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Earthquake-prediction research in a natural laboratory - PRENLAB

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EARTHQUAKE-PREDICTION RESEARCH IN A NATURAL LABORATORY PRENLAB

by

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Summary

PRENLAB is a two years multinational project of earthquake prediction research, starting March 1, 1996. In this project multidisciplinary European technology and science are applied in a common action aimed at progress in earthquake prediction research and at reducing seismic risk. The questions are where, when and how large earthquake ground motions will occur. Answers are sought by studying the physical processes and conditions leading to large earthquakes. Iceland, sometimes called a Natural Geophysical Laboratory, is the test area for the project. The episodic character of crustal movements and high seismicity, the well-defined earthquake zones and shallow sources, as well as the extensive knowledge of the geology and geophysics of Iceland, make it an excellent test area for earthquake prediction research. Frequent short-term variations in strain rate can be utilized as a time variable input to the experiment. Among other significant facilities of this laboratory is the existence of a high quality earthquake data acquisition and evaluation system. The partners of the project come from various branches of geosciences of 11 institutions in 6 European countries: France, Germany, Iceland, Italy, Sweden and United Kingdom. PRENLAB-2, a continuation of PRENLAB is planned to start a two years period March 1, 1998.

Key words

Mitigating risk, Hazard assessment. Multidisciplinary approach, Geodynamic approach, Modelling earthquake processes, Microearthquake technology, Earthquake precursors, Premonitory changes, Short-term warnings, Database.

Introduction

The classical hazard assessment as it has been applied in Iceland and more countries is based mainly on historical documentation and limited information from instrumental earthquake catalogues of this century and a general knowledge of where the earthquake generating plate boundaries are. Although such hazard assessment has been extremely useful in many aspects, it has the obvious limitations that it is only based on a few hundreds of years of history, and in fact assumes that we should only expect hazards that are comparable to those which have happened within this short history. Also it does not take into consideration the exact position of and the interaction of faults that are expected to move in earthquakes or earthquake sequences. It intergrates effects over large areas in time and space while it is well known that by far the largest destruction is related to the proximity of the faults which are activated in the earthquakes each time and to the areas where the faults rupture the surface. Hazard assessment based mainly on catalogues of earthquakes and their magnitudes has come to the state that it cannot have more progress:

- Until a better modelling of the fault processes has been achieved.
- Until we can recognize better the involved faults and monitor their movements and interaction.

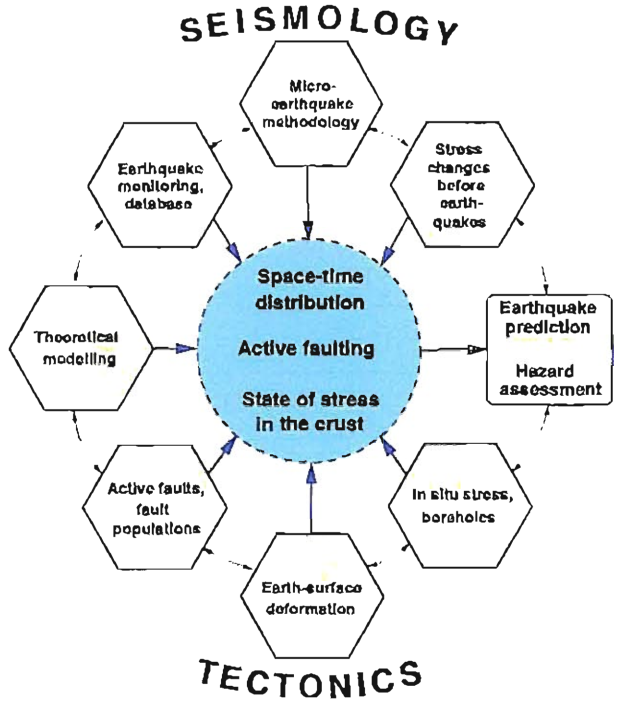

Figure 1: *In the project multidisciplinary European technology and science are applied in a common action aiming at progress in earthquake prediction research and for reducing seismic risk. Scientists from 11 institutions in 6 European countries participate in the project.*

- Until we can monitor better the stresses in the adjacent area and understand better the rheological properties and the role of fluids in the crust.

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

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

The dynamic models to be created must comply with a multiplicity of observations in time scales ranging from seconds to millions of years, ranging from historical seismicity to microearthquake information, ranging from geological field observations to observations of deformation with space technology methods and borehole observations. The PRENLAB project collects information, developes methods and models to base further observations on to create a basis for a more general multidisciplinary modelling (Figure 2).

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

- To develop methods for automatic extraction of all information available in the frequent microearthquake recordings, including fault mapping, rock stress tensor inversion, and monitoring of crustal instability.

- To make use of this information, geological information, historical as well as older seismological information for physical interpretation of and modelling the tectonic processes leading to earthquakes.

- To improve the understanding of the space and time relationship between earthquakes and other observable features associated with crustal deformation.

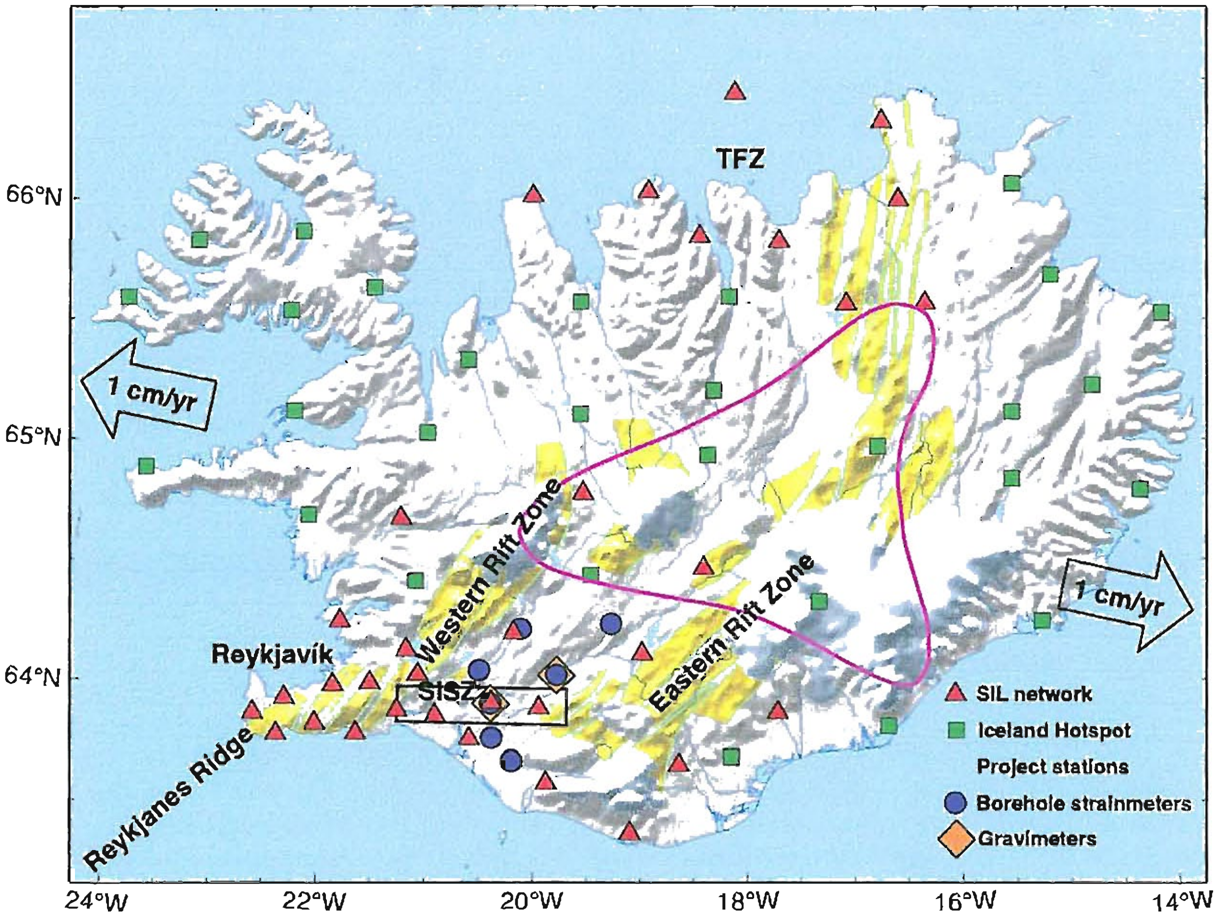

Figure 2: *The available 3 component digital earthquake monitoring in Iceland. The Mid-Atlantic Ridge goes through Iceland from the Reykjanes Ridge along the South Iceland seismic zone (SISZ), the rift zones to the Tjörnes fracture zone (TFZ) in the north. The most destructive earthquakes occur in the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

- To apply this knowledge for improved real-time evaluations and alert systems and for improved hazard assessments.

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

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

is to distinguish between the fault plane and the auxiliary plane. Methods for doing this have been developed with three different approaches, firstly by comparison with geological fault data, secondly by basing on groups of solutions on the same fault and thirdly by applying stability criteria on the possible fault plane solutions for each earthquake.

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

- The geological field studies and interpretations have revealed significant variations in the direction of stress fields in the same area. Such changes have also been indicated in evaluating microearthquakes and former modelling of historical activity also shows the significance of such changes in time and space. The borehole loggings also indicate the existence of stress directions that do not coincide with the prevailing stresses. and also show changes with time.

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

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

- Modelling work on a large scale based on multidisciplinary data is still on a preparatory stage. Much modelling work has been carried out with the purpose of interpreting observations in various fields. An example of this is the modelling of observed tension gashes on the surface following an earthquake, based on knowledge of the upper crustal structure. By this modelling it was concluded that it is possible to draw conclusions about the underlying stress field from open fissures striking a few degrees away from the fault strike. Modelling work has been carried out also with the aim of adapting and developing existing methods for the special conditions in Iceland, with its rifting, time dependency of stress field, etc.

- The significance of the multidisciplinary approach of PRENLAB has been clearly demonstrated in the first steps that have been taken within the project to try to answer the questions where, when and how large earthquakes can be expected in the three main earthquake risk areas of Iceland (Figure 2). These are the SISZ, the Húsavík–Flatey transform fault within the Tjörnes fracture zone (TFZ) in the north (Figure 3), and the seismic zone near to the city of Reykjavík. In the available earthquake history large events do not repeat in the same way in these areas. Prediction, long or short–term, must thus be based on earth realistic models of the present day tectonical conditions in and around the seismic zones [74, 76].

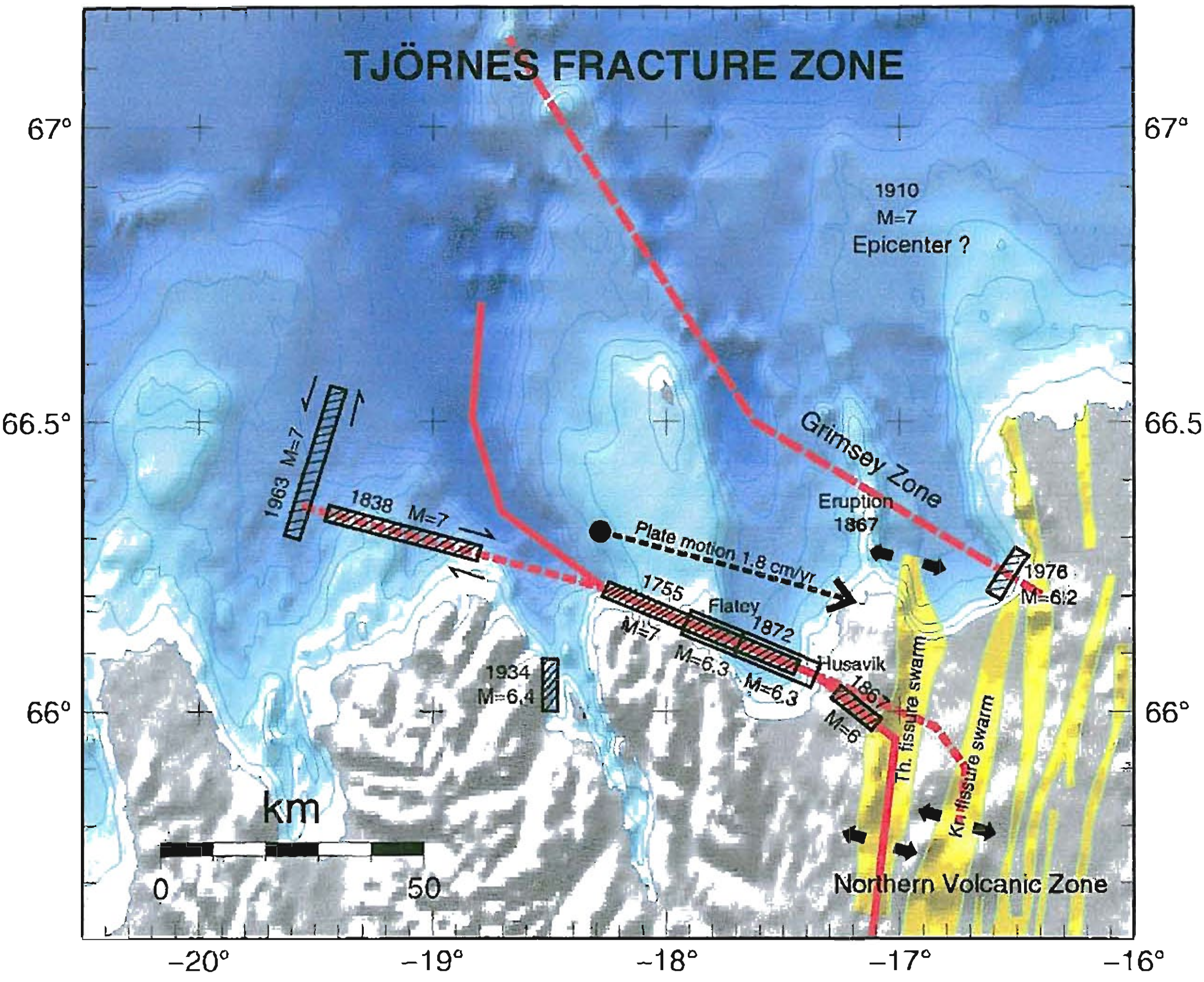

Figure 3: *The Tjörnes fracture zone is a complicated right-lateral transform zone which connects the rifting in the northern volcanic zone of Iceland to the ESE–WNW rifting in the Mid-Atlantic rift zone to north of Iceland. The general plate motion according to NUVEL-1A is indicated. The red lines indicate the lines where it is proposed that the most significant transform–rifting motion presently takes place. The most pronounced feature is the Húsavík–Flatey transform fault, which with its proposed westward continuation is the only well developed transform fault of Iceland, up to 10 million years old. Historical seismicity has been interpreted and is assumed to lie mostly on this fault. The Grímsey zone is much more volcanic and geologically a more recent feature. These two zones are proposed to take up the main part of the plate motion. It is not known what is the contribution of each, and it is assumed this is variable with time, depending on changing conditions in and around the fracture zone.*

In the following the methods and result of the PRENLAB project will be described in more detail.

Methods and results

$\boxed{1}$ Real–time evaluation of earthquake–related–processes and development of database

The work described here is basically a responsibility of the Icelandic Meteorological Office, Department of Geophysics (IMOR.DG) in cooperation with all the other groups involved in PRENLAB. In developing methods for acquisition and evaluations there has been an especially close cooperation with Uppsala University, Department of Geophysics (UUPP.DGEO).

Extension of the monitoring networks

A very significant achievement in the data collection is the increase of number of operating seismic stations in Iceland. Since the start of the PRENLAB project in March 1996, the number of permanent seismic stations, SIL stations, in operation has increased from 18 to 33. The new stations are funded by Icelandic communities, hydrothermal and hydroelectrical power companies, civil defence funds, a private tunnel–digging company, the Icelandic Research Council, and indirectly by research groups carrying out tomographic studies, which can make use of the powerful SIL acquisition system. The largest supporter of this build–up project of the SIL system is IMOR.DG, which besides contributions to the initial costs guarantees the operation cost of the system. These stations are as other permanent stations of the SIL network available for the PRENLAB project and of great significance for it.

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

Acquisition, evaluation and storing of data

A refined and easily accessible database for seismic data, mainly based on microearthquakes acquired by the SIL system is under construction. Since 1991, 90.000 earthquakes have been recorded by the SIL system. The data were automatically evaluated and manually corrected.

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

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

In order to insure against loss of data, procedures and facilities have been developed to back up all data onto magnetic tapes. All new data and modifications are written to tape each day and all data are written to tape approximately every two weeks. Periodically, a set of tapes is moved for storage to a different site. As magnetic tapes only last a few years, and the long–term stabilty of optical storage media is not well established, this is possibly the most effective way to permanently preserve the data, and it has the advantage that the data is always readily accessible [52].

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

Work has been carried out for a new, reevaluated and refined catalogue of instrumentally measured 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 [47].

Spatial changes in seismicity have been studied in an area along the Reykjanes Peninsula, the South Iceland Lowland, into the eastern volcanic zone, and off coast of north Iceland [46, 56, 66].

Work has been carried out for refined estimation of magnitudes and locations of historical earthquakes as well as felt events, not instrumentally detected since 1926 [45].

Much work has been carried out in interpreting data from volumetric borehole strainmeters, which has lead to very significant results. Premonitory and coseismic changes, volumetric strain, and foreshocks of the magnitude 5.8 earthquake at Vatnafjöll, near the eastern end of the South Iceland seismic zone, have been studied. These can be interpreted and have been modelled as magmatic fluids intrusion coinciding with the foreshocks and the main shock [11].

A long-term overview (since 1979) of 7 volumetric strainmeters in the SISZ (Figure 2) has been worked out. Methods have been developed for correcting the strainmeter record of weather influences. As a result of this work can be mentioned a change in strainrate 5–6 months before the start of the 1996 eruption in Vatnajökull, which may be caused by magma intrusion there, i.e. more than 150 km from the strainmeter stations [7, 8, 77].

The seismicity of Katla volcano which is beneath the Mýrdalsjökull glacier has been studied. Eruptions in Katla pose a considerable danger because of enormous water- and mudflows which accompany the eruptions. It is one of the objectives of the SIL network and the attached alert system to help to warn for the the future eruptions [43].

The seismicity of the volcanic eruption in Vatnajökull was studied as concerns hypocenters and mechanism of the earthquakes which were linked to the eruption. Much effort was put in saving data on this remarkable eruption from the seismic networks, both earthquake data as well as data on volcanic tremor. Vatnajökull is directly above the Iceland mantle plume and changes of the plume activity greatly affect the seismicity along all of the plate boundary in Iceland, and is thus of a great significance for the PRENLAB objectives [75, 79].

Although the SIL system is a seismic data acquisition system, that is primarily designed for automatic acquisition and evaluation of data from local microearthquakes, it can also be used for collecting teleseismic and regional data for deep structure studies. It broadens the scientific use of the network and has made it easier to obtain funds for extending the network to a large part of the plate boundary in Iceland. The SIL station software has now been modified allowing for selection of waveform data additionally at 20 and 4 samples per second. This makes it economically possible to save long time intervals of seismological data from the SIL stations. We have developed an automatic procedure to select and store teleseismic data in the SIL system, based on USGS/NEIC information on teleseismic events in the whole world, which are measurable in Iceland. From USGS NEIC we receive E-mail messages with a single-line information on earthquakes they have determined, the so-called "E" type messages. A selection program reads the messages and selects events that fulfill certain criteria of magnitude and epicentral distance. The program uses the IASPEI91 model to compute the first arrival time at each station. The teleseismic body wave data are fetched with a sampling rate of 20 samples (in some cases 100 samples) per second and the surface wave data with sampling rate of 4 samples per second from the 1-3 days long ringbuffer of the SIL site stations. Since mid-year 1996 waveform data from 230 teleseismic events have been stored by this automatic procedure [44].

A real-time filter has been introduced into the on-line process of the SIL system, to be tuned for detecting harmonic tremor and signals which now are not identified automatically. The continuous seismic signal at the SIL site stations is bandpass filtered at 0.5–1 Hz, 1–2 Hz and 2–4 Hz and the 1 minute mean amplitude is scanned and sent to the SIL center. Visual presentation of this data gives a useful indication of the multiplicity of activity in real-time. This data has been calibrated and procedures developed to estimate magnitudes of local events larger than magnitude 2, independent of the waveform processing [53].

The extension of the SIL system into the highlands of Iceland has lead to many problems in the automatic detection and analysis which are gradually being solved. The SIL system was developed for use in the seismic zones. Automatic monitoring in the highlands revealed in many ways new problems because the crustal structure is not as well known and the earthquake sources are often more complicated. Much work has been carried out to lower the detection threshold for earthquakes in the volcanic Central Iceland. The new real-time filter mentioned above is significant for this purpose as well as further tuning of all detection parameters [48].

To search for time and space patterns in the multiplicity of information in the SIL data

Results have been obtained in using seismological data for mapping active earthquake faults in the Tjörnes fracture zone at the north coast of Iceland (Figure 4). The method used is a

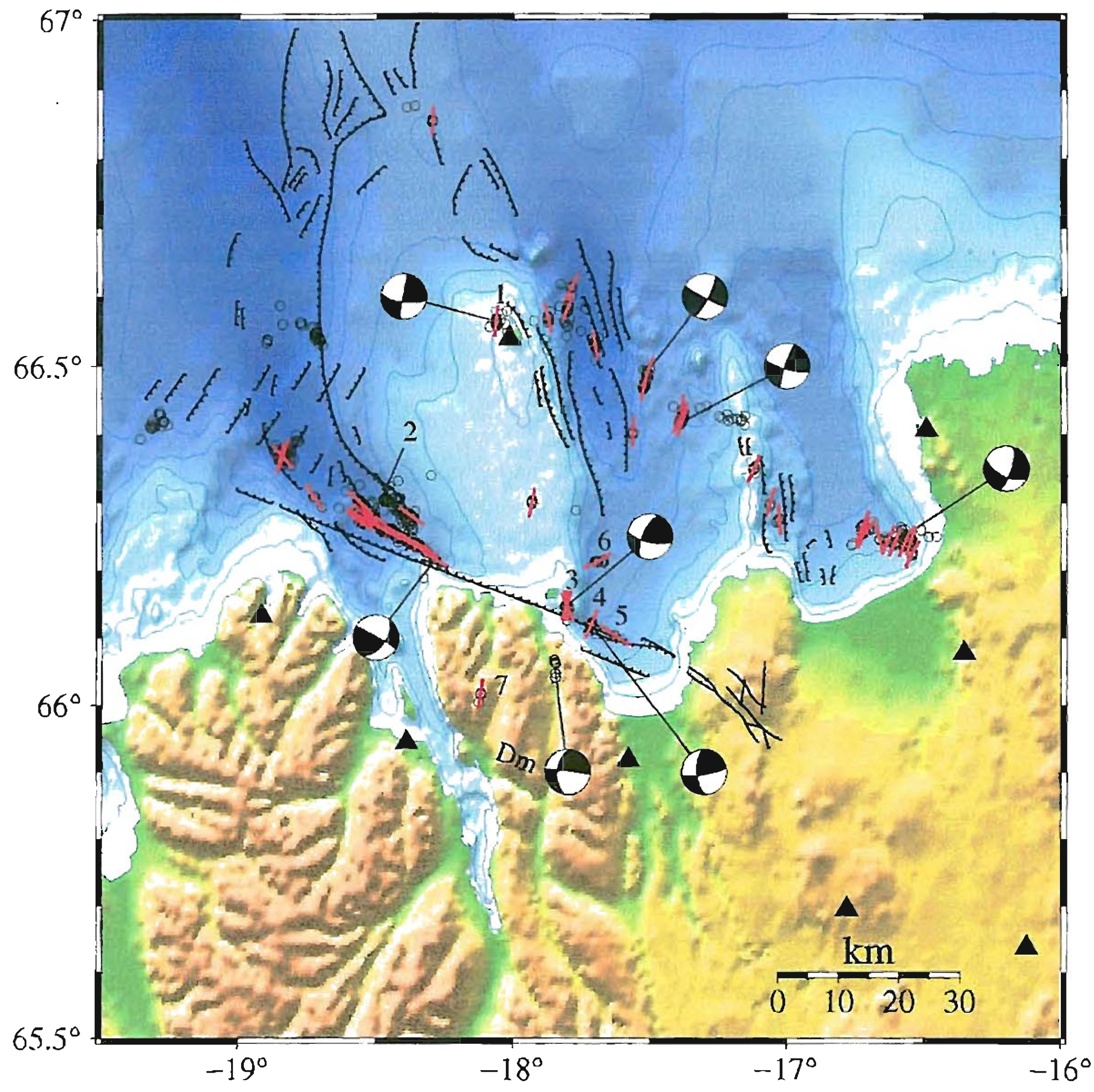

Figure 4: *Mapped faults within the Tjörnes fracture zone off the north coast of Iceland. Black lines indicate faults mapped with conventional reflection seismic methods or by direct observations on-land. Red lines are 60 active fault segments mapped using accurate relative locations of microearthquakes recorded by the SIL network. Seismic stations are denoted by triangles. Dark patches are sites of recent volcanism. The depth contour interval is 100 m.*

multievent method based on cross-correlating similar signals at the the same seismic station [65]. Provided the time accuracy of the seismic data of the SIL system, close to 1 millisecond, active faults can be mapped with accuracy of the order of 10 meters. Fault plane solutions based on spectral amplitudes of P- and S-waves are then used as a part of the mapping to reveal the sense of the fault motion. Several special fault mapping efforts have been carried out related to ongoing earthquake sequences in other parts of the country, so gradually information on fault arrangement in different parts along the plate boundary is being collected.

Results have been obtained on basis of investigation of recent high seismic activity near the Hengill triple junction in SW-Iceland, spatial and temporal variations of activity have been studied and migration within the area. Fault plane solutions of more than 20.000 earthquakes have been studied in the area and faults have been mapped by multievent location procedure (Figure 5) [63, 64].

Introduction of new algorithms into the alert system and other evaluations of the SIL system

The basic option of the SIL seismic system techniques is to use microearthquakes to bring to the surface information from the source areas of earthquakes. Based on detailed microearthquake analysis it is possible to monitor active faults and movements across these, as well as stresses and stress changes in their surroundings. The smaller the earthquakes are which can be used the closer we are to continuous monitoring of such features, and the more detailed information we obtain of the spatial conditions. Therefore it is so significant to be able to obtain automatically as detailed and secure information as possible [50].

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

Preliminary testing has demonstrated that the approach described here is possible. It is expected that the first version of the algorithm will be ready for automatic routine operation within the SIL system in October 1998, and thus as a basis for an enhanced alert detector algorithms.

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 and background noise (tremor) in both unfiltered and filtered bands of the seismic waveform data is operated on all the SIL stations. It has been tuned for different types of sensors as the SIL system operates according to need with 1 second, 5 seconds and broadband sensors [9, 10, 49].

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

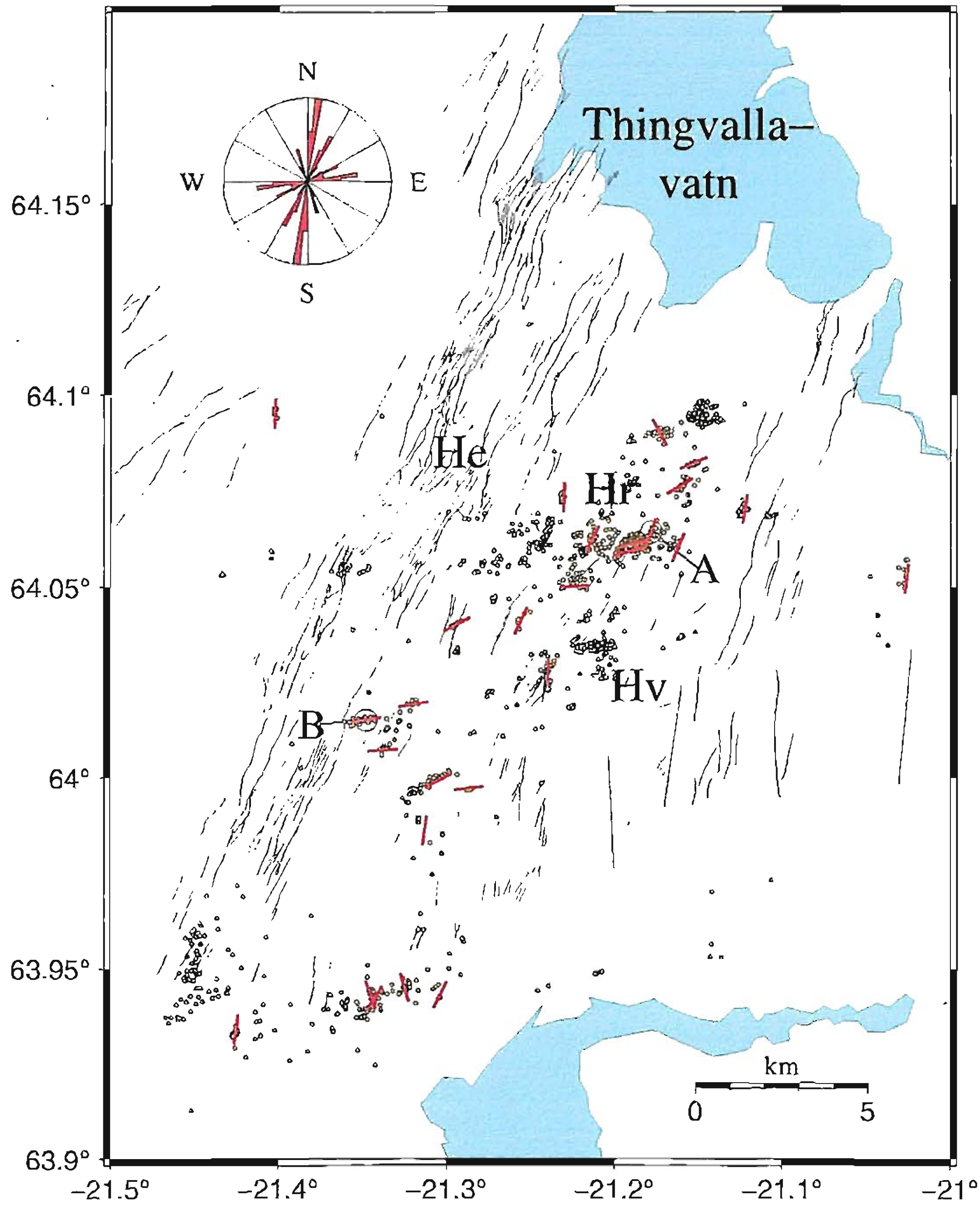

Figure 5: *Earthquakes in the Hengill volcanic area, SW-Iceland. The red lines show the location and orientation of fault planes estimated from the relative location of earthquakes. The black lines are mapped surface faults, yellow circles are relocated earthquakes. The inset rose diagram shows the orientation of the 28 faults mapped using accurate relative locations of earthquakes.*

noise monitoring is already now used to monitor volcanic acivity. The experience will also be a good basis for designing a new detector in the SIL system which will be aimed at detecting and automatically evaluating "slow earthquakes" (meaning small earthquakes with corner frequencies of the order of 1 Hz) which are often observed in Iceland.

Retrieving of data and other preparatory work for modelling destructive earthquakes

Work has started to retrieve seismic data and older models which have direct relevance for modelling where, when and how catastrophic earthquakes occur in three of the main seismic risk zones of Iceland. These are the SISZ, the TFZ and the seismic zone close to Reykjavík. Models based on older information from seismological, geological and geodetic information will be a significant input to the modelling work based on the new multidisciplinary approach of PRENLAB [78, 80].

A tentative model of earthquake occurrence based mainly on data on historical and recent seismicity and older geological data and tectonical interpretations has been set up for the TFZ (Figure 3) [81].

Although much of the plate motion is probably taken up by a main transform fault it would be wrong to assume that the earthquakes on this fault would follow a simple kinematic model of stable/unstable strain release as a result of an even plate motion in its surroundings. Based on geological evidence it is indicated that during the last tens of thousands to hundreds of thousands of years this transform fault only takes up a small fraction of the total plate divergency. However, the earthquake activity during the last 200–300 years suggests that presently most of the transform motion is taken up by this fault. Also it is evident from these data that large earthquakes repeat in a different manner on the same fault segments.

What is said here highlights the significance of earth realistic modelling of the present day general seismotectonic conditions in this zone for long or short term prediction of hazards.

Evidence from historical seismicity or the lack of evidence in the other main risk zones highlight the same for these zones. We do not see the repetition of "nearly identical" hazardous earthquakes, highlighting the significance of earth-realistic dynamic models for these zones.

$\boxed{2}$ Development of methods using microearthquakes for monitoring crustal instability

The SIL microearthquake system produces detailed results of automatic analysis of large number of microearthquakes. To be able to work efficiently with this kind of information a special interactive program had previously been created. During the PRENLAB project, this program has now been further developed and allows now the results from single event location, from multievent location, from fault plane solution, and from rock stress tensor inversion as input. The program can now be used for steering results from one analysis to another, for example can the relative locations give constraint on the fault plane orientation which can be used in the input for both fault plane solutions and rock stress tensor inversion. The development of this interactive software has also required modifications in all other software to facilitate the information flow between the different algorithms. The work detailed in this chapter is basically the responsibility of Uppsala University, Department of Geophysics (UUPP.DGEO) [26,65,72,73].

Methods for subcrustal mapping of faults

The algorithm for absolute and relative location of microearthquakes has been implemented in the SIL system routine analysis. This software has been applied in a search of crustal faults, both in the TFZ and the SISZ. This work has been in cooperation with geologists within PRENLAB and these faults, found from the microearthquakes, show a remarkable agreement with the fault information available from sea bottom and land surveys. These studies also indicate the power of the multievent location technique for discriminating the fault plane and the auxiliary plane.

An example of the results using this algorithm is shown in Figure 4.

Methods for monitoring the local rock stress tensor

New methods and software have been developed to estimate a regional or local stress tensor based only on microearthquake focal mechanisms and locations [72]. The inversion scheme is based on existing techniques which has been improved along two major lines of work:

- The method takes advantage of the SIL fault plane solution algorithm and is thus able to handle a range of acceptable fault plane solutions for each event which significantly improves the stress tensor estimation (Figure 6).
- The crucial point of choosing which nodal plane to include in the inversion, i.e. choosing the fault plane, has been tackled both the traditional way, by goodness of fit between observed slip and estimated shear-stress direction, and with two new approaches. The fault plane can be chosen as the one least stable, using a simple Mohr-Coulomb criterion, in the tested stress regime or with information from the fault mapping SIL system algorithm for absolute and relative location. Difficulties concerning the generality of the stability algorithm have recently been solved. Both new methods show very promising results (Figure 7).

The software has been developed and implemented in the SIL system context. Tests with synthetic data, semi-synthetic (geological) data and real data from Iceland have been performed [55].

Methods for monitoring of stable/unstable fault movements

Methods are in development for monitoring what usually is characterized as aseismic fault movement by use of microearthquakes. The commonly observed interaction between microearthquakes, often over large distances compared to the earthquake sizes, is most probably related to deformation expressed by stable aseismic slip. Utilizing the extensive information carried by the large amount of microearthquakes has the potential to find a rock-mechanical connection between microearthquakes during episodic activity. In principal this opens indirect possibilities to achieve knowledge about the aseismic fault slips. Such an analysis may be performed by deducing possible aseismic fault movements from the microearthquakes and vary unknown parameters to put the earthquakes into physical chains of effects and consequences. This approach is totally physical (rock-mechanical) and can be expected, together with theoretical models, to develop models of fault slip process. Such models based on laboratory studies have already been proposed and have found great support from numerical modelling and comparisons with earthquake observations [25,27,67].

Methods for monitoring crustal wave velocities from microearthquakes

Work has been carried out to find 3-D crustal velocity structure in SW-Iceland from local earthquake tomography. The first results show a very interesting velocity anomaly at the lower boundary of the brittle crust which may significantly influence the the modelling of the tectonics of the SISZ (Figure 8) [84].

$\boxed{3}$ Monitoring stress changes before earthquakes using seismic shear-wave splitting

The World Wide Web is being used to access seismic data from the SIL seismic network at IMOR.DG. Seismicity maps demonstrate that a number of stations are sited over sufficient seismicity for analysis of shear-wave splitting to be viable. This work is mainly the responsibility of University of Edinburgh, Department of Geology and Geophysics (UEDIN.DGG).

Observed stress dependent shear-wave splitting

Shear-wave splitting is widely observed (Figure 9), displaying unusually large time-delays prob-

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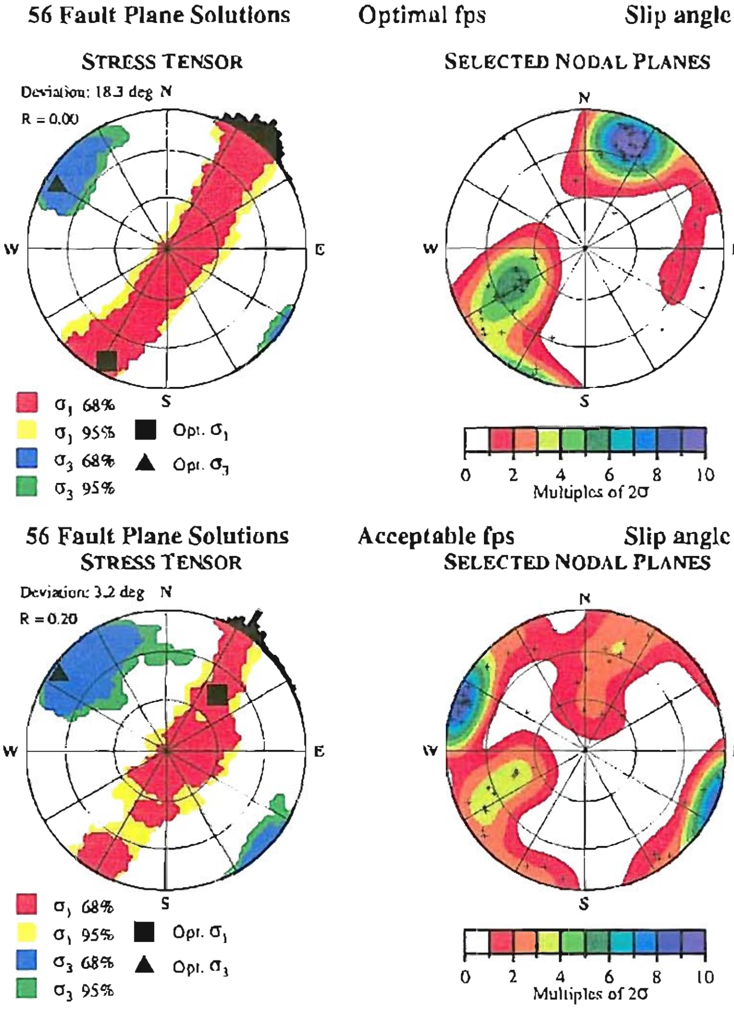

Figure 6: *Example of stress tensor inversion using 56 microearthquakes in the SIL area. The figure shows lower hemisphere equal area projections, in the left column are the resulting principal stress directions with 68% and 95% confidence limits and the optimal solution marked by a black square, σ_1, and a black triangle, σ_2. Deviation is the average angular misfit for the optimal solution, $R = (\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$, is the relative size of the intermediate principal stress. The black rose diagram around the circle is the 95% confidence limit for the direction of maximum horizontal compression. The right column shows the nodal planes that the inversion algorithm picked as fault planes. The plus signs are the poles to the individual planes and they have been overlayed by a Kamb contour diagram. The upper row shows the result when only the optimal fault plane solutions (fps) were included in the inversion and the lower row is the result when a range of acceptable fps were used for each event. We see that although the confidence limits for the stress directions do not change much the deviation decreases dramatically when using acceptable fps. There is also a large difference in the chosen fault planes. In the optimal fps case the algorithm picks NW-SE striking subvertical planes and a large number of subhorizontal planes. The acceptable fps case on the other hand picks mostly NE-SW striking subvertical planes and fewer subhorizontal planes [72].*

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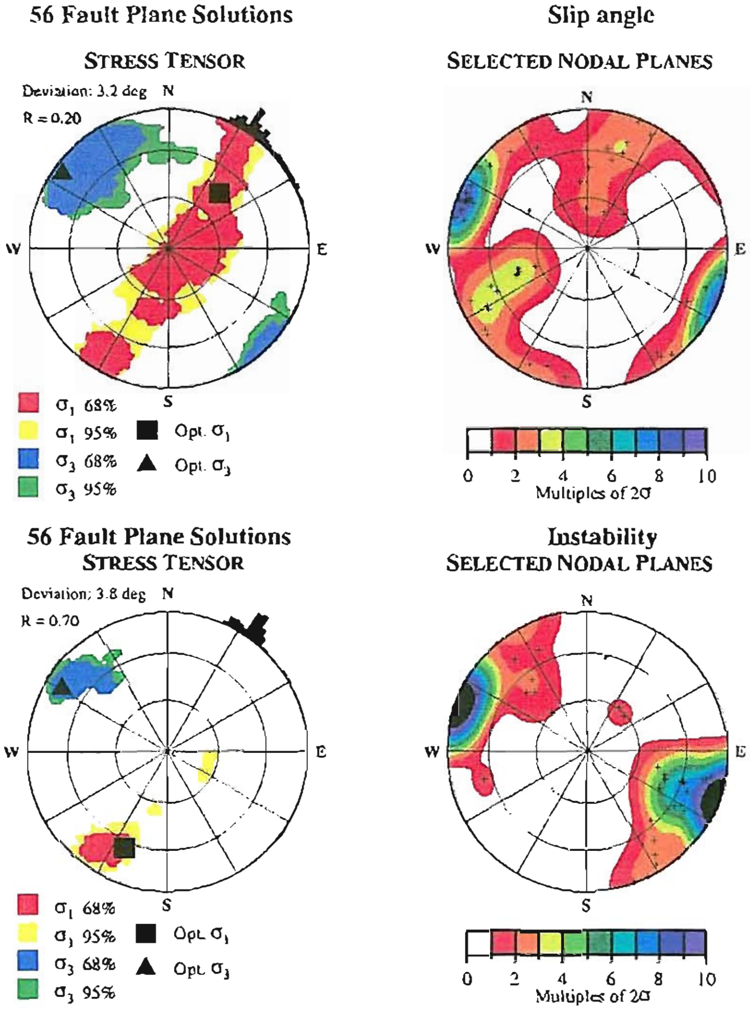

Figure 7: *Same 56 microearthquakes as in the previous figure but now inverted with different nodal plane picking algorithms. Both examples in this figure have been inverted with acceptable fault plane solutions (fps). The upper row is the same as the lower row in the previous figure and used a plane selection criterion based solely on the fit of the theoretically calculated shear-stress direction to the direction of observed slip on the plane. Whichever plane had the smallest misfit angle was chosen. In the lower row a more physical criterion was applied. The plane with lowest stability, calculated using a simple Mohr-Coulomb failure criteria, was chosen as the fault plane. This criterion gives a slightly higher average deviation, but as can be seen in the figure, much more well defined principal stress directions. The direction of maximum horizontal compression is likewise more well defined and the stress regime is now more decisively strike-slip. The chosen nodal planes are preferably NE-SW striking subvertical planes for both algorithms although the instability method picks them more frequently and does include very few subhorizontal planes [72].*

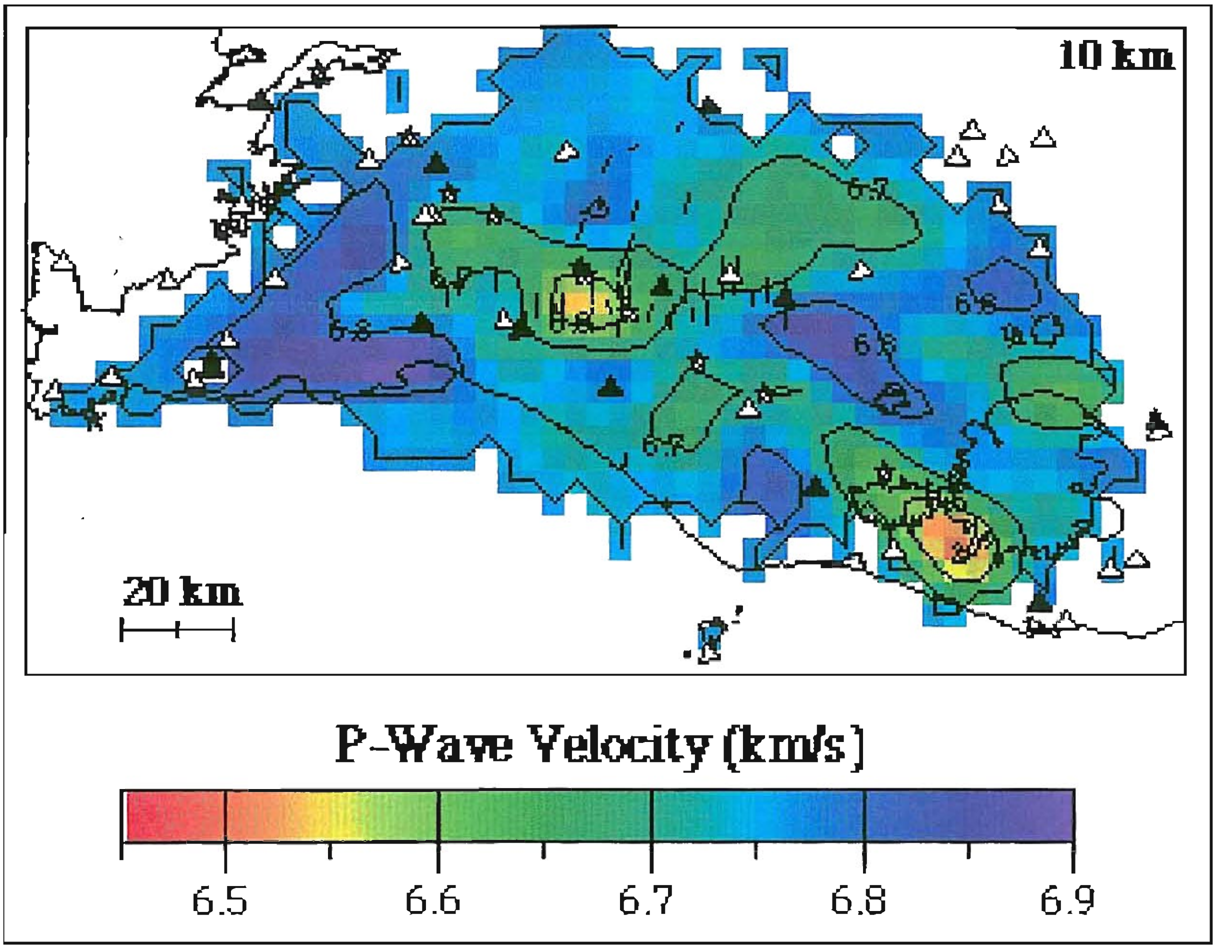

Figure 8: *3-D P-wave velocity at 10 km depth in the crust beneath SW-Iceland estimated from local earthquake tomography.*

ably caused by high temperatures and/or high pore-fluid pressures both of which may well be present in the upper crust in Iceland (Figure 10) [26,28,29,30,31,32,33,34,35,36,37,54,89,90].

The remarkable observations are that, the first 200 days of the first SIL seismic station examined, which was the station SAU in the SISZ, showed variations in shear-wave splitting similar to those observed before 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 workshop in Reykjavík, September 10, 1996, but since this was the first data analyzed from SIL, the interpretation was not confirmed. In fact, SAU is about 160 km WSW of the eruption on September 30, 1996, beneath the Vatnajökull ice cap. Since the eruption more data have been analyzed and it is planned to better constrain the observations before the eruption by more observations also in that time period. Figure 11 shows the different behaviour of shear-wave splitting between ray path directions 0°–15° and 15°–45° to stress directions. 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 [62,79].

The observed variations at SAU suggest that shear-wave splitting may be a very 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.

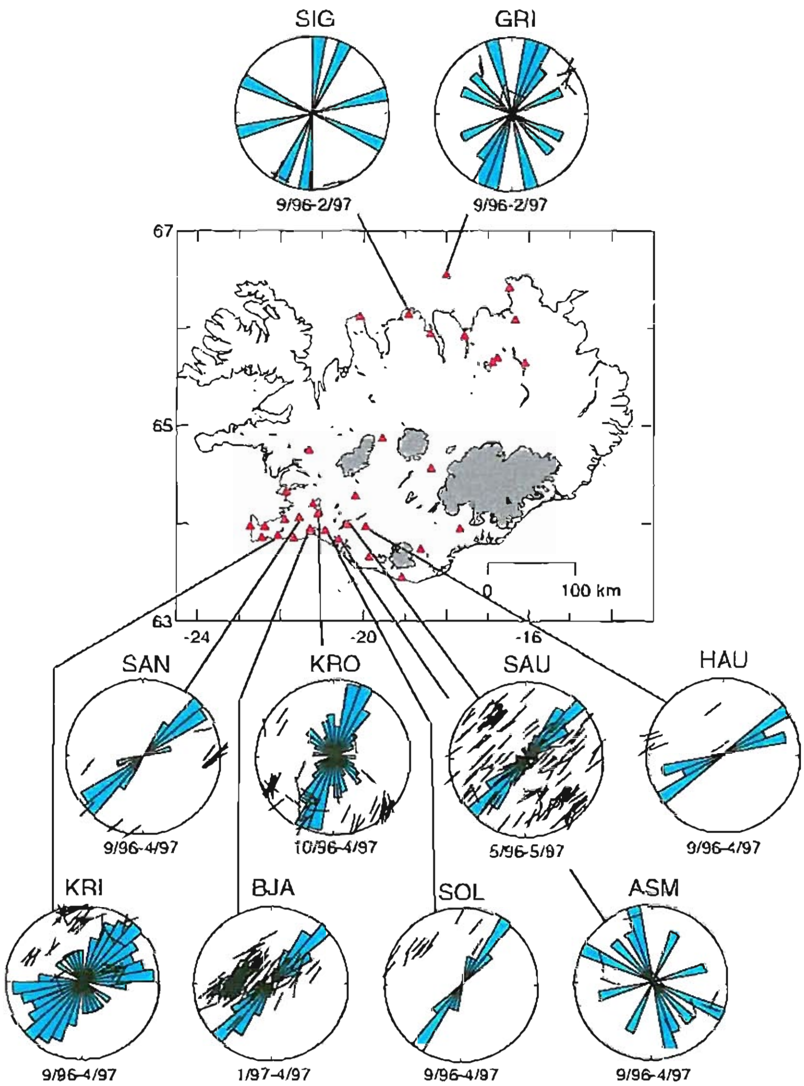

Figure 9: *Map demonstrating ongoing work in studying shear–wave splitting polarizations below seismic stations in Iceland, where seismic data are available with angle of incidence within the shear–wave window, during September 1996 – April 1997.*

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

Identify optimum areas and developing routine techniques

The ongoing work of will gradually allow the identification of suitable areas for deployment of more closely spaced SIL stations for more effective studies of precursory changes. Development is planned of routine techniques that can be used for real–time monitoring of splitting parameters in Iceland [35].

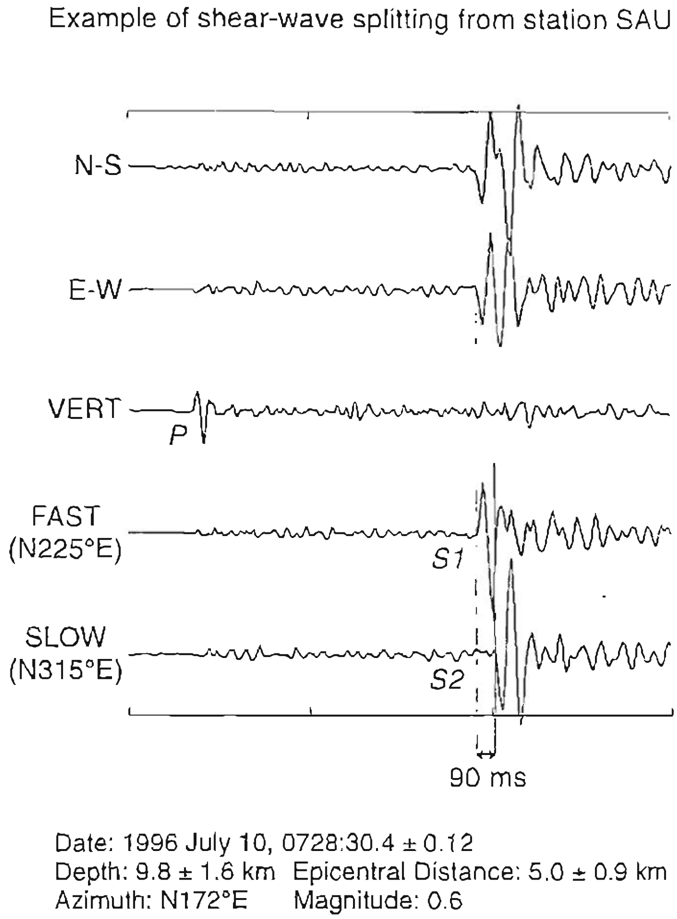

Figure 10: *Three-component seismograms of an earthquake (at 07:28:30.4, July 10, 1996) at SAU with time marks at every second. Upper traces are N-S, E-W, and vertical components. The lower traces are horizontal components rotated to the faster (N225° E) and slower (N315° E) shear-wave polarizations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

4 Borehole monitoring of fluid–rock interaction

Geophysical loggings

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

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

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

There are two main objectives: The first is to measure stress induced changes in physical parameters of rocks by repeated logging. The measured parameters are the acoustic velocity and the conductivity of the rock surrounding the borehole as well as the geometry and degree of fracturing of the borehole wall. The second aim is to get supplementary information about the

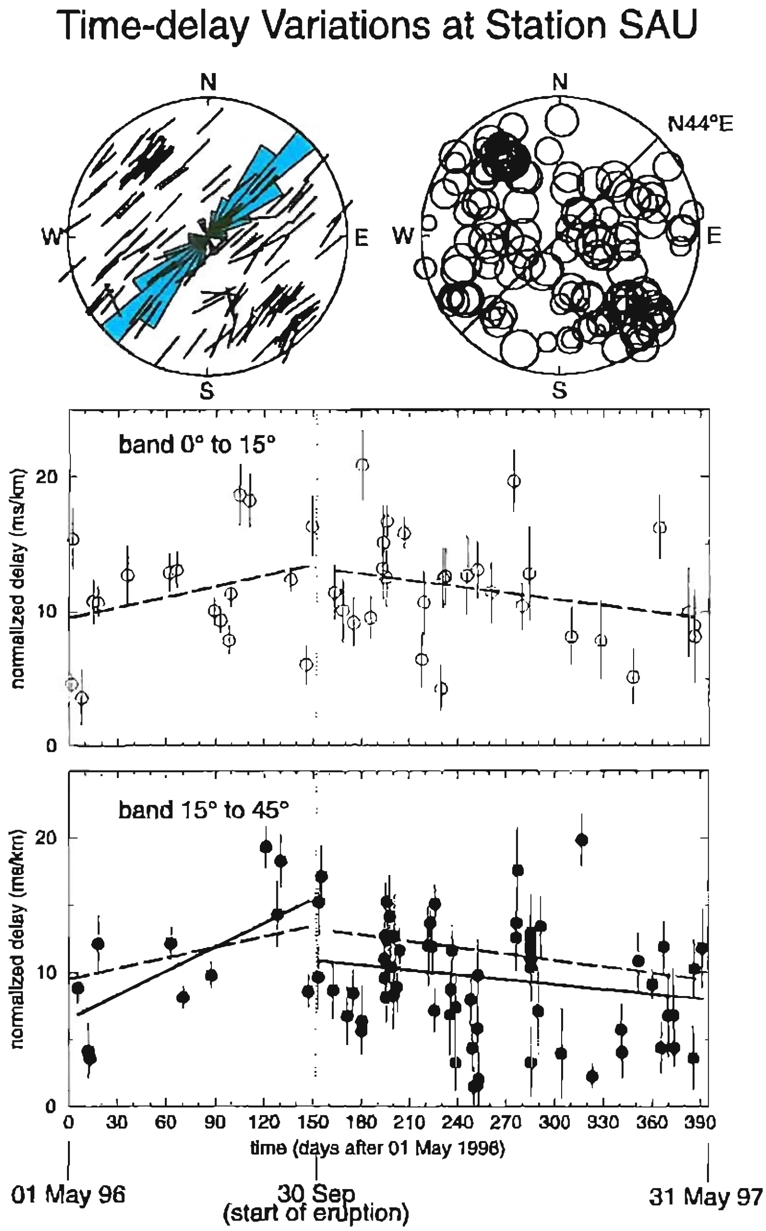

Figure 11: *Variations of shear-wave splitting at SAU for 390 days from May 1, 1996. Polar equal-area maps out to 45° of left shear-wave polarizations, with rose diagram indicating average direction, and right circles scaled to normalized time-delays (ms/km). Variation with time of normalized time-delays for ray paths in bands with incidence 0° to 15° to the crack face (sensitive to crack density), and for 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 the lower plot repeat lines in the upper plot. Error bars are approximate.*

stress field and its changes inside the SISZ by the detection of borehole breakouts.

This work is mainly under the responsibility of GeoForschungsZentrum Potsdam, Division 5-Geomechanics and Management of Drilling Projects, Section 5.3-Rock Mechanics and Stress Field of the Earth's Crust (GFZ.DR.DBL). Besides the other partners of the PRENLAB there is a special cooperation with Valgarður Stefánsson at the Icelandic Energy Authority in this work.

Equipment and methods

The following tools are used: the borehole compensated sonic tool (BCS) to measure the P-wave velocity of the rock, the dual-induction-laterolog (DIL) to get an estimate of the resistivity in three different penetration depths, the gamma-ray (GR) and spectral gamma-ray (SGR) tools to help evaluating the lithological sequence, and the borehole televiewer which provides a complete image of the borehole wall. The BCS also allows registration of the whole wavetrain which is helpful for fracture identification and distinguishing the different phases of arriving waves. With the BCS, the DIL and the GR several runs are performed one immediately after the other. After a careful depth match these runs are averaged. This procedure is repeated after different time intervals and is intended to be continued. So far, two repetitions have been performed, the first after a time interval of three months, the second approximately one year later. The borehole televiewer allows detection of borehole breakouts, which are stress induced elongations of the borehole indicating the orientation of the lesser principal horizontal stress which is perpendicular to the greater horizontal principal stress. Additionally, fractures can be picked in depth and azimuth and closed fractures can be distinguished from open ones. Thus repeated televiewer-logging allows to observe changes in borehole geometry and in opening of fractures [61].

Results

Concerning the repeated logging it can be said that the repeatability showed to be extremely good. Significant changes in the measured curves are not due to instrumental errors and can be assumed to be real. Some changes in the P-wave velocity have been observed between last year and this year. The same is observeable in the DIL-logs.

The breakouts found in the borehole at Nefsholt (Figure 12) seem to be in agreement with the secondary stressfield in this area found by the geologists as described in section 6 (NNE-SSW to NE-SW extension). The analysis of fractures shows open, mainly steeply dipping fractures or bedding interfaces with an average strike of 45°. This coincides with the strike of fractures measured at the surface. Examples of televiewer data for a fractured borehole-section and an interval containing breakouts is shown in Figures 12 and 13.

These primary results are examined further by carefully combining the available datasets and evaluating the theoretical background by modelling.

Radon related to seismicity in the South Iceland seismic zone

This work is carried out at the Division of Geophysics, University of Iceland (UICE.DG).

Build an improved LSC apparatus to measure the radon content of water and gas samples

This work is in progress and funds have been secured to apply it for regular monitoring in the SISZ [82,83].

Revive the radon sampling program in South Iceland

A radon sampling program started in the SISZ in 1978, and samples were collected on a regular basis for 17 years. This monitoring will be revived with improved techniques, by using the improved LSC apparatus which is being developed. As a part of reviving the program an overview investigation has been carried out on observed interrelationship between seismic activity and radon signals. The main results of this can be summarized as follows:

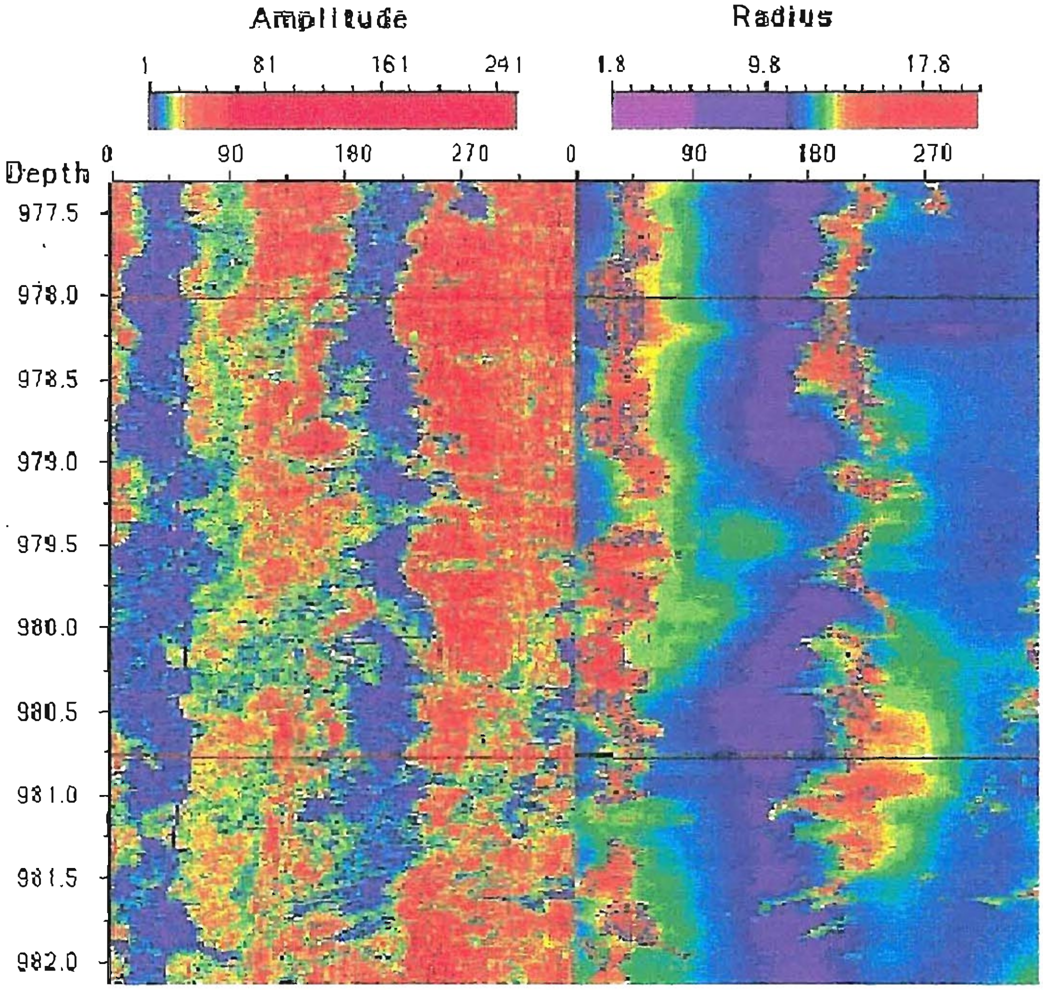

Figure 12: *Televiewer logs run in borehole LL-03 in a depth interval containing breakouts.*

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

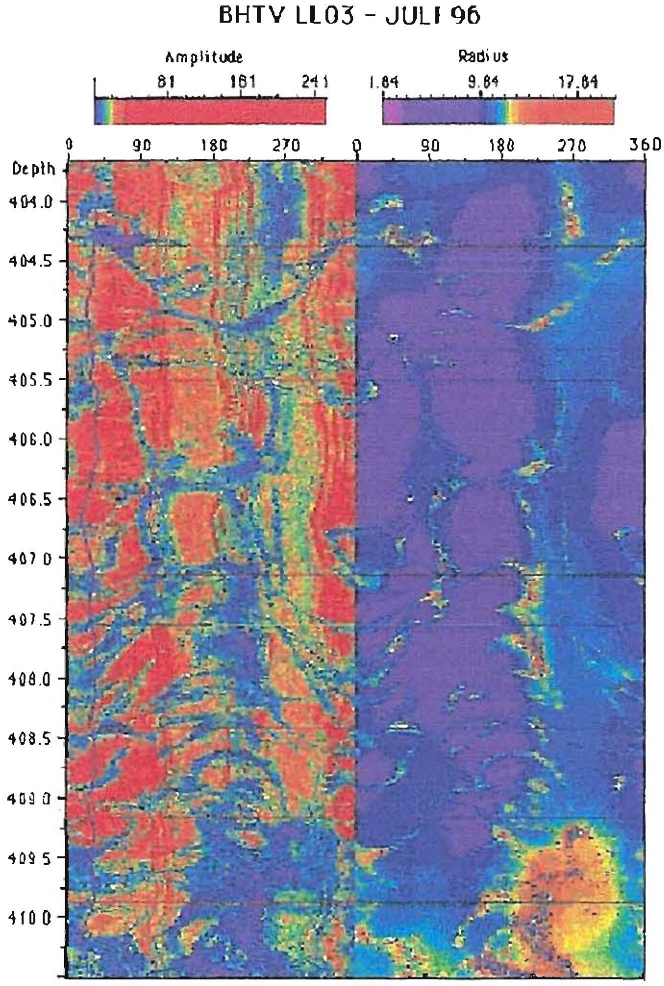

Figure 13: *Televiewer logs run in borehole LL-03 in a fractured section.*

- Radon anomalies were detected that seem to be related to eruptions of the neighbouring Hekla volcano. Eight anomalies were found, five of which occurred prior to the eruptions [51].

5 Active deformation determined from GPS and SAR

The objective is to measure crustal deformation, understand how it relates to seismicity and distribution of faults, and use it for better understanding of earthquakes. In particular, deformation monitoring will be used to improve the understanding of elastic strain accumulation, tectonic setting of seismic zones, coseismic slip during earthquakes, and aseismic slip on faults during interseismic periods. The work is in first hand carried out by Centre National de la Recherche Scientifique, UPR 0234-Dynamique Terrestre et Planétaire (CNRS.DTP) and the Nordic Volcanological Institute (NVI) in special cooperation with Uppsala University (UUPP.DGEO), University of Iceland (UICE.DG) and Icelandic Meteorological Office (IMOR.DG).

Analysis of SAR images from the ERS-1 and ERS-2 satellites

Technique

In applying the SAR inteferometry the entire deformation field is recorded with an unsurpassed spatial sampling density ($\sim$1000 pixels/km^2) at intermittent times. For the interferometry work we have used data acquired by the European ERS-1 and ERS-2 statellites. They pass over a given study area at an altitude of 785 km, transmitting along ray paths at an average angle of 23° from the vertical. These satellites provide SAR images, each of which is a map of the ground reflectivity sorted by range. The phase of each 4 by 20 m pixel measures both the range and the phase shift due to reflection of the wave from the ground surface. The latter quantity can be eliminated between two images of the same area if the dielectric characteristics of the ground remain constant and the orbits satisfy the conditions necessary for coherence. The remaining path difference, known only to within an integer number of wavelengths, contains information from three sources: relative orbital positions, topography as seen in stereo by the satellite from slightly different orbital passes, and any change in position of the ground. From a suitable pair of images, we reconstruct the phase of each pixel using a phase-preserving correlator. We adjust the satellite orbital parameters to minimize the number of fringes at the four corners of the image, assuming that the far field displacement is negligible. The stereoscopic path difference is eliminated using a digital elevation model. The resulting interferogram is a contour map of the change in range, i.e. the component of the displacement which points toward the satellite. Each fringe corresponds to one cycle (28 mm or half the 56 mm wavelength) of the ERS-1 SAR. The accuracy of the measurement is better than several cm in range.

Main results

- We have demonstrated that satellite radar interferometry can be used to measure plate motion and accumulation of strain in seismic zones, under favorable conditions.
- We have advanced the understand of earthquake triggering in volcanic areas.

Satellite radar interferometry has been applied 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. Interferogram spanning 2.29 years and a model referring to that time period is displayed in Figure 14.

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 its utilization by a power plant. The deflation we infer is in good agreement with levelling data. This gives confidence in the interpretation of more subtle deformation signal in the interferograms, fringes aligned in the direction of the plate boundary caused by plate boundary deformation. Relying partly on geologic evidence we assume the shape of the horizontal and vertical crustal velocity field. We estimate best-fit model parameters by maximizing the global coherence of the residual interferograms, the difference between observed and model interferograms. The data constrain the locking depth of the plate boundary to be about 5 km. Below that level the plate movements are accommodated by continuous ductile deformation, not fully balanced by inflow of magma from depth, causing about 6.5 mm/yr subsidence of the plate boundary. Previous regional geodetic data agrees with this interpretation [85,86,69].

Another interferometry study of the Krafla volcano in North Iceland has clearly demonstrated the usefulness of radar interferometry for volcano monitoring. In that study we detected the readjustment of the the Krafla spreading segment, to ongoing postrifting readjustment of the spreading segment to rifting episode from 1975 to 1984 [71].

GPS geodesy

It measures relative position between stations using signals transmitted by the satellites of the Global Positioning System (GPS). The technique has been used in Iceland since 1986, but only

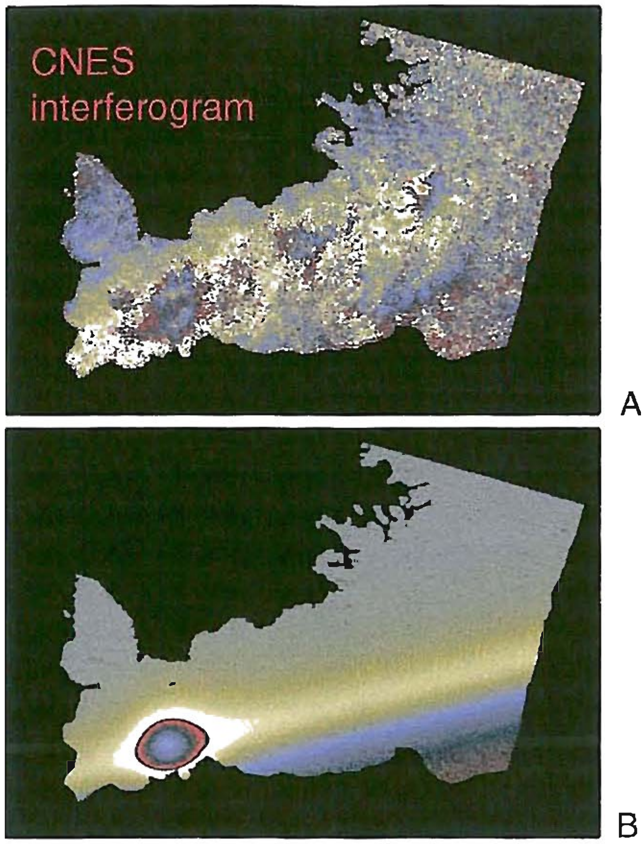

Figure 14: *SAR study of the Reykjanes Peninsula, SW-Iceland. Interferogram 2.29 years (A) and model interferogram showing best-fit simulated 2.29-year deformation (B). Time-progressive fringes appearing consistently in the interferograms are indicative of crustal deformation. Phases coded into bytes (8 bits) are represented with a false colour table. A complete colour cycle, for example from blue to blue, represents one complete fringe; a 28-mm change in range in the case of ERS. Concentric fringes are located at the Reykjanes central volcano and manifest a time-progressive increase in range to the satellite. An increase in range along the whole plate boundary, indicative of spreading, is visible as a central fringe in the 2.29-years (A).*

as intermittent measurements performed every summer. We have installed a semi-continuously recording GPS station in the SISZ to monitor deformation there in real-time.

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 millistrain, sufficient to trigger earthquakes if the crust in the area was previously close to failure [68,70].

6 Formation and development of seismogenic faults and fault populations

This work includes extensive geological field work and related theoretical work based on that, concentrating on the SISZ and the TFZ. It also includes geodetic investigation and comparison of results and methods with seismological investigations. The partners mostly responsible for this work are the Nordic Volcanological Institute (NVI) and the Centre National de la Recherche Scientifique, URA 1759-Tectonique (CNRS.TT). There is a very close collaboration with all the other partners in this work, especially with the University of Bologna (UBLG.DF), the Icelandic Meteorological Office (IMOR.DG) and the Uppsala University (UUPP.DGEO). Also, there is cooperation with Thierry Villemin of Université de Savoie and Olivier Dauteuil, Geosciences Rennes, in France.

Paleostress tensor

The paleostress tensors of 25 localities in the SISZ have been calculated, using fault-slip datasets, and compared to focal mechanisms of earthquakes in the SIL dataset. Preliminary studies of the paleostress field in the TFZ were carried out during the summer of 1997 [39].

Stress fields and mechanisms of seismogenic faults

In the SISZ, the recent and present-day tectonic mechanisms are studied by geological and geophysical means. The determination of the stress regimes is done through calculation of stress tensors, involving the use of inverse methods. Data inversion is applied in a nearly identical way to fault slip data and to sets of double-couple focal mechanisms of earthquakes.

The methodology applied includes the following four geological and geophysical criteria: (1) the consideration of the nodal plane attitude (strike and dip), as compared with that of all geological faults and planes of mechanical weaknesses known from field observation at the sites, geological mapping and aerial photograph analyses; (2) the comparison with the recent fault mechanisms observed in the field (including pitch and sense of motion as well as strike and dip of fault); (3) the mechanical probability of either of the two fault plane solutions, based on taking friction into account (e.g. a shallow dip is more likely than a steep one for a reverse fault); (4) the best fit criterion relative to the stress tensors calculated. If external (i.e. comparisons with geological tensors), it is of good value. If internal (i.e. the nodal planes resulting in the best possible fit within the data inversion process), it is somewhat circular, hence disputable.

The systematic use of the four criteria for nodal plane selection within a weighted approach allowed more accurate determination of the stress regimes in the SISZ than earlier studies and thus better understanding of the geological significance of the earthquake mechanisms [1,2,4,20,87].

Determination of the paleostress tensor in the SISZ

In the SISZ present-day tectonic activity is mainly associated with a conjugate system of NNE-trending right-lateral strike-slip faults and ENE-trending left-lateral ones; NW-trending faults are also present. All these faults affect basaltic lavas and hyaloclastites, Upper Tertiary-Pleistocene to Holocene in age. In the SISZ we collected about 700 brittle tectonic data at 25 sites. The major stress regime, a NW-SE trending extension, includes 70% of the total population of faults, whereas the minor one, a NE-SW trending extension, includes 30%. Of a total of 718 fault slip data, 55% indicate primarily normal-slip and 45% primarily strike-slip. The ratio normal/strike-slip faults is lower than in other areas in Iceland. The above results indicate that the dominating stress field in the SISZ favours strike-slip faulting, with an horizontal σ_3 axis trending approximately WNW-ESE to NW-SE. We point out, however, that in addition, there is a contrasting minor, stress field, characterized by approximately NNE-SSW to NE-SW extension. These results were compared to the stress regimes determined from earthquake focal mechanisms. This comparison reveals that the paleostress and stress regimes are identical and that the changes in the stress field of the SISZ are characterized by stress permutations between σ_1 and σ_2 and between σ_1 and σ_3 [3,18,19,20,42,87].

Determination of the paleostress tensor in the TFZ

During the summer of 1997 a very detailed study was made of the paleostress field of the TFZ. The study was carried out at several sites within the on-land part of the fracture zone on the Flateyjarskagi Peninsula, as well as at several sites to the south of the zone itself, on the Flateyjarskagi Peninsula. In addition, fault-slip data sets were collected along the eastern part of the Dalvík lineament.

Preliminary results indicate a rather complex stress history of the TFZ, particularly in the in-land parts on the north coast of Flateyjarskagi. The datasets are currently being analyzed in more detail, and it is hoped that the final results will be ready in early 1998. The paleostress data from the Tjörnes fracture zone and the Dalvík lineament will be compared with the current seismic data from these areas and with results of geodetic work and other ongoing geological investigation ongoing in the area [16,17,41].

Field and theoretical studies of fault populations

Detailed study of faults in the TFZ and the SISZ

Maps have already been made of some of the most important faults in the Holocene part of the SISZ.

Detailed field data on faults in the Pleistocene part of the SISZ have also been collected.

An analytical study has been made of the controlling stress field and the secondary fracture pattern of the best-exposed faults in the Holocene part of the SISZ.

As regards the TFZ, field studies were made in the summer of 1997 of the infrastructure of the on-land parts of that zone at the north coast of the Flateyjarskagi Peninsula. This work focussed on the overall evolution of the fault rock from large-scale blocks, bounded by major faults, to fault breccia and crushed rock. The results indicate that many parts of the TFZ contain zones of completely crushed rock where the crustal movements may be mostly by aseismic creep.

Another aspect of the work on the infrastructure of the TFZ concerns the effects of crustal fluids on faulting in that zone. The results indicate that there are sets of very intense mineralization that presumably formed in areas of transtension along the main strike-slip fault [38,40,85].

Detailed tectonic map of the TFZ

A detailed set of GPS points within and in the vicinity of the TFZ was installed in 1994 by the NVI. This network was extended in 1995 and again in the summer of 1997 by NVI in cooperation with Villemin and his group. Altogether there are now 44 GPS points in this area. In 1997, 32 points were remeasured, as well as the 12 new points. The results from 1997, compared with 1995, are not yet available but should be so in early 1998.

Mapping of the whole Krafla fissure swarm has also been made and a detailed map of the junction between the Húsavík fault and the rift zone is under the way. A SAR study is planned of the TFZ and its junction with the rift zone [88].

Boundary-element studies of the TFZ

New general models for the crustal deformation and the distribution of seismicity within the TFZ are being developed, combining the results of analytical and boundary-element studies with the field results.

Analog models of the the TFZ

This work is focussed on large-scale Holocene crustal deformation in the area south of the TFZ using glacio-morphological data. The purpose of this work is partly to try to detect the Holocene crustal deformation in the area that could be related to the controlling stress field of the TFZ [24].

$\boxed{7}$ Theoretical analysis of faulting and earthquake processes

This involves modelling of earthquake and rifting related space and time behaviour of the stress field in Iceland. The modelling work is based on results of geological, seismological and geodetic investigations. The main responsible partners for this work are Department of Physics, University of Bologna (UBLG.DF) and GeoForschungsZentrum Potsdam (GFZ.DR.DBL). This work is based on the work of all other partners.

Crust–mantle rheology in Iceland and Mid–Atlantic Ridge from studies of post–seismic rebound

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

Global studies of post-seismic and post–rifting rebound in Iceland were performed employing spherical, radially stratified Earth model [57,58]. Earthquakes and rifting episodes are modelled in terms of suitable distributions of equivalent body forces. The method of solution is based on a spectral approach to the equations which govern the deformations of a spherical Earth due to seismic sources located within the crust. The method, has the advantage of including a realistic mantle layering and a self–consistent description of the gravitational effects. Post–seismic and post–rifting deformation are proved to be significant transient components of plate motion. Studies on a local scale are performed employing the theory of elastic dislocations in layered media. Comparison is constantly made with observations obtained in the framework of structural geology [12,14,15]. Near field studies on the stress field induced by ridge activity are performed employing original methods of theoretical fracture mechanics in plane–strain configuration. The singular integral equations governing fault and ridge dynamics are solved by means of suitable polynomial expansions, yielding a linear inverse problem which is solved by standard numerical methods [13,21].

Far–field displacement field following rifting episodes

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. A simple Earth model is preliminarly employed, which includes a 100-km thick elastic lithosphere, a uniform mantle with Maxwell rheology, and a fluid inviscid core. The source of deformation consists of a 200 km long tensile fault buried at a depth of 50 km. Figure 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° from top to bottom). The surface displacement is decomposed along the spherical unit vectors r, θ, and ϕ (dash-dotted, solid, and dotted curves, respectively). Figure 16 shows the long term relaxation of the displacement field. The time–scales governing the transition from coseismic to postseismic displacements depends essentially on the viscosity stratification of the mantle. For an upper mantle characterized by a relatively low viscosity (such as the mantle beneath Iceland) these time–scales amount to a few years. Large amounts of relaxation may affect all of the components of the displacement field. In particular, we observe amplifications by a factor of 2 for the θ and r components of displacements. Another interesting feature of Figure 16 is the large spatial scale of the region experiencing horizontal motions in the postseismic regime [6].

Stress changes induced by magma uprise in a layered medium

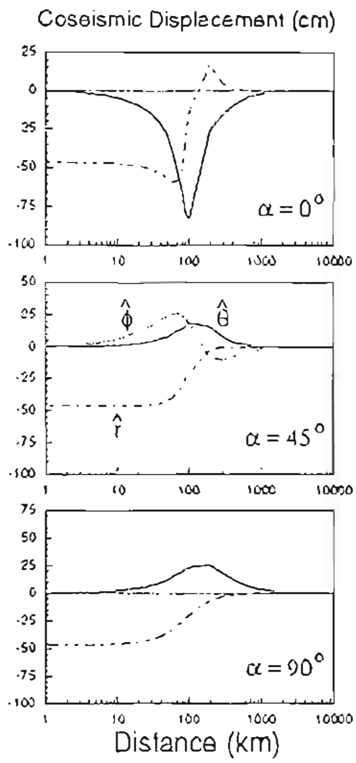

Figure 15:

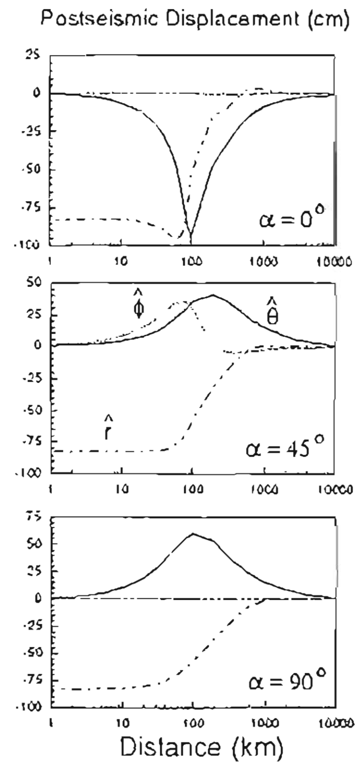

Figure 16:

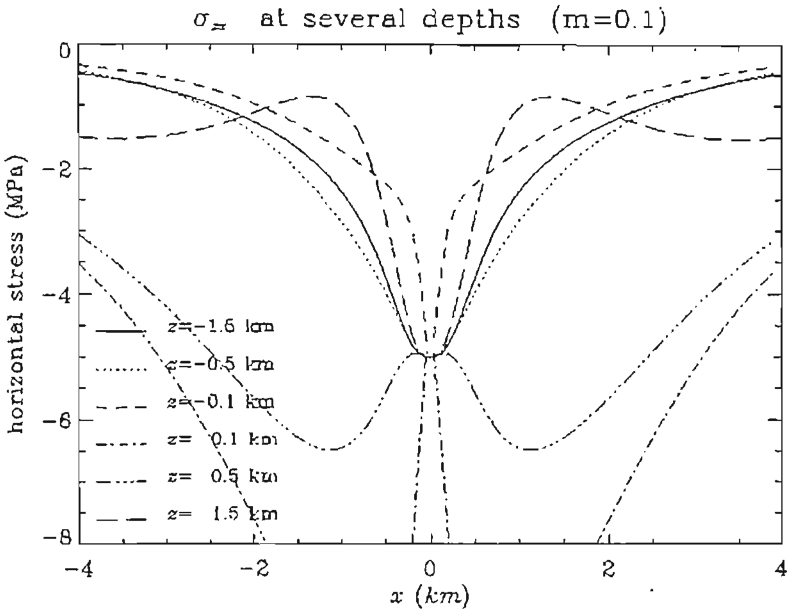

Figure 17:

Magma ascent through a mid-oceanic ridge can be modeled as a tensile crack within which the overpressure is determined by magma buoyancy. Explicit analytic solutions are given for the elementary dislocation problem in the most simple layered medium, made up of two welded half spaces characterized by different elastic parameters. Particularly interesting appears to be the case of a crack cutting across the boundary between the two media. In this case a further singularity appears in the kernel of the integral equation, which is connected with the presence of the boundary surface. The problem can be solved by splitting the crack into two interacting open cracks. The application of a constant overpressure within the crack is found to produce drastically different stress regimes in neighbouring regions located on opposite sides of the interface; this feature may provide a straightforward explanation for the episodic reversal (from sinistral to dextral) of strike-slip mechanisms observed in the South-Iceland seismic zone. If the rheological discontinuity between the lithosphere and the asthenosphere is considered, model results predict a much larger horizontal flow in the asthenosphere than is accomplished by motion of lithospheric plates. Furthermore, the stress field near the transition depth is strongly controlled by differential shear flow in the asthenosphere, thus yielding a simple explanation for the different stress regimes prevailing in the seismogenic zones of Iceland. Figure 17 shows graphically a result of great interest in interpreting Iceland seismicity: if a dyke 4 km long cuts across the interface between the half-space $z>0$, with rigidity 10 times greater than the half-space $z<0$, the horizontal compression in the stiffer medium may be much higher than magma overpressure (5 MPa) in the magma [22,23].

Surface cracks in fault regions as indicators of the state of stress

Most earthquakes in the South Iceland seismic zone occur on NNE-trending dextral and ENE-trending sinistral strike-slip faults. Many of the earthquake fractures rupture the surface in basaltic (pahoehoe) lava flows of Holocene age. The resulting rupture zones display complex en-echelon patterns of secondary structures including arrays of (mostly) NE-trending fractures and hillocks (push-ups). The field data indicate that the arrays consist of both mixed-mode cracks and pure mode-I cracks, concentrated in a narrow belt trending in the direction of the strike-slip faults in the Pleistocene bedrock buried by the Holocene lava flows. For the dextral faults,

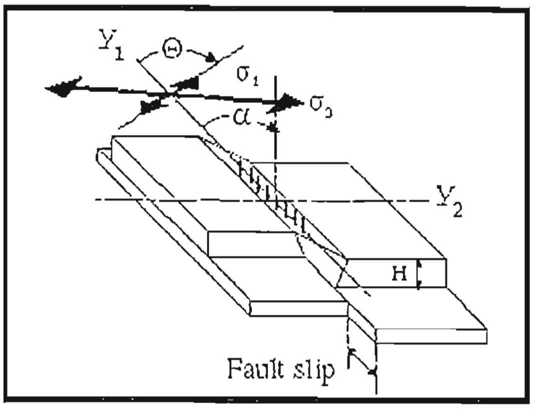

Figure 18:

the angle between the strike of the fault array and the strike of individual secondary fractures ranges over several tens of degrees, but is commonly 10°–30°. Modelling indicates that if the arrays consist of pure tension (mode–I) fractures, the angle between the strike of the hidden fault and each tension fracture must be between 22.5° (if the prestress dominates with respect to the seismic stress) and 45° (if the prestress is negligible). assuming that faulting occurs according to the Coulomb–Navier failure criterion and the prestress is purely deviatoric. If the arrays consist of mixed-mode cracks, the angle between the fault strike and individual cracks is lower than 22.5°, this value being attained if the seismic stress dominates (Figure 18). Modelling suggests that all fractures, being narrowly concentrated near the fault strike, form as a consequence of slip–induced local stresses during major earthquakes, small angle fractures being predominantly mixed–mode cracks, while higher angle fractures may be pure mode–I cracks. The role played by the regional prestress field is found to be significantly dependent on the rigidity contrast between the shallow layer and the basement rock. Useful inferences on the regional stress field can be extracted from such modelling [12,14,15].

Comparison between flat and spherical Earth models

Two different approaches were compared to the study of post–seismic deformations. In the first one, we considered a flat earth model forced by a vertical strike–slip fault embedded in an elastic lithosphere. In the second one, we have solved the same problem in spherical geometry. 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 19 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 19 has also been carried out on the stress fields induced by a strike–slip earthquake. Significant corrections to both the time-

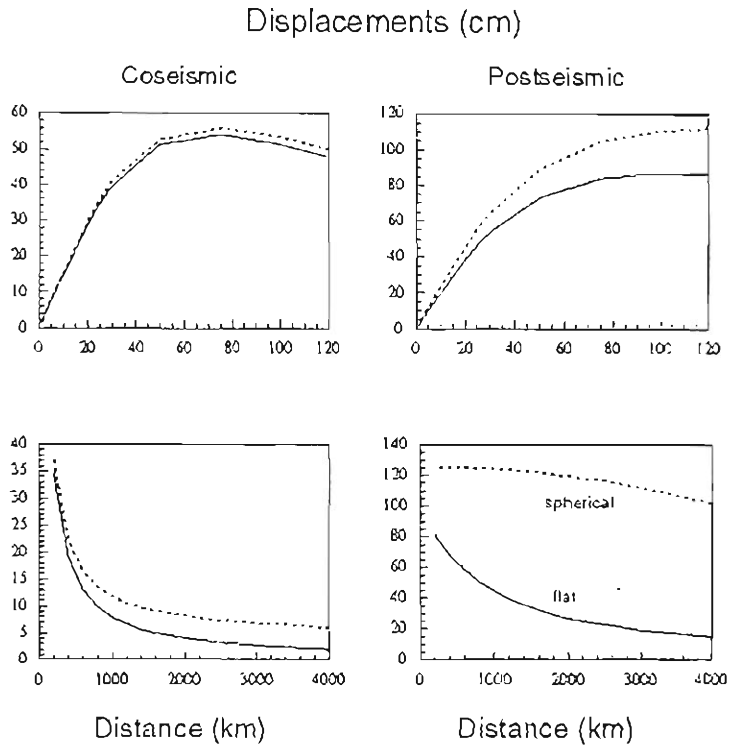

Figure 19:

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 [5].

Modelling the earthquake related space–time behaviour of the stress field in the fault system of southern Iceland

To model the space–time development of the stress field using data on strain and stress changes from the other experiments and from databases.

In detail, this aims at the modelling of:

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

Following models are addressed:

- Calculation of the stress field due to motions on the main faults.
- Comparison with the seismic moment release.
- Stress build–up by these motions and stress release by the major earthquakes.

- Forward modelling of the rheological parameters of the lithosphere asthenosphere in southern Iceland using data of postseismic deformations.

Methods and results

The modelling is performed by applying static dislocation theory to geodetic data and data obtained through seismic moments from seismic measurements. The method and software used 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 seismic or other short lived events, the changes caused by the movement of plates can be included.

The existing programs programs have been tuned for faster performance and extended to allow calculation of six instead of five layers to account for detailed knowledge of velocity depth profiles.

Preparational study has been 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.

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

Two models are being prepared:

- A scheme comprising the main ridge parts on Iceland and the North Atlantic Ridge to the north and to the south of Iceland.

- A model of the SISZ and the adjacent part of the eastern volcanic zone.

The models include both faults and the load due to the Katla, Hekla, etc. volcanoes, i.e. driving forces from rifting and from the mantle plume below Iceland [59.60].

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