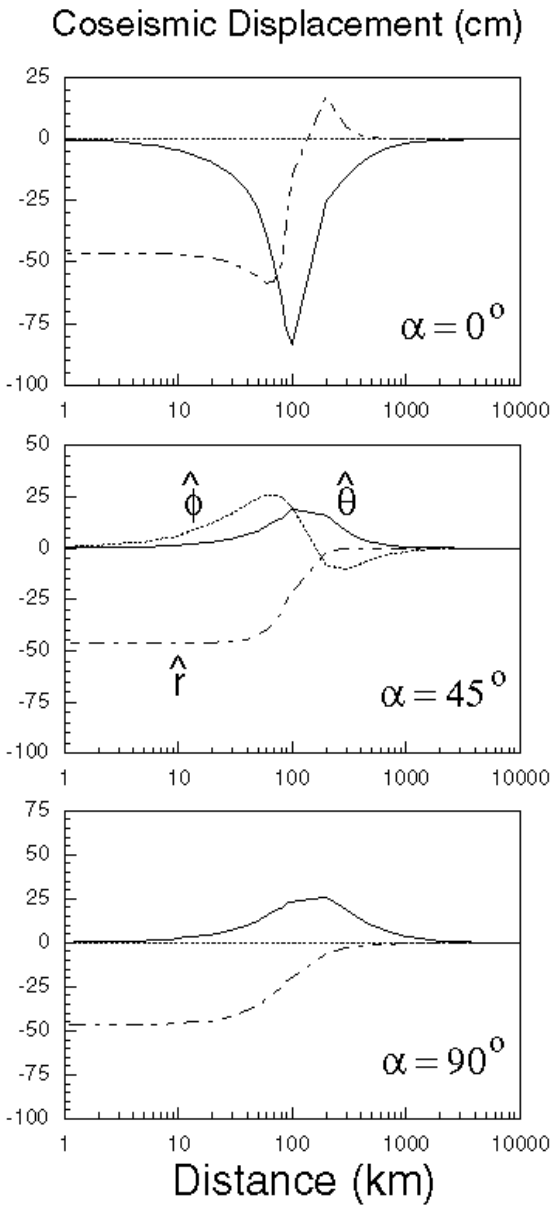
Coseismic Displacement (cm)
25
0
-25
-50
-75
-100
1
10
100
1000
10000
$\alpha = 0^o$
50
25
0
-25
-50
-75
-100
$\hat{\phi}$
$\hat{\theta}$
$\hat{r}$
$\alpha = 45^o$
75
50
25
0
-25
-50
-75
-100
$\alpha = 90^o$
Distance (km)

Figure 15:

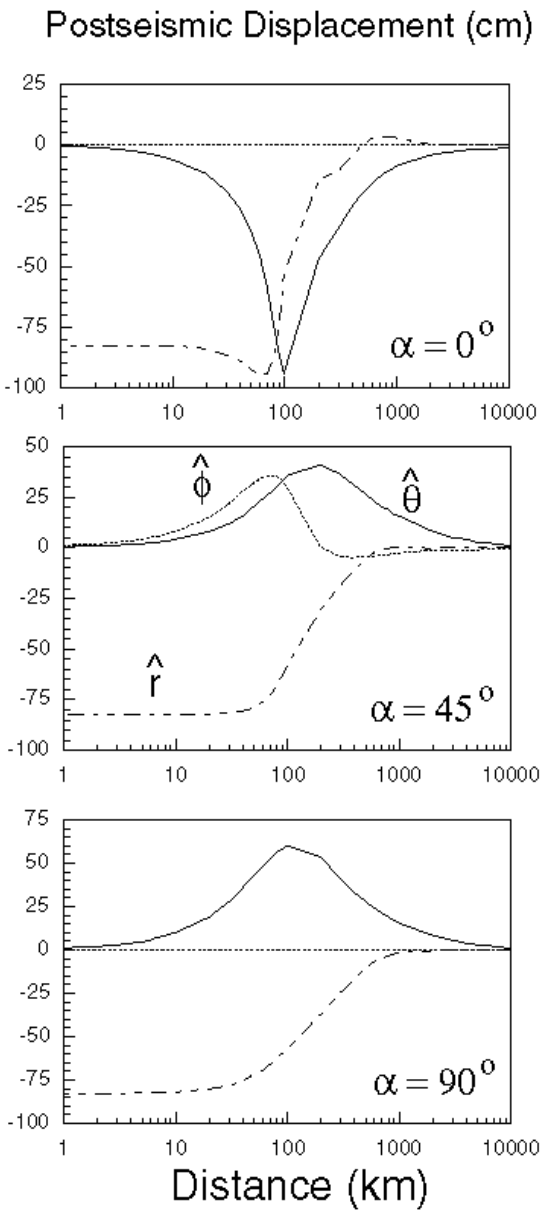
Postseismic Displacement (cm)
25
0
-25
-50
-75
-100
1
10
100
1000
10000
$\alpha = 0^o$
50
25
0
-25
-50
-75
-100
$\hat{\phi}$
$\hat{\theta}$
$\hat{r}$
$\alpha = 45^o$
75
50
25
0
-25
-50
-75
-100
$\alpha = 90^o$
Distance (km)

Figure 16: