Veðurstofa Íslands
Report

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Earthquake-prediction research in a natural laboratory -Two
An EC proposal

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Contents

Chapter 1

Objectives

1.1 Main issues involved

The basic objective of the present proposal is to provide knowledge about earthquakes and related earth processes which can be a basis for reducing seismic risk. This project is proposed in order to respond to the increasing requests from society, engineers, city planners and rescue teams for improved knowledge on where a destructive earthquake is likely to take place, how large it will be and when it is likely to occur. Where are the hidden faults that might move in the next big earthquake, and how will the ground motion be in the area close to the epicenter? Is clustered microearthquake earthquake activity a sign of stress buildup or a sign of ongoing aseismic stress release? Is the absence of earthquakes for a long period of time a sign of aseismic motion or a steady buildup of strain which might be released in a large earthquake? Can stable buildup of stress over a large area on the time scale of days to years be monitored for assessing increased probability of earthquake in specific areas? Is it possible to discover the nucleation stage in the near-field of a large earthquake, i.e. from precursory microearthquakes or from other measureable changes? These are the direct questions which we will try to answer in this project by studying the physical processes involved in or related to large earthquakes.

The questions above are partly answered by the usual seismic hazard assessment, which is based on historical information and on conventional seismic catalogue information, in addition to general understanding of the associated tectonics. Such hazard assessment is available in many countries. We have now come to the state that much more cannot be squeezed out of the historical and catalogue data, without a much better understanding of the physical processes involved in earthquakes.

Development of science and technology during the last decades makes it possible to study earthquake processes better than has been possible before. For this a multidisciplinary approach it is necessary to involve state-of-the-art technology and science in the fields of seismology and tectonics (Figure 1). In this project we plan such a concerted action, centralizing in, as many name it, "Iceland Geophysical Laboratory".

1.2 The test area

The seismic zones and rift zones of the Iceland plate boundary are the test area of the project (Figure 2). Shallow destructive earthquakes reaching magnitude 7 occur every century in the transform zones in southern and northern Iceland. Both of these areas are among the most densely populated in Iceland and there the population is exposed to considerable earthquake risk. Furthermore, the Iceland plate boundary provides an excellent test area for increasing our understanding of earthquake processes, understanding which can be useful anywhere.

There are several conditions in Iceland which make it an excellent laboratory for earthquake prediction research.

- The tectonics of Iceland provides changes of stress conditions on a short and a long

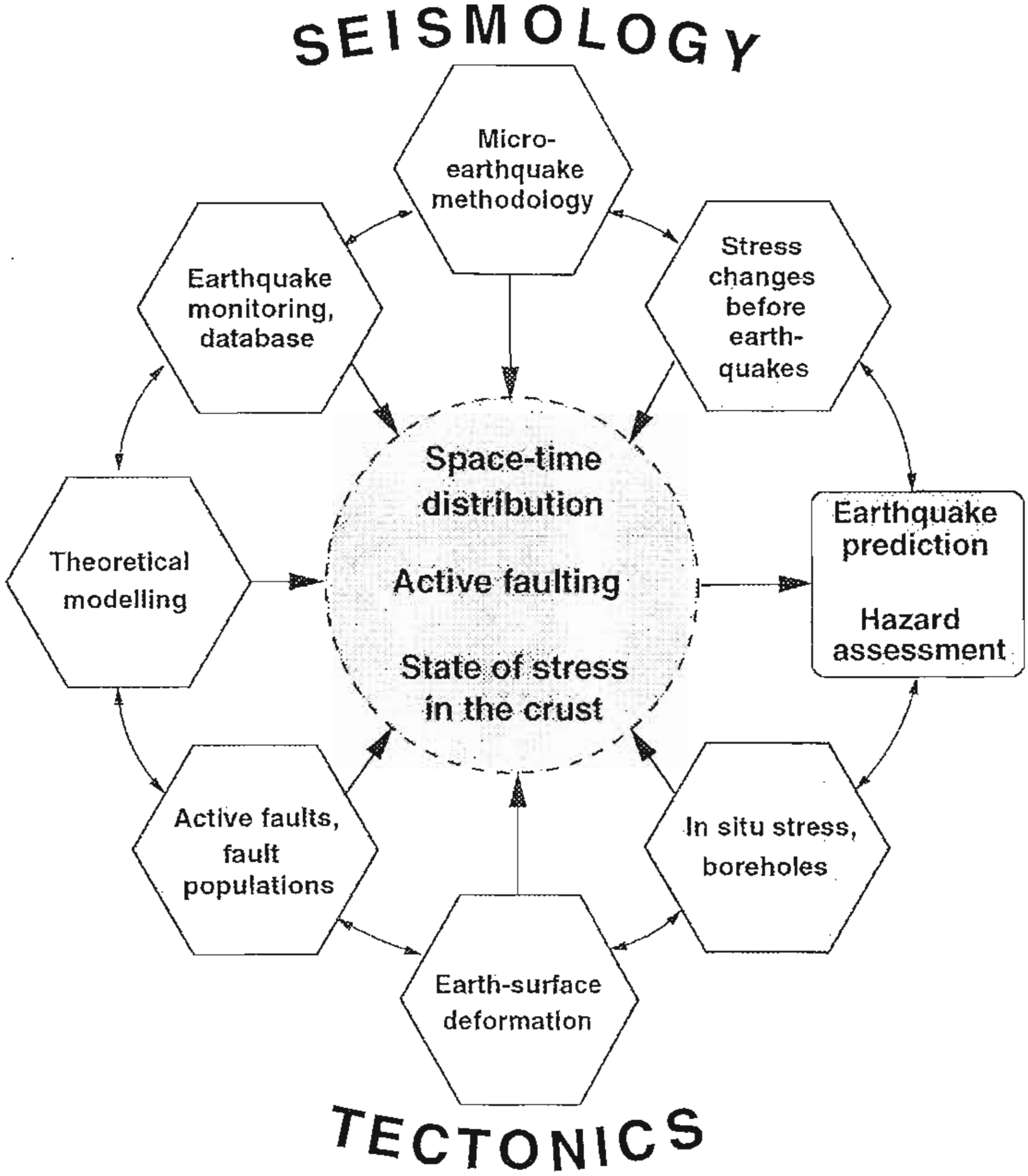

Figure 1: *In the project multidisciplinary European technology and science are applied in a common action aiming at progress in earthquake prediction research and for reducing seismic risk. Scientists from 14 institutions in 7 European countries participate in the project.*

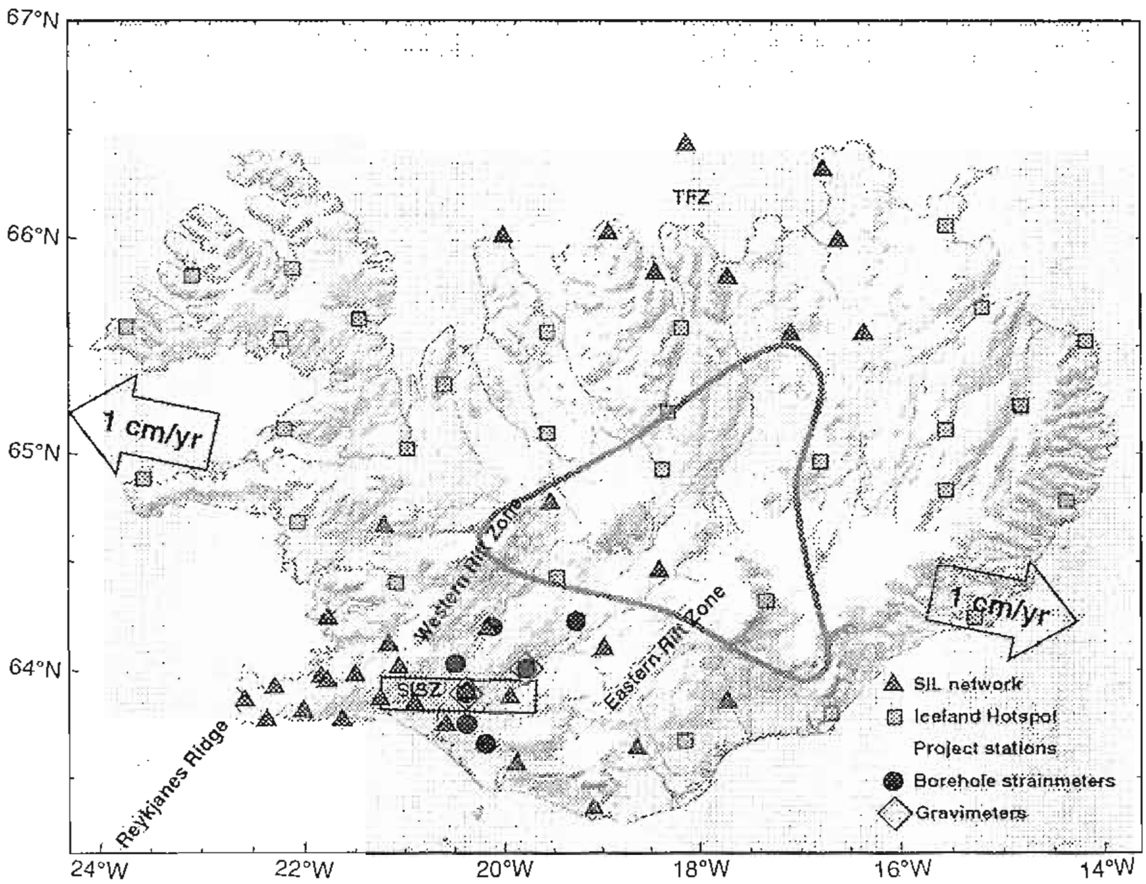

Figure 2: *The available 3 component digital earthquake monitoring in Iceland. The Mid-Atlantic Ridge goes through Iceland from the Reykjanes Ridge along the South Iceland seismic zone (SISZ). the rift zones to the Tjörnes fracture zone (TFZ) in the north. The most destructive earthquakes occur in the 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.*

time scale. This is related to intrusive activity in the rifts, especially above the Iceland mantle plume. On the basis of historical evidence, clustering of activity in time over large distances is indicated, and has been defined as strain waves (strain transients) or strain episodes. These are large events. Recent studies indicate that such changes can be monitored and occur much more frequently than the large historical events. Along the Iceland plate boundary all types of faults can be found, strike–slip zones, normal faulting zones, even areas where thrust faulting can occur.

- The poor vegetation in large parts of Iceland, and the lack of thick sediments make the earth processes on geological time scale visible in exposed faults, fissures and dykes which reveal the processes that have been active, and the interplay between paleostresses and faulting. For the same reason current deformation and fault movements can be more easily measured than in most other areas.

- The state of knowledge in science and technology makes it possible to study earthquake processes in much more detail than was possible only a decade ago. This is especially true in Iceland, with its high quality facilities for acquisition and analysis of microearthquake processes and activity, as well as facilities for monitoring several types of slow changes, including active deformation, by GPS and SAR monitoring. The level of geophysical research is high in Iceland, with much international participation. Among significant international research projects which create a basis for this project are the SIL project of the Nordic countries (1988–1995), and the PRENLAB project which is an EC Environment and Climate project that started on March 1, 1996. The present proposal is a continuation of PRENLAB. Several ongoing international research projects for studying crustal/upper mantle structure of Iceland and its surroundings are also a significant base for this project.

1.3 Available facilities for monitoring, evaluation and alerts

The microearthquake SIL network operated in Iceland provides detailed results of automatic analysis. In semi real–time it provides information on hypocenters, fault plane solutions, moment magnitudes, and several other source related parameters. As it is automatic, such information is available from very small earthquakes, down to magnitude 0 in some areas, and thus providing a semi-continuous row of information, which if correctly interpreted, express fault movements and the state of stress near the plate boundary.

The network consists of 33, 3–component short period and broad band seismic stations along the plate boundary (Figure 2). The GPS clocks used and the way the digitization and time stamping is performed at the site stations, guarantees 1 ms time accuracy of the waveform data, which is essential for microearthquake studies. The communication between the site stations and the center is through the X.25 link of the commercial telephone system. This secures stable operation of the network and semi real–time evaluation of data which makes the system capable of serving as a warning system.

An alert system operates as a part of the SIL network. It provides basically two kinds of alerts, center alerts and station alerts. The center alert warns within a few minutes if some features of seismicity reach predefined levels within any of 30 defined alert regions. The site station alert warns within seconds if large signals or large and stationary oscillatory motion is detected. The purpose of the alerts is to activate the seismologists in the initial state of seismic or volcanic hazard.

A system of 7 volumetric borehole strainmeters is operated in and near to the South Iceland seismic zone (SISZ) (Figure 2). The digital data are radiotransmitted, and evaluated and stored at the SIL center. The same is valid for 2 continuously monitoring gravimeters (Figure 2). Thermometers with m°C accuracy are operated with the strainmeters, expected to measure temperature changes because of changes in ground water flow.

GPS measurements and other surface deformation measurements are a part of the available monitoring system, as well as SAR measurements that are already performed. Continuous GPS measurements are being initiated at 3 of the SIL system stations.

From 1996–1998, 30 broad–band seismic stations will be operated in Iceland, collecting digital data as a part of the international Iceland Hotspot Project (Figure 2). This is a significant addition to the SIL network, which is mainly operated near the plate boundary and near the zones of large earthquakes. The temporary Hotspot stations are complementary to the SIL network in providing seismic data which are collected evenly from the whole country during this period of time. The Hotspot Project is mainly aiming at finding the structure of the deep roots of Iceland. However, the data will be merged with the SIL data to find a more detailed characteristics of the prevailing stresses in the whole of Iceland, i.e. also outside the most active seismic zones.

A program for radon monitoring in geothermal wells was operated in the seismic zones during 1977–1994. Very significant data from this monitoring are available. A new radon program is now in its initial state as a part of the PRENLAB project. Data on water level and pressure changes in boreholes in the SISZ, collected by various Icelandic institutions, are also available for the project.

1.4 The state of earthquake prediction research in Iceland

The state and the tasks of the ongoing PRENLAB project are a measure of the scientific level of earthquake prediction research in Iceland. As the project proposed here is a direct continuation of the PRENLAB we will describe shortly the state of the PRENLAB project.

1.4.1 Using microearthquakes for monitoring the earthquake zones

A very significant basis for the proposed project is the ability of the SIL center in Iceland to use microearthquakes to monitor the stresses and movements in the earthquake area.

A database is under construction for an easy access for the scientists concerned. It contains hypocenters, fault plane solutions, moment magnitudes and several other source related parameters, based on monitoring from the SIL network. The number of recorded and evaluated earthquakes since 1991 is around 60.000. The database also contains information on alerts and alert levels. All the SIL seismic stations have also a real-time filter and information in spectral ranges which may be characteristic for endogen noise. The database will gradually also contain comparable information from a temporary network of the 30 broad-band stations which are operated in Iceland during 1996–1998. Local seismicity measured by this temporary network will go through the same evaluation procedures as the SIL data [17]. The database also contains older seismological data and historical earthquake data, data from volumetric strainmeters and some other data on monitoring of slow changes [14, 4]. Significant parts of the database are accessible now, and the plan is to finalize it as concerns all basic information during the PRENLAB project which ends in February 1998.

With multievent analysis based on cross-correlation of similar signals it is possible within the SIL microearthquake system to locate earthquakes with relative accuracy of 10 or a few tens of meters. This together with fault plane solutions which are carried out on routine basis, based on spectral amplitudes, opens the possibility of detailed mapping of faults and of fault motions. Detailed mapping of active faults using seismic microearthquake data is currently carried out within the PRENLAB project at some sites (Figure 3) of the plate boundary and is being compared with other features, such as surface faults and paleostresses [2, 27, 26].

Pre- and postseismic signals as well as coseismic offsets on the volumetric strainmeters associated with a 5.8 magnitude earthquake and its fore- and aftershocks, occurring in 1987 at the eastern end of the SISZ, has recently been modelled as strike-slip earthquake motion connected with fluid intrusion into the fault (Figure 4). This result may have general relevance for modelling the large earthquakes of the SISZ [3].

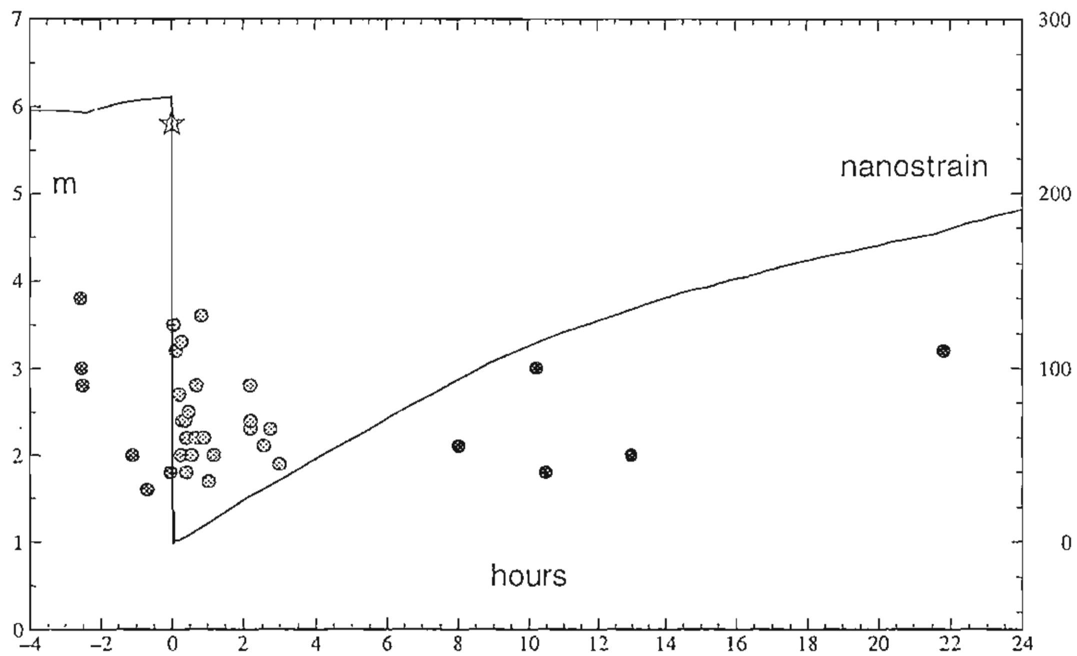

Figure 4: *Occurrence of fore- and aftershocks and strain changes at the magnitude 5.8 Vatnafjöll earthquake, May 1987. Time is in hours whith reference to the time of the mainshock. The mainshock is denoted by a yellow star, the foreshocks by red circles and afteshocks by green and blue circles. The vertical axis on the left is magnitude. The strain record is from the borehole strainmeter at station BUR, located 20 km from the epicenter of the main shock. Units are in nanostrain on the right and expansion is up in the figure. About 2 1/2 hours before the mainshock, at the same time as the first foreshocks occur, an expansion is observed, which continues with increased speed immediately after the mainshock. The mainshock is shown by contraction at this station [3].*

the SWS signal (Figure 5). These results are of a great significance, both as concerns the possibility of using SWS for monitoring stress changes and thus for predicting increased probability for earthquake occurrence, but also as concerns the significance of fluid rock interaction in modelling active stresses, and to explain how small stress changes seemingly can be transmitted over long distances [7].

Inversion of microearthquake information, multievent hypocenter determinations and fault plane solutions are used for inversion for obtaining regional stress tensor. Software for rock stress tensor inversion based solely on microearthquake information is under construction. Work is currently going on for stress tensor inversion by this method in some areas [18, 29].

1.4.2 Active deformation

A SAR interferometry study of the Reykjanes Peninsula has provided new results on plate spreading, during a period of time with no significant earthquakes (Figure 6). Most significant result of this study is that it demonstrated that the SAR technique can be applied to monitor long-term strain buildup due to plate movements, and the technique is well suited to monitor crustal deformation in Iceland [36].

Figure 5: *Variation of shear-wave splitting at SIL station SAU showing angular differences for 137 days from May 1, 1996. Polar equal-area maps of (a) polarizations, with rose diagram indicating average direction, and (b) normalized time-delays. (c) Variation with time of time-delays normalized to ms/km. Open circles (and dashed line) are time-delays for ray paths within the bands with incidence* $\pm(0° - 15°)$ *to the crack face (which are sensitive to crack density), and solid circles (and solid line) are time-delays for ray paths within the bands with incidence* $\pm(15° - 35°)$ *to the crack face (which are sensitive to aspect-ratio). The arrow marks the onset of the eruption on September 30, 1996 [7].*

Figure 6: *SAR study of the Reykjanes Peninsula, South-West Iceland. Interferograms covering 0.83 years (A), 2.29 years (B), and 3.12 years (C), and model interferogram showing best-fit simulated 2.29-year deformation (D). 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. The change in range is largest in the 3.12-year interferogram (C), where it is ~1.5 fringes. An increase in range along the whole plate boundary, indicative of spreading, is visible as a central fringe in the 2.29-year (B) and 3.12-year (C) interferograms [36].*

GPS geodesy is also carried out in the PRENLAB project. Continuous GPS recording is being initiated at three SIL seismic stations in the SISZ. Older GPS data as well as geodetic measurements have been used to shed light on persistent seismic activity at the Hengill triple junction in South-West Iceland [31].

1.4.3 Borehole measurements to study fluid–rock interaction

Borehole measurements to reveal geoparameters and changes in these, related to buildup and release of stresses, have been carried out at two occasions in an 1100 m deep hole in the SISZ. Processing of these data has begun. The information from these measurements have much significance for the modelling work. The inferred logs will be compared with data on seismicity, anisotropy (SWS), crustal deformation, gravity, etc. [28].

1.4.4 Studies of seismogenic faults and fault populations as exposed on the surface

Studies of open fissures, faults and dykes have for a long time been the main source of information on the tectonics of Iceland [11, 13, 12]. During the PRENLAB period much work is being carried out by field studies as well as by analytical/numerical studies within the main earthquake zones of Iceland with the objective of advancing the general understanding of the evolution of these zones and of the associated seismogenic faults.

A very significant result which already has been reported is based on inversion for stress tensor from SIL data, combined with paleostress study, at a site within the SISZ. It indicates changes of local stress directions with time [2]. This is of a great interest. Indication of such changes in Iceland have been reported before [11, 34].

1.4.5 Theoretical modelling

Theoretical modeling is carried out with the aim to explain observations of deformation and faulting processes. Several studies have shown that the seismicity in Iceland is related to the activity of the Mid-Atlantic ridge. In this interaction a major role is played by the enhanced rheological properties of a shallow asthenospheric layer, which concentrates deviatoric stress transients inside the elastic lithosphere, making it possible to transmit significant deformations to large distances, in the post-seismic phase. Following the general scheme proposed by [25, 24], theoretical studies have defined the importance of earth's sphericity, rheological stratification and self-gravitation in modelling strike-slip earthquakes and ridge spreading transients. After finalizing this modelling to the tectonic environment of Iceland, the objective should be reached of understanding in which way plume dynamics may act to trigger major strike-slip earthquakes in the SISZ. Steps will be taken in modelling the space/time behaviour of the stress field in the fault system of southern Iceland. In reports on the modelling work a result has already been reported which is significant for interpretation of fault systems. It is about modelling of observations of tension gashes on the surface following an earthquake with the aim to infer the stress field producing the earthquake. It is concluded that the presence of open fissures striking a few degrees away from the fault strike can be used to draw conclusions about the orientation and intensity of the regional stress field and fault movements at depth.

1.5 Measureable objectives

Any earthquake prediction project should try to answer the questions "where", "how" and "when" a destructive earthquake motion will take place. In this case "where" means within a few kilometers, "how" applies to how the earthquake rupture takes place and what will be the effects at various sites, especially near the source, and "when" means a useful short-term warning time, i.e. down to days or hours. In the present proposal we try to answer these questions, or to test if such an answer is possible in different cases. The approach is multidisciplinary, making use of advanced technology and research in the fields of seismology and tectonics and modelling of the dynamics of the processes at and near the faults.

Using such a physical approach all the 3 questions above become accessible. The answers are partly being dealt with in the ongoing PRENLAB project. The PRENLAB project is much concentrated on methodology for detecting and monitoring active tectonics. The present proposal is a continuation of PRENLAB, but it concentrates more on using the new understanding of active tectonics to develop technology for reducing seismic risk. This is expressed in the tasks undertaken in various subprojects in the next chapter. Below is a short description of the common products aimed at in the terms "where", "how" and "when".

1.5.1 Where will a destructive earthquake occur?

A basis for answering this is a detailed mapping and modelling of faults and fault populations resulting from large historical earthquakes with geological methods, as well as a detailed and accurate mapping of active subsurface faults by seismological methods, which also provide the direction and size of individual fault slips. On basis of this the local rock stress tensor is monitored as well as interaction between closely spaced faults. Stress and strain changes are monitored by seismological methods like SWS, seismicity, multievent stress inversion of fault plane solutions, as well as by strainmeters, GPS monitoring and SAR monitoring. Borehole measurements and seismic measurements provide rheological parameters necessary as a basis for modelling the dynamics of the seismic areas.

All this basic work has started and significant results are already available within PRENLAB for some areas. These results will be used in the present proposal to estimate in a detailed way where aseismic or stable strain release prevails, and where stress is built up, which can release large earthquakes, and also to estimate where observed aseismic motion can lead to buildup of large stresses in adjacent areas.

1.5.2 What ground motions are to be expected?

How will ground motions caused by large earthquakes affect different sites, especially in the near-field of specific earthquakes?

The first question is what is the likely rupture process at specific earthquake sites. A significant basis for shedding light on this is an available, detailed information on destruction, and on surface faults in some of the historical earthquakes. This is the most significant basis for the existing hazard assessment in Iceland. When combined with the knowledge acquired in the present prediction project about active faults and dynamics of fault processes, this historical information can be used to increase our understanding for earthquake processes at individual faults.

The second question is what is the site specific effect on the ground motion. Surface sediments are rare and thin in Iceland. Most buildings are based on bedrock or on lavas. A very significant site specific effect in Iceland is the proximity of buildings to faults, not only the faults which are a part of the earthquake faulting process, but also faults and fissures not directly involved. Another significant site specific effect is the structural inhomogeneity in the crust. A 3-D velocity structure tomography is under way in the ongoing PRENLAB project. Special geological mapping of crustal material and of fissures exposed on the surface, which are available for some communities within the seismic zones, add to the knowledge of site specific effects as well as seismic mapping of interior faults and surface amplification observed in minor earthquakes.

On the basis of likely rupture process and site specific effects, attempt will be made to create a dynamically realistic model to explain the damage and fissures observed in 2–3 of the best documented magnitude 7 earthquakes in the SISZ, with the purpose of using this model to predict likely effect of future earthquakes in the area, in the terms of acceleration, velocity and displacement.

1.5.3 When will a large earthquake occur?

This is usually considered the most difficult part of prediction, and any gains are therefore of enormous significance.

For long-term prediction, this question is related to 1.5.1, that is where inside, for example the SISZ will the next large earthquake occur. Also within the ongoing PRENLAB project work has started to model the earthquake related space-time behaviour of the stress field in the fault system of southern Iceland. This work is based on results from all other subparts of the project, and will gradually give a better constraint on the long-term prediction as well as on time relationships between clustered activity of large earthquakes, which often has occurred in the SISZ. Such work will continue through the present project and will be extended to other seismic zones along the plate boundary.

Precursory activity on the time scale of hours to days are frequently reported in Iceland [33]. If such precursors are to be useful for short-term earthquake warnings, it is necessary to understand the physics behind the precursor. Foreshocks are frequently observed in historical earthquakes as well as in smaller instrumentally observed earthquakes. Precursory changes in volumetric strain as well as in radon in borehole water have been observed before medium size and small earthquakes. The explanation of such phenomena, which are related to the earthquake nucleation phase, will be included in the interdisciplinary modelling of the earthquake processes, with the aim of testing what significance they have for warnings.

Strain waves (strain transients) and migration of earthquake activity have often been reported on a time scale of days to weeks. Stress changes with time or strain signals have been indicated by volumetric strainmeters, by microseismicity and now recently by time dependent shear-wave splitting signals. Common to all these observations in Iceland is that effects of small stress changes or strain changes seem to be transmitted over very long distances, that is in comparison with what is expected from homogeneous half space models [33, 34, 27].

Combined use of active deformation and fault monitoring, together with observed rheological properties of the crust and fluid-rock interaction, will be an input to model the time and attenuation of stress and strain changes in the Iceland crust and rift zones. The aim is to make it possible to use observation of such changes to warn for increased probability of the triggering of earthquakes.

1.5.4 Stress map of Iceland

In the ongoing PRENLAB project information is being acquired from various sources about the direction of crustal stresses, and in some cases about the size. Crustal stresses are inferred from microearthquake source studies, from SWS in the ray paths, from borehole measurements and from geological mapping of faults and dykes. A stress map based on these studies is a significant objective of the present proposal and will be a basis for further tectonic modelling, and a basis for monitoring stress changes.

1.5.5 Exporting the technology developed in the Iceland Natural Laboratory

The objectives of the present proposal are not only limited to Iceland. Through the multinational participation in this project it is directly or indirectly linked to other projects aiming towards the same direction. This is significant for the fast realization of the common objectives.

A significant objective of the present proposal is to export its technology to other seismic risk areas. Collaboration has now been established to export the SIL system technology to one such area in Europe (see Chapter 7.2). This means rewriting the basic software, so it can be more easily used by other groups, and then of course to exchange technology and knowhow for further development.

1.6 Innovations

A significant innovation in the field of using microearthquake source information to study faulting processes, is an investigation with the objective to monitor the interaction between stable and unstable fault movements. Understanding of this is a basis for using slip motions inferred from small earthquakes for monitoring of fault slips. Special application of this is to try to monitor total slip on major faults. Present slip weakening models for fault slip predicts long time of accelerating stable fault slip prior to big earthquakes.

Significant new results have been obtained at one site within the SIL network in Iceland which indicate that it will be possible to use changes in shear–wave splitting at selected sites for monitoring regionally applied stresses. This has an immediate consequence for a row of innovative studies including the incorporation of shear–wave splitting changes into a wider earthquake prediction scheme in Iceland and even using it for automatic monitoring.

SAR interferometry has already provided new results on plate spreading in Iceland. The conditions in Iceland are such that relative small plate motions can be detected and SAR can provide a detailed picture of the deformed area. Studies by SAR technique of detailed deformation using available ERS images with time span of 3–5 years will become a source of innovative studies of deformation along the plate boundary.

The planned multidisciplinary approach is in itself a significant innovation in earthquake prediction research in general. It uses information about stress changes and faulting which spans geological age to the detailed information of the present time, based on the most advanced technology. In earthquake research it takes the step from kinematic deliberations to consider the whole dynamics of earthquake processes. Based on such understanding of the faulting processes, it will be tried to create a physically realistic model, which complies with the historical data on destruction in these large earthquakes.

Among innovative objectives of the proposal is to model the effects of crustal fluids and fluid pressure on the transfer of tectonic stresses. This is based on information from various sources within the proposed project, and tries to explain how effectively small stress changes seem to be transferred.

1.7 How the proposal complies with the 1994–1998 workprogramme

The proposal is a significant contribution to carry forward all the main objectives of the Environment and Climate 1994–1998 seismic risk workprogramme.

It is in complete agreement with 4 of the 5 main objectives of the workprogramme, i.e. with objectives 2–5. It will also lead to a new understanding about expected ground motions which is a necessary input for the advancement of objective 1.

- It complies with the objective of site specific effects in objective 2.

- It complies with the content of all three paragraphs of objective 3.
- It complies with the mapping of faults, and identification and characterization of risk areas of objective 4.
- It complies with the integration and validation of real-time alert systems for earthquakes of objective 5 of the seismic risk programme.

Chapter 2

Work content

The present proposal is a direct continuation of PRENLAB, which started on March 1, 1996. The work packages which will be described in the following, contain new work items which, however, are in many cases direct continuation of, or based on work carried out under PRENLAB.

2.1 Subproject 1: Monitoring crustal processes for reducing seismic risk

Subproject 1 serves all the subprojects of this proposal by providing data from a multidisciplinary database, historical as well as instrumental seismic data, strainmeter data and data on other continuous monitoring, results from seismological evaluations, as of active faults in the crust and of inferred stresses. It operates the SIL acquisition and evaluation system consisting of 33 stations, borehole strainmeters at 7 sites, gravimeters and borehole m°C thermometers in boreholes and several other earthquake related geophysical data. It evaluates on a routine basis tens of thousands of earthquakes per year for epicenter, fault planes, moment magnitudes, etc. It brings together new results from all the subprojects to become an integrated part of the SIL automatic evaluation procedures and of the existing alert system. Among the tasks of Subproject 1 is also to take initiative for and to carry through some research projects which are based on results from some or all of the research groups in this multidisciplinary project.

Of the 174 man months estimated for the tasks below, funds are requested for 48 man months.

2.1.1 Task 1: Database development and service for other scientists

This task continues throughout the project. New data have to be incorporated because of geographical extension of the SIL monitoring system, as well as because of the extension of data acquisition included in the monitoring system. In addition to data from the 33 permanent SIL stations and data from the 30 stations of the Iceland Hotspot Project network, data from a dense network of seismic stations will be evaluated and stored. An example of this is a dense SIL type network applied for a special study in a geothermal area in northern Iceland (see Chapter 7.2).

The SIL system will be developed for further acquisiton and evaluation of slow data, especially of hydrological data. In cooperation with the institutions concerned, continuous data on water level in boreholes, especially in thermal areas in and near the seismic zones will be integrated in the system. Because of the deep roots of thermal areas, precursory signals are probable there, [32, 15].

Based on ongoing research new interpretations of the multiplicity of available data will continuously be incorporated into the database information. The other participants and cooperators will be served with information from the ever growing database. 48 man months are estimated for this work.

2.1.2 Task 2: Improving the basis for alerts, warnings and hazard assessments

This task brings together research results from the project participants and from other scientists for identifying risk areas within the seismic zones and to describe their properties. The questions to try to answer are:

1. Where in the seismic zones will the next large earthquake occur? How large motions are to be expected? What fault plane(s) and what type of source time function is to be expected? In the terms of classical hazard assessment procedure this is done partly in terms of probability of occurrence during a period of time, based on stochastic models applied to mainly historical evidence. Here we go a step further. Work will be carried out to try to answer the questions above especially for the SISZ and for the adjacent Reykjanes Peninsula. It will be based on available mapping of surface and subsurface earthquake faults, on detailed knowledge of spatial variations of seismicity, and of stresses and on theoretical modelling. 24 man months of work are planned for this part of work, finalized by a paper which is based on work of all the other subprojects and will be written in cooperation with these.

2. The possibility of assessing increased probability of the occurrence of an earthquake on a short time scale, weeks to months. Here we take the step to evaluate the possibility to use information obtained on changes in the confining stress or strain changes to tell about increasing probability of earthquake triggering. Changes of the confining stress conditions "leading to earthquakes" are indicated by historcal evidence, and have been named strain waves. There are now strong indications from studies of microearthquakes (SWS) and from borehole strainmeter monitoring in Iceland that such changes may be monitored and have the potential of medium term warnings on increased probability of triggering. An overview paper will be prepared, summarizing such precursory changes, and estimating the alerting significance of these. Estimated work time is 12 man months in cooperation with other subprojects.

3. To evaluate the possibility of short term prediction. It is known from history that many large earthquakes in Iceland are preceded by foreshocks or large precursory swarms or earthquakes. The precursory activity differs from place to place. An overview paper of seismic activity preceding large earthquakes in Iceland will be written. In that results obtained from seismological and geological fault mapping, from stress conditions inferred from paleostress studies as well as from microearthquake studies, and results from studies of fluid rock interaction will be used to model the characteristics of foreshocks at different sites. An assessment will be made of the possibility to transfer achieved knowledge on stress/strain changes preceding a medium size earthquake to observe precursors of large earthquakes. The interpretation and modelling here will be carried out in cooperation with all other subprojects. The expected work time is 24 man months.

2.1.3 Task 3: Modelling of near–field ground motions in catastrophic earthquakes in Iceland

By this task some of the questions posed in 2.1.2 are addressed. Task 3 is to predict the detailed characteristics of earthquake motion in the near–field of catastrophic earthquakes in Iceland, described in acceleration, velocity and displacements. 24 man months are estimated for this.

The motion depends both on the earthquake source and the structure of the crust. Effect like directivity are due to the source [5, 16]. Sedimentary layers and irregularities in the crustal velocities can affect and amplify the ground motion [23].

This task involves in first hand to model the destruction that was caused in some of the historical earthquakes. Detailed information which is available about destruction caused by the approximately magnitude 7 earthquakes in the South Iceland seismic zone in 1784, 1896 and 1912 are a base for such a modelling. But the knowledge about the general character of the SISZ faulting processes which are evolving in the PRENLAB project will also be a significant input in this modelling.

2.1.4 Task 4: Mobile stations for shear–wave splitting monitoring

Mobile SIL network of 3 stations will be constructed and operated temporarily within the S–wave window above swarms of small earthquakes. The purpose is to observe and investigate shear–wave splitting at selected sites. This is a part of creating shear–wave splitting map of Iceland and to search for sites where temporal changes are likely to be observed. This task is in cooperation with Subproject 3. These stations will also serve the purpose of obtaining better hypocenter depth control at some sites. 6 man months of scientists/technical engineers are allocated for this.

2.1.5 Task 5: Extending the alert system functions by real–time research

The SIL system technology and the advances in real–time monitoring and analysis during the PRENLAB period make it possible to evaluate in real–time changes of stresses and development of faults, this together with knowledge of the physics of earthquake release and faulting in the region will enhance our possibilities for mitigating seismic risks. Monitoring of a large seismic activity can enormously increase our understanding of the earthquake processes and its destructive effects. Such new understanding can be applied even within an elongated earthquake sequence. It is known from history that large earthquakes tend to occur in clusters during weeks or months over distances of several tens of kilometers. A scheme will be set up for utilizing in real–time the new information achieved during high seismic activity to predict. The purpose spans everything from helping in rescuing and in evacuation during destructive activity by pointing out the areas most likely to be severely struck and to predict the probable site and effects of a probable following earthquake. The allocated time for setting up such a scheme is 24 man months.

2.1.6 Task 6: Prepering the SIL system and the alert system for use in other risk areas

Significant parts of the SIL system algorithms were written a long time ago and developed on basis of experience gained during at least 20 years. Many seismologist groups are interested to obtain the SIL system as a whole or at least significant parts of the software. The system is, however, difficult to use by those who have not participated in this long–term development.

Many parts of the SIL system software have to be rewritten in a form which makes it more easily useful for other seismologists. It is significant for the success of our project that other seismologists go along the same path in prediction research and it is significant for the process of the environment workprogramme to export the development of SIL and PRENLAB. This work will be carried out in close cooperation with Subproject 2. The bulk of work as concerns the application software will be carried out under Subproject 1 and is expected to take 12 man months.

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

During recent years, powerful methods for automatic analysis of microearthquakes have been developed. They include reliable and robust algorithms for fault plane solutions, high accuracy absolute and relative multievent location techniques and stress tensor inversion algorithms. It is now also generally recognized that the microearthquakes are important carrier of information related to the crustal deformation processes. The full benefit of the possibilities created by these developments require dense networks of seismic stations with high clock accuracy. Such networks are now available in many areas and older networks are being upgraded to reach the requirements. In conclusion there are now possibilities to apply the algorithms and to go into a more general physical/rock–mechanical interpretation of the information carried by the microearthquakes. This is the aim of this subproject.

2.2.1 Task 1: Investigation and monitoring of stable/unstable fault movements

The significance of aseismic stable slip on faults and its interaction with earthquakes (unstable slip) are now generally recognized. The commonly observed interaction between microearthquakes, often over distances large 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.

A special application is the monitoring of total slip on major faults. Present slip weakening models for fault slip predicts a long time of slow acceleration of the stable fault slip prior to big earthquakes. The use of the microearthquakes to detect this mostly stable slip may together with numerical models of fault behavior lead to possibilities to issue earthquake warnings when the fault slip is expected to become unstable.

Data from a dense SIL type network (see Chapter 7.2) in a geothermal area in northern Iceland will be used to study water/rock–fracture interactions.

2.2.2 Task 2: Statistical and adaptive analysis of space/time distribution of microearthquakes

There have been many reports of special patterns in the statistical behavior of earthquakes and microearthquakes prior to major earthquakes. The time dependency of these patterns is related to the size of the main shock. With access to very small microearthquakes, (ML=0), one expects to observe these patterns also prior to relatively small main shocks (M=4). One part of this subproject is to systematically look for proposed patterns for observed main shocks. Another part is to establish the long-term behavior and its variations. Of obvious interest is to find patterns of predictive value. This will require that the methods to be continuously applied and include all kind of false alarms.

2.2.3 Task 3: Investigation of variations of relative crustal velocities

In seismically active regions with dense networks of seismic stations the number and rate of microearthquakes will be high. This will allow a routine monitoring of the relative wave velocities of the P– and S–waves if careful multievent analysis is applied to numbers of groups of similar earthquakes (events having highly similar waveforms). This task may be based for instance on algorithms for absolute and relative multievent location of similar events. If such a group consists of microearthquakes from two different time periods, changes in the S–P times can be detected and measured with a millisecond accuracy. With a good station coverage it is possible to discriminate between effects from location difference and effects due to wave velocity changes. Wave velocity changes can be interpreted as due to stress changes and may contribute to the understanding of the total fault movements. Another obvious possibility is to monitor stress changes.

2.2.4 Task 4: Implementation of these new methods in other European Union countries with high seismic risk

It is of great interest to extend the microearthquake analysis with exactly the same algorithms to completely different geological and geophysical conditions. This is true not only for the physical and rock–mechanical approach but also for the statistical analysis as one expects to be able to test the methods quicker. The flow of knowledge, ideas, and approaches is also stimulated and if valuable results in the field of earthquake warnings are achieved it will be easier to get a fast implementation to other high risk areas. Collaboration is already being established between our group and seismologists in a high seismic risk area in the European Union (see Chapter 7.2). The work in this field will mainly include:

- Generalization of the automatic analysis software to be able to handle all type of focal depths and larger size ranges.
- Breaking up the seismological software in sub–functions to increase the adaptivity of the software to desirable changes.
- Simplify the interactive interfaces for starting up and operate the automatical analysis software.
- Create a software package which can be generally available for making use of the information carried by the microearthquakes.

2.3 Subproject 3: Shear–wave splitting to monitor in situ stress changes before earthquakes and eruptions

2.3.1 Objectives

- As part of Subproject 1 the SIL seismic network will be extended by a mobile network, which will for example be operated near the SIL station SAU, where extremely significant SWS results have already been obtained and at other sites where much is to gain by denser network, based on experience. This will provide multi-path data for interpreting shear-wave splitting.
- Analyze three-component seismograms at stations above local seismicity for stress-induced changes to shear-wave splitting for studying long-term (and possibly short-term) stress changes before larger earthquakes, before volcanic eruptions (changes before the recent Vatnajökull eruption have already been identified), during strain waves, and during other magma- or plume-induced phenomena.
- Analyze three-component seismograms during controlled-source experiments to investigate particular local effects of stress in comparatively shallow crust.

2.3.2 State-of-the-art

Stressed fluid-saturated rock is compliant to changes in stress. Observations in the field and laboratory and theory suggest that the buildup of stress before large earthquakes and other phenomena can be monitored by the effects of stress-induced changes to the intergranular fluid-filled microcracks present in all igneous and metamorphic rocks. Field observations and theory show that the approach of large earthquakes can be "forecast" by monitoring the buildup of stress [8].

The reality of these field observations has been confirmed by numerical evaluations of the effect of an increasing stress on intergranular fluid-filled microcracks by an (a)n-isotropic (p)oro-(e)lastic (APE) model for the behaviour of pre-stressed fluid-saturated rocks, which match the field observations [9, 6]. Laboratory experiments also confirm these results. Consequently, monitoring stress with APE is now a confirmed fully-authenticated model for earthquake prediction [37, 10]. The seismic activity in Iceland and the records and recording facilities of the SIL seismic network make Iceland a natural laboratory to investigate and evaluate these new developments as set out in the objectives. Changes in shear-wave splitting have been detected at station SAU at the east end of SISZ over a five-month period from beginning of May 1996. These changes are consistent with for earthquake prediction.

The seismic activity in Iceland and the records and recording facilities of the SIL seismic network make Iceland a natural laboratory to investigate and evaluate these new developments as set out in the objectives. Changes in shear-wave splitting have been detected at station SAU at the east end of SISZ over a five-month period from beginning of May, 1996. These changes are consistent with increasing tectonic stress as magma was injected into the lower crust before the Vatnajökull eruption starting on September 30, 1996. The eruption was 160 km ENE of SIL station SAU [7].

Note that observations of changes in shear-wave splitting before the eruption demonstrate the relevance of shear-wave splitting analysis in Iceland, and suggest an enlargement of the work content.

2.3.3 Task 1: Continuous monitoring of shear–wave splitting

Continue to monitor shear–wave splitting for precursors of larger earthquakes, volcanic eruptions, and other changes of stress. This is the basic remit of Subproject 3.

2.3.4 Task 2: Analysis of shear–wave splitting measurements

A requirement for improved shear–wave splitting analysis is additional SIL type stations within the shear–wave window of the same earthquakes. That is, clusters of at least three stations within about 8 km of each other, and above swarms of small earthquakes. This will allow much quantitative interpretations of shear–wave splitting.

- Investigate reasons why observations of time–delays between split shear waves in Iceland appear to be approximately twice those observed elsewhere (probably due to high subsurface temperatures and/or high pore–fluid pressures).

2.3.5 Task 3: Establishment of a shear–wave splitting map of all seismic stations in the whole of Iceland

The recent observations of changes at station SAU confirms that shear–wave splitting is sensitive to stress changes in the crust from whatever source, earthquakes or eruptions, and suggests that analysis of shear waves can monitor stress changes beneath Iceland.

- Create a map of spatial variations in shear–wave splitting in Iceland.
- Search map for possible changes in shear–wave polarizations which would monitor stress orientations that are thought to accompany strain waves.
- Search map for possible orthogonal changes in shear–wave polarizations which may indicate high fluid pressures.
- Search for other temporal changes in time–delays which may indicate precursory sequences before earthquakes or eruptions, or may indicate passage of strain waves.

2.3.6 Task 4: Calibrate techniques and crustal behaviour where known changes occur

Since large earthquakes are infrequent, to get results more quickly, it is necessary to calibrate shear–wave splitting with other possible variations. This will be possible by collaboration with other contractors in this project.

- Monitor and model cold–water injection in a well near Akureyri which has a SIL type network there (see Chapters 2.1 and 7.2). Collaborate with Subproject 4 by correlating changes in boreholes with changes in shear–wave splitting at neighbouring seismic stations.
- Collaborate with Subproject 5 in calibrating subsidence near high–temperature extraction.
- Monitor and model extraction of high– and low–temperature geothermal water at pumping stations. Although the low–temperature water extraction is thought unlikely to show first–order effects, but a necessary investigation.

- Where appropriate digital three-component records exist, monitor and model the rock before and after the suggested dyke injections.
- Monitor and model rock behaviour during continuing swarm activity for example at Hengill and Torfajökull, believed to be caused by magma injection and water cooling, respectively. Note that monitoring stress before the Vatnajökull eruption demonstrates the potential value of such investigations.

2.3.7 Task 5: Incorporate shear–wave splitting interpretations into routine analysis

Develop techniques to make shear-wave splitting results available in routine analysis of other seismic parameters involving shear waves, such as fault-plane-mechanisms and earthquake locations. This task will involve collaboration with Subproject 2.

2.4 Subproject 4: Borehole monitoring of fluid–rock interaction

2.4.1 Objectives

Although much progress has been made during the past decades in investigating the nature of active faults, most of this progress has involved kinematics issues. These can be observed directly using numerous geological, geophysical and geodetic techniques. The dynamics of the processes at faults are far more elusive and difficult to characterize using the established methods of earth sciences. Neither the applied stresses nor the rheological response to these stresses are observable using surface–based instruments or techniques because of the depths within the lithosphere at which critical processes occur. The same applies to pore fluids, their presence and temperature, their composition, their physical and chemical behaviour, their pressure and the rock permeability in situ.

Key questions in earthquake prediction research are still unanswered, for instance:

- What forces, or stresses, are required to cause fault slip?
- Are active fault zones weak? If so, why?
- What factors determine whether a fault is seismically active or aseismic?
- What is the role of fluids in fault processes and where do they originate?
- How does fault zone behaviour change with depth?
- How do geophysical observations relate to fault zone properties?
- Are there fundamental differences between faults in oceanic versus continental settings? If so, what causes these differences?

In the framework of the first phase of the EC Environment and Climate project, PRENLAB, a pilot study has started in spring 1996 to obtain a time series of borehole 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 seismological station SAU is used and provides the unique opportunity to perform measurements in a fault zone, much nearer to earthquake sources than usual – the hypocenter depths at the 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 crustal deformation, the creation of borehole breakouts, changes in the number and size of cracks, movement of fluids combined with heat transport and poro-/thermo-elastic stresses, a possible variation of the stress direction, etc. Therefore, the following set of geo-parameters is monitored:

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

This is achieved by repeated logging with tools as:

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

The neutron log is run with the logging equipment of the subcontractor, the rest with the logging truck of contractor.

Emphasis is laid on the detection of changes in the abovementioned parameters. Nevertheless, from the logs and from combining information from several log types, further rock physical parameters can be deduced in several ways under model assumptions: density, elastic parameters of the rocks, permeability, layering, bedding planes, rock types, etc.

Logs obtained in the initial logging campaigns of the PRENLAB project (three up to the end of 1996) are analyzed. This includes:

- Correlation of several log runs in one campaign to obtain a value for the precision of the measurements.
- Correlation of logs from different campaigns to look for temporal variations.
- Search for anomalies via a comparison of different log types and via cross checks between the series of logs and data bases or time series obtained in other experiments as there are: seismicity, fault plane solutions, shear-wave splitting, surface deformation, gravity, borehole strainmeter recordings, etc.

In the proposed project, the sequence of logs should be continued with another three campaigns in 1998. In addition, emphasis will be laid on forward modelling of effects observed. Data on rock types around the borehole and neighbouring wells are gathered and will be compared to published laboratory data on physical properties of the rocks. These data will be used with source parameters of earthquakes below the drillhole and information on pumping in other wells of the area to calculate effects of natural and man-made influences (changes in temperature, load, stress, crack density) on the site of the borehole. Results will be compared to those obtained from the logs.

The project will provide information on the state of stress of the rock near the borehole and about varying water content in cracks. As part of the multi-method approach to monitor pre-, co- and post-seismic stages in the SISZ, these experiments are thought to provide essential additional information on the critical state of processes in the earth's crust in a seismic cycle.

2.4.2 Logging equipment

To monitor changes in physical rock parameters and the migration of fluids due to tectonic activities, it is of crucial importance that other changes are as small as possible or can be discriminated from the interesting ones. As the borehole which is used is already

19 years old, drilling induced changes in the formation will have strongly diminished by all experience. Further, without tectonic activity, one would assume that the borehole will have reached a rather stationary state with the surrounding rock, concerning for example temperature or diffusion of the drilling mud into the formation and diffusion of formation fluids into the borehole, respectively. Logging tools whose signals penetrate to some depth into the formation, as induction, sonic and neutron log, will permit to discriminate between deeply reaching effects and those confined to the borehole wall.

Concerning the tools, it is important to achieve a high resolution of the measured signals, of the logging depth, and of the azimuth from where the signals originate.

The logging tools available are:

Contractor: Logging truck:
- Borehole compensated sonic tools (BCS).
- Dual induction/latero log tool (DIL, including spontaneous potential tool).
- Borehole televiewer (BHTV).
- Four electrode dipmeters (FED: dipmeter and 4–arm–caliper).

Subcontractor: Logging truck:
- Neutron–neutron logging tools.
- Short normal (16") and medium normal (64") resistivity logging tools.

With these tools, we intend to monitor the following geo–parameters (tool to be used):
- P– and S–wave travel time, porosity (BCS).
- Resistivity at different distances from the borehole (DIL and 16"/64" resistivity log).
- Stress information from borehole breakouts (BHTV, FED).
- Porosity/water content (NNL).
- Crack density and crack closing/opening (BHTV, FED).

Concerning the azimuthal sensitivity, two tools, BHTV and FED, are supplied with a navigation subunit that determines azimuth and inclination of the tools. The sensitivity of the other tools, DIL, BCS and the normal resistivity tools, is only slightly anisotropic.

The project will be conducted and reported on basis of 6 separate tasks.

2.4.3 Task 1: Logging campaigns in months 3, 5, and 7 of the project

2.4.4 Task 2: Cross correlation of logs from different campaigns and earlier loggings

2.4.5 Task 3: Comparison of changes in logs of different type

2.4.6 Task 4: Comparison of changes in logs with changes in seismicity, fault plane solutions, shear–wave splitting, gravity, borehole strain meter readings, crustal deformation, etc.

2.4.7 Task 5: Forward modelling of effects of pumping hot water from a neighbouring well

2.4.8 Task 6: Forward modelling of effects of stress increase on rock around the borehole

2.5 Subproject 5: Active deformation determined from GPS and SAR

2.5.1 Objectives

Our objective is to measure ongoing crustal deformation in the South Iceland seismic zone and relate it to distribution of faults and seismicity there. We will estimate both how much elastic strain accumulates and how much elastic strain is being released in the seismic zone by small earthquakes and aseismic slip. The difference between accumulated and released strain is stored as elastic strain energy, and is the energy source for large earthquakes. Determining the size of that source is a fundamental part of any attempt to evaluate, and then mitigate, seismic risk.

We will use two advanced geodetic techniques, Global Positioning System (GPS) geodesy and Synthetic Aperture Radar (SAR) Interferometry to accomplish our objectives. SAR interferometry which provides unsurpassed sampling density (about 1000 pixels/km^2) will be used to get a complete coverage of the deformation field, and will in particular be used to provide constraints on aseismic slip on all recently active faults in the seismic zone. GPS measurements at selected stations will be conducted in a semi-continuous mode and the data will be processed along with data from GPS stations far within stable plate interiors in Greenland, America, Scandinavia, and continental Europe, in order to infer absolute plate movements at selected stations in the seismic zone.

The two techniques complement each other in the sense that SAR provides near-total spatial coverage while GPS provides nearly continuous temporal coverage.

2.5.2 Research tasks

The work is a continuation and extension of previous studies of crustal deformation in the South Iceland seismic zone, and has the aim to better understand crustal deformation and seismicity in general. We propose two new and significant research tasks.

2.5.2.1 Task 1: SAR study of the South Iceland seismic zone

We propose a detailed study of the South Iceland seismic zone using SAR interferometry. This new geodetic technique has been used to determine earthquake deformation, both large co-seismic displacements [22] and much smaller post-seismic displacements [20], and for volcano deformation [19]. Recently SAR interferometry has been used to measure crustal spreading on the Reykjanes Peninsula in South-West Iceland [36]. SAR interferometry has therefore by now been validated as a very useful geodetic technique that works well in Iceland [21].

It remains to apply it to the South Iceland seismic zone, and this we propose. We will determine deformation in the seismic zone from 1992 to 1997, using about 20 radar images taken from the European ERS satellites. With this number of radar images we will be able to form more than several interferograms, which are contour maps of the change in range from ground to satellite, that is the component of the displacement vector which points toward the satellite.

The interferograms will completely cover the deformation field, allowing us to evaluate the amount of aseismic slip on faults in the seismic zone. To make this measurement, we will carefully inspect the interferograms near faults identified as active from mapping on the ground or, in the seismicity catalogue. The interferograms will also help identify the areas of highest elastic strain accumulation within the seismic zone. If we understand the earthquake budget, these areas should coincide with the areas of highest microseismicity.

The proposed SAR study is as well important for the monitoring of future earthquakes in the seismic zone that will produce measurable deformation signal. After we have completed our proposed study of 1992–1997 deformation we will have collected sufficient radar data, experience and knowledge to be able to quickly estimate coseismic displacement in the seismic zone once it exceeds a few centimeters.

2.5.2.2 Task 2: Semi–continuous GPS measurements of absolute plate motion

We propose semi–continuous GPS measurements in the South Iceland seismic zone, and to analyze these data along with other GPS data collected far within the stable plate interiors in Greenland, America, Scandinavia, and continental Europe. Previous GPS measurements in the seismic zone [30] give indication about the general deformation pattern in the zone, but the proposed joint analysis of GPS data within the seismic zone and data from stable plate interiors will lead to new constraints on absolute plate movements near the seismic zone. This is important in the case of the South Iceland seismic zone, as it is located between overlapping rifts [11]. These rifts modify the stress field and may cause secular displacement directions to deviate locally from the far field plate motion. Joint analysis of GPS data from the seismic zone and adjacent plate interiors will help to understand how the stress field is rotated in the vicinity of the seismic zone due to the overlapping rifts, and will help to understand the mechanism of faulting in the seismic zone. The semi–continuous GPS measurements are important for other purposes as well. They will provide continued information on temporal variation in deformation rates within the seismic zone, that can be compared to seismic moment release in the seismic zone during the study period. They will also help with the interpretation of subtle deformation signals in the SAR images, as they can serve as fixed points of known deformation, in the interpretation of the interferograms. Continuous GPS measurements are the best method to provide temporal coverage of deformation, but the approach we take calls for semi–continuous measurements. This is only to reduce the cost of the project, we will use 3 GPS receivers that are at our disposal for this project for about 8 months a year, when the instruments are not needed for other projects. To minimize antenna set–up errors, we will acquire additional GPS antennas for the receivers and install these permanently at the three semi–continuous monitoring sites.

2.6 Subproject 6: Effects of stress fields and crustal fluids on the development and sealing of seismogenic faults

2.6.1 Objectives

A successful seismic risk assessment requires not only a knowledge of the stresses controlling the initiation and activity of the seismogenic faults, but also how these stresses accumulate, transfer and relax during the earthquake cycle. There is increasing evidence that crustal fluids play a large role in the nucleation, propagation, arrest and sealing of seismogenic faults.

The main objectives of this subproject are:

- To study the stress field controlling the fault populations of the test sites, the South Iceland seismic zone and the Tjörnes fracture zone. The stress tensors will be determined from fault–slip data sets, using an recently improved and further developed version of stress inversion software [1]. Analytical and numerical studies on the driving stresses of individual seismogenic faults in the test areas will also be made.

- To continue analytical and numerical, and, when needed, field studies of the seismogenic faults controlled by the stress fields of the test sites. The focus will be on the near–field stresses and displacement associated with individual faults and fault populations, with a view of improving our understanding of how the faults nucleate, propagate and develop in space and time. the concentration, transfer and release of tectonic stresses, and how rapidly seismogenic faults are sealed, with application to the earthquake cycle in the test areas. Results from PRENLAB indicate that, in Iceland, relatively local and small stress changes may be transmitted to very long distances. An attempt will be made to model such changes through the effects of fluid pressure.

2.6.2 State–of–the–art

Paleostress and present stress determinations provide a powerful tool to study the deformation at plate boundaries, the relationships between paleostress and structure must be carefully analyzed. Of particular interest is the relation between three groups of methods involving stress field reconstructions and brittle deformation studies: (1) the inversion of large sets of focal mechanisms of earthquakes, (2) the seismotectonic analysis along active fault scarps, and (3) geodetic analysis of present–day motion. The project presented offers excellent opportunities of cooperation between institutes with different fields of methodological expertise.

The way that faults, fault arrays and fault populations develop has received much attention in recent years. Despite considerable progress, we still do not have the answers to some of the central questions regarding the growth of individual faults, and the development of fault populations. Fault populations exhibit certain scaling relationships, describing the size–frequency distribution of fault lengths and fault displacements, but the physics behind these scaling relationships is still poorly understood.

A question of particular concern in earthquake prediction research is: How rapidly do seismogenic faults heal and how do changes in fluid pressure in one region (e.g. associated with earthquakes or volcanic eruptions) affect slip on faults in nearby regions? There is considerable body of evidence that changes in fluid pressure can be transmitted over large distances and thus trigger stress changes and earthquakes in areas far away from the source of the initial pressure change. This may be partly the reason for the observed stress changes in the South Iceland seismic zone at a distance of 150 km from the volcanic fissure of the Vatnajökull eruption in September–October 1996. Fluid pressure also affects friction on fault planes, hence the probability of fault slip.

2.6.3 Task 1: The stress field

- Determine the stress fields associated with the test areas, the Tjörnes fracture zone and the South Iceland seismic zone from fault–slip data.

- Reconstruct the stress field in the test areas: (i) inversion of large sets of focal mechanisms of earthquakes, (ii) seismotectonic analysis along active fault scarps, and (iii) geodetic analysis of the present–day crustal displacements. This part will be made in collaboration with participants from other subprojects, in particular Subproject 1.

- Use analytical and numerical models, together with field data and the appropriate elastic parameters for the test sites, to determine the driving stresses associated with slip on individual faults at the test sites.

2.6.4 Task 2: Field, analytical and numerical studies of the seismogenic faults

- Make numerical studies of the faults and the fault populations in the South Iceland seismic zone, the Tjörnes fracture zone, and the adjacent parts of the rift zones. A general seismotectonic study of some of the faults in these areas will be made, including an attempt to relate the fault–array patterns to patterns in the seismic data obtained from the seismic arrays and from historical seismic data. Use will be made of the stress tensors obtained in task 1 of this subproject to provide boundary conditions for this analysis. If needed, more field data will be obtained on the faults, but the focus is on the modelling.

- Analytical studies of the fault development. This work focus on the faults in the South Iceland seismic zone, in particular the development of the tension fractures associated with the strike–slip faults in the Holocene lava flows. This work is made in collaboration with participants from Subproject 7.

- Carry out a two and three–dimensional numerical modelling of the seismogenic faults. Use will be made of the Distinct Element Method and the Boundary Element Method to estimate the interactions between faults and improve the understanding of evolution of seismogenic faults and fault populations.

2.6.5 Task 3: Crustal fluids and sealing of seismogenic faults

- Investigate the potential effects of the fluid pressure on the probability of faulting, particularly in the South Iceland seismic zone. We will collect data from the geothermal activity related to active faulting in the main low–temperature areas of Iceland.

- Study the examples of changes in hot springs and geyser activity associated with faulting in the seismic zones, in particular in South Iceland. In particular, how does permeability changes during faulting and how is it related to increase in breccia thickness and gauge formation during seismogenic faulting.

- Make theoretical studies on how the fluid pressure can transmit stresses and trigger earthquakes at small and great distances from the stress sources. To study the mechanism of fluid migration from areas of raised mean stress to areas of lowered mean stress during faulting. Also, how do hydrofractures propagate along the fault planes and into the country rock.

- Make theoretical, observational and experimental studies on the sealing of earthquake fractures with application to the test areas in Iceland.

2.7 Subproject 7: Theoretical analysis of faulting and earthquake processes

The present subproject aims at modelling the space–time evolution of the stress and strain fields generated from tectonic activity of the Mid-Atlantic ridge in Iceland, employing geophysical (mainly seismic and geodetic) and structural data gathered within the project.

In detail, the modelling subproject will focus on studying:

- The changes in crustal strain and stress due to earthquakes and aseismic movement in the fault system of the South Iceland seismic zone, in order to understand the formation and growth of faults and their interaction, and the role of rheological properties in the time evolution of geodetic data.
- The interaction between a spreading ridge and seismic faults in the South Iceland seismic zone, in order to assess the mutual influence between volcanic and earthquake activity, e.g. magmatic upwelling and shearing at fault zones.
- The distribution of seismicity in space and time, its clustering and migration in Iceland including search for a critical stress level above which earthquakes occur.

The research program will be carried out by two research units. The first unit will focus on global (i.e. large scale) modelling, on the role of rheological structures (i.e. long time scales), employing mainly analytical methods; this modelling and the ridge-induced stress field constitutes the basis for the second unit who will concentrate on inserting geometrical and structural complexities in versatile numerical models, including elastic and anelastic properties, in order to describe stress migration mediated by fault interaction. Several topics will be studied in close cooperation in order to achieve the previous targets.

2.7.1 Ridge–fault interaction in Iceland employing global viscoelastic earth models

2.7.1.1 Introduction

Several studies have shown that the seismicity in Iceland (and in particular in the South Iceland seismic zone) may be related to the activity of the Mid-Atlantic ridge according to an interaction mechanism between upwelling magma and seismogenic faults. In this interaction a major role is played by the enhanced rheological properties of a shallow asthenospheric layer, which focalizes stress transients inside the elastic lithosphere, acting as a stress guide. Great relevance must be also ascribed to geometrical factors, particularly to the discontinuity in the ridge axis, occurring in the South-West sector of Iceland, which may act to convert efficiently spreading motions into large deviatoric stresses and may give rise to major strike-slip faulting. According to the above scheme, two complementary scenarios can be proposed: (1) magma upwelling along rift valleys constitutes the driving mechanism for stress buildup, its following amplification in the brittle lithosphere and its migration along the stress guide; (2) stress release in major earthquakes in turn removes constraints hindering the further expansion of the ridge or, more generally, magma upwelling within the crust. The detailed understanding of the mutual interplay between the two mechanisms is clearly needed to interpret correctly geodetic measurements and precursory seismicity in a deterministic prediction model.

Recent theoretical advances in the theory of quasi–static normal modes excited by dislocation sources in a rheologically stratified earth model, presently allow to compute coseismic and postseismic deformations following: (1) lithospheric earthquakes in a spherical, radially stratified, self–gravitating earth model with Maxwell rheology; (2) the opening of a linear spreading ridge. Differently from previous studies, mainly based on flat earth models, these approaches are based on a spherical self–gravitating earth model with radially varying mechanical properties. Attention will be mainly focussed on specific applications of the above models to the geometrical and tectonic setting of Iceland.

2.7.1.2 Task 1: Magma upwelling as driving mechanism for stress buildup in the lithosphere

The role of vertical heterogeneities, (discontinuities of elastic parameters) crossed by upwelling magma along rift valleys, will be studied employing crack models in layered media. Differently from dislocation models, in which the displacement discontinuity is assigned over a fracture surface, crack models provide solutions for the displacement and stress fields which take into account correct boundary conditions at the transition between magma and host rock. The distinction is not academic, particularly in layered media, since a tensional stress field at depth may be replaced by a compressive stress field in shallow layers, due to the mentioned boundary conditions imposed by magma onto crack surfaces. It seems plausible that several observations (heterogeneity of focal mechanisms, rotation of stress axes, antitethic strike–slip mechanisms, geochemical anomalies) will be correctly interpreted within this scheme. In particular it might be possible to characterize focal mechanisms diagnostic of magma upwelling beyond structural discontinuities.

2.7.1.3 Task 2: Space–time evolution of the stress field following transient upwelling of magma along the ridge axis

Episodic uprise of magma along the Iceland rift is likely to be associated with stress accumulation in the surrounding areas and possibly to play a role in the release of seismic energy along transform faults. In order to provide a quantitative description of this complex tectonic process, it is necessary to employ realistic geometries and structures, pertinent to the South Iceland seismic zone. The model to be developed is based on a quasi–analytical spectral approach for a spherical earth and will provide a realistic modelling of the non–stationary opening of a rift and of the subsequent transient deformations and stresses induced within the crust and the upper mantle. The process of stress diffusion is expected to be sensitive to both the duration of the episodic uprise of magma and to the rheological properties of the crust and of the upper mantle. This study will be approached by means of the normal mode technique, based on the explicit analytical expression of the fundamental matrix for the toroidal and spheroidal components of the field equations, propagated from the core–mantle boundary to the earth's surface. This study should be able to predict where and when large deviatoric stresses should be expected after a transient episode of ridge spreading.

2.7.1.4 Task 3: Transient effects of major earthquakes on the dynamics of a spreading ridge

The processes of stress diffusion and migration of seismicity in Iceland will be studied by means of the model proposed in [25, 24]. Of particular interest will be the study of post–seismic motions following major earthquakes in Iceland, and the study of stress diffusion along the boundaries of an oceanic plate. Iceland is a particularly interesting region in this respect since, due to the presence of a shallow low-viscosity asthenosphere, postseismic motions are expected to be sensibly enhanced even in the far field with respect to other tectonic environments. Comparisons between the responses of flat and spherical models have already revealed that in a spherical earth the post-seismic stress fields decay in a much slower manner with increasing distance with respect to flat models. The time-scales which characterize stress diffusion amount to a few years in the case of earthquakes occurring at shallow depths if the asthenosphere behaves as a low-viscosity layer. By means of a forward approach we will investigate the role of stress diffusion on the triggering of seismic activity along the boundaries of oceanic plates.

Another potentially interesting tectonic process consist in the effects of seismic activity along transform faults on the evolution of the Mid-Atlantic ridge. In order to focus on this and on the previous topic, we will also need to adopt a numeric approach which allows for a self-consistent description of complex geometrical and rheological features.

Computations of post-seismic deformations and stress fields in Iceland will take advantage from geodetic data obtained by GPS measurements performed in South Iceland [30]. The use of these data, in conjunction with information about the seismicity of this region, is expected to provide constraints on the rheological profile of the upper mantle beneath Iceland and possibly to give new insights on the role of post-seismic motions on the ongoing deformations in this area. Furthermore, in analogy with previous studies [25], it will be possible to assess the relative importance of post-glacial uplift signatures and postseismic deformations due to major earthquakes.

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

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:

- Determination of fault plane solutions of earthquakes.
- Monitoring of changes in the propagation of elastic waves.
- Measurements of displacements from which strain and stress changes can be calculated.
- 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 databases.

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 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. Furthermore, the model calculations will make use of data on crustal deformation, especially on distance changes measured by geodimeters and GPS techniques. Moreover strain changes are recorded by volumetric borehole strainmeters. In general, it is based on the current state of knowledge of seismotectonics of Iceland and the interpretations of crustal strain and movements in the region.

The objectives of these investigations are:

- A better understanding of the distribution of seismicity in space and time, its clustering and migration in Iceland.

- To seek an 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 N–S right–lateral strike direction.
- To mark areas with stress concentrations (slip deficits).
- To check if a characteristic stress level preceding seismic events exists.
- To make a contribution to the intermediate–term earthquake forecasting 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.

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.

Computer programs are provided 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.

Following work will be done:

2.7.2.1 Task 1: Extrapolation of the stress field, already calculated within PRENLAB for the next years

2.7.2.2 Task 2: Pin–pointing of stress concentrations in space and time

2.7.2.3 Task 3: Search for a characteristic pre–seismic stress level

2.7.2.4 Task 4: Including the effect of volcanic loads into the stress field determination

Chapter 3

Project milestones and deliverables

3.1 Research program milestones

The tasks described in 2.1–2.7 will be conducted within the timetable shown in Figure 7. The end dates represent project milestones. At these end dates contractors present task reports to the coordinator to be distributed among the participants. Participants will present progress reports on individual ongoing tasks in each common progress report.

3.2 Contractor/project reviewing workshops

Contractor/project reviewing meetings are planned approximately in months 5, 12, 17, and 24 (Figure 7). These meetings will be in the forms of workshops open to the contractors, associated contractors, scientists working on the project and other invited guests and experts nominated from EC. The purpose of the meetings is to plan future work and publications, and to review the work already done. Generally speaking the purpose is to focus this multidisciplinary project towards the common goals.

The workshops are planned to coincide with European geoscience assemblies, i.e. ESC, EUG and EGS meetings, where papers resulting from the project will be presented. Besides these general meetings there will be minor meetings of participants cooperating on specific tasks.

The internet will play a significant role in the reporting/communication among the participants, through the coordinator's homepage on the World Wide Web.

3.3 Reports to the European Commission

Two 12–monthly progress reports together with edited summary reports will be submitted and published not later than 13 and 25 months respectively after the start of the project. A final report covering all the 24 months of the project period will be submitted not later than 26 months after the start of the project. A technology implementation plan will be prepared and submitted not later than 2 months after the end of the project (Figure 7).

Information about available computer software and about how to access data from databases will be distributed to a wider audience by including it in peer–reviewed papers when it is adequate. Such information will to some extent be circulated through the World Wide Web as well as information about the progress reports and how to access them. A common colour leaflet will be published to give a short oveview of the project objectives and milestones.

3.4 Publications in peer-reviewed journals

All the participants will submit papers in peer-reviewed earth science journals based on obtained results. All the work topics and most of the work tasks of the planned work content will result in papers to be submitted for publication soon after finishing the tasks.

Figure 7: *Anticipated dates for research and task milestones. W_1, W_2, W_3 and W_4 are workshops, R_1 and R'_1 are first year progress report/edited report, R_2 and R'_2 are second year progress report/edited report, R_3 and R'_3 are final report/edited report and R_4 is technology implementation plan.*

It will be emphasized that papers be prepared jointly by members of different research groups involved.

Chapter 4

Benefits

Earthquake prediction, in the sense practically useful knowledge of where, how and when an earthquake takes place, is a request from people to science in any earthquake prone country of Europe. Development in science and technology during the last decades opens the possibility to provide answers to such requests. For success multidisciplinary approach in geoscience and technology is necessary.

Scientists from 14 institutions in 7 European countries join hands in this project to try to answer the questions above. Their contribution is in different fields, uniting hands towards the common objectives. As concerns level of science and technology relevant in this project all the groups are of a high level and internationally recognized for their work.

Iceland is the test area for the project. It has for a long time attracted scientists from all over the world to study earth processes. They have named the country a natural laboratory for earth sciences. As a test area for earthquake prediction research in Iceland is significant for many reasons.

The tectonics and the sediment-free surface of Iceland provides conditions which make it especially useful for studying faults and fissures, as well as crustal deformation. The interplay between the ridge and the hotspot activity provides time dependent and measureable changes in stress and strain, making it possible to study how stress changes are transmitted and how they lead to rock failure. The enhanced rheological properties in Iceland, for example the significance of fluid rock interaction in crustal processes, make it easier than elsewhere to study such processes. Similar processes are, however, active worldwide although often on a smaller scale making them more difficult to study.

High level microearthquake technology is available in Iceland for monitoring faulting processes and stress changes. The same is to say about the deformation monitoring by GPS, SAR, volumetric strainmeters and other methods. Geology in Iceland in general is at a very high scientific level. The present proposal is based on very significant results from earlier prediction projects. It is based on the acquisition and evaluation technology which was created by the SIL project of the Nordic countries (1988 – 1995). It is based on scientific research of the EC supported PRENLAB project (March 1996 – February 1998) which has further advanced the SIL technology. A significant base for the project is the international Iceland Hotspot Project and other similar international projects of recent years aiming at studying the crustal and upper mantle structure of Iceland and its surroundings. It is not of least significance for the use of Iceland as a test area that earthquake prediction and reducing earthquake risk is of a vital interest, which is reflected in positive attitude and support for the project.

This project if carried out will be a significant contribution to the development of seismology, solid earth physics and geology in Europe.

It will be a significant contribution to development of technology for reducing seismic risks and thus for fulfilling European Commission policies in that field.

Because of the physical approach in this project it will be a significant contribution to other fields as well, e.g. which is expressed in collaborative efforts in this proposal. Mapping of the detailed structure of active fault systems at depth, as well as successful monitoring of, and modelling of the migration of crustal fluids is of a great value in solving many hydrological problems.

The seismic alert system which is in practical operation in Iceland will be continuously upgraded as new results from analysis and modelling are tested. The technology developed and the experience and knowhow that will be gained during the proposed project can be applied in any area of high seismic risk.

It is the intention of the multinational group of the participants to export the technology gained and tested in Iceland to other earthquake prone countries. In this proposal there is already a step taken for using, on a cooperative basis, the seismic acquisition and evaluation technology developed in Iceland in another European site of high seismic risk.

Chapter 5

Economic and social impacts

Information about what ground motions are to be expected in earthquakes, where faults will rupture the surface and when, are of a significance in any earthquake prone country. Increased knowledge will if correctly applied lead to better security and living conditions.

Many earthquakes that have struck the world during recent years have surprised by ground motions that were not expected at that place. Earthquakes continue to strike unexpectedly, although there are several reports of useful short term warnings.

It is generally accepted that earthquake prediction progress is a very gradual process and the approach to useful information will be uneven and different at various sites. However, any gain which is achieved can be of enormous economic and social advantage.

The physical approach to earthquake prediction research which is the basic idea of the present proposal has the potential of increasing in general our understanding of crustal processes and thus bring us closer to the main goals of reducing seismic risk.

Such a physical approach requests multidisciplinary participation of earth sciences. Which also means that the project leads to development of earth sciences in general and to better understanding of the crust that we live on.

The technology developed during earlier prediction projects in Iceland are already applied in other fields as for example in studying underground water conduits and the environmental effects of excavation of energy and water from thermal areas. Still further development is expected during this proposed project which can be applied in this field, especially to study the effects of fracturing in geothermal reservoirs.

The project proposed here is economically and socially significant for the test area, Iceland. It is based on high level European technology and science. But experience, scientific gains, knowhow and technology developed in this project will be transferred to other European countries to be of comparable significance there.

A by-product of the project of a general significance is the ability to reduce volcanic risk. This is done partly by short term warnings based on earthquake activity as well as by better understanding of stress changes and deformation processes that can lead the outbreak of eruptions.

Large eruptions, especially in the eastern rift zone of Iceland, can have influence on life conditions in large parts of Europe. Eruptions that start without warning can cause immediate threat to air traffic. In Iceland eruptions are a special threat to some hydro-electrical and geothermal power plants. That is one of the reasons for that companies running these facilities have provided considerable support for extending the SIL seismic network, to the benefit of earthquake prediction research, as well as monitoring and alerting in general.

The faith that people and authorities in Iceland have for the prediction projects have been expressed in providing funds for building and operating the high quality permanent seismic network, which is the basis for our proposal. This is one of the signs of the enormous economic and social impact that the prediction research work includes.

Chapter 6

Project management structure

The subprojects and participants are summarized in Figure 8. Further information about the division of work, work items and tasks are found in Chapter 2. Figure 7 summarizes when various tasks will be carried out. Figure 7 also includes the approximate dates for 4 workshops/meetings during the period of the project, and the reporting dates, i.e. not later than 13 and 25 months, respectively, after the start of the project.

Figure 9 shows the various institutions, contractors and associated contractors responsible for carrying out the tasks of the workprogramme.

The 7 subgroups carrying out this proposal are composed of scientists that have experience in working together in their fields in an organized way and with good success. The proposed project, *Earthquake-Prediction Research in a Natural Laboratory - Two (Earthquake Prediction Natlab-2)* is a direct continuation of the EC project *Earthquake-Prediction Research in a Natural Laboratory (PRENLAB)*, starting when the former programme ends.

Subproject 1, with its base at the Icelandic Meteorological Office, Department of Geophysics, is the center of the project: (1) because the contractor for it is also the coordinator for the total project: (2) because all the other subprojects will be in close contact with it to interchange data. The general database of the project will be in development and service under Subproject 1. Most of the real-time monitoring will be there also, and thus testing and validation of the algorithms created, for example in the alert system.

The contractors of the project will report to the coordinator not later than a week before scheduled meetings/workshops of the contractors. The meetings will be planned to coincide with European assemblies on geosciences, i.e. ESC, EUG and EGS meetings, and will be open to participation of all scientists involved in the project. By having the meetings coinciding with these conferences the possibility opens for presenting results and having results tested within the European scientific community, but also this way we have the prospect of attracting more scientists to the workshops.

The coordinator will provide progress reports to EC on basis of the contractor reports and their evaluations at the common workshops.

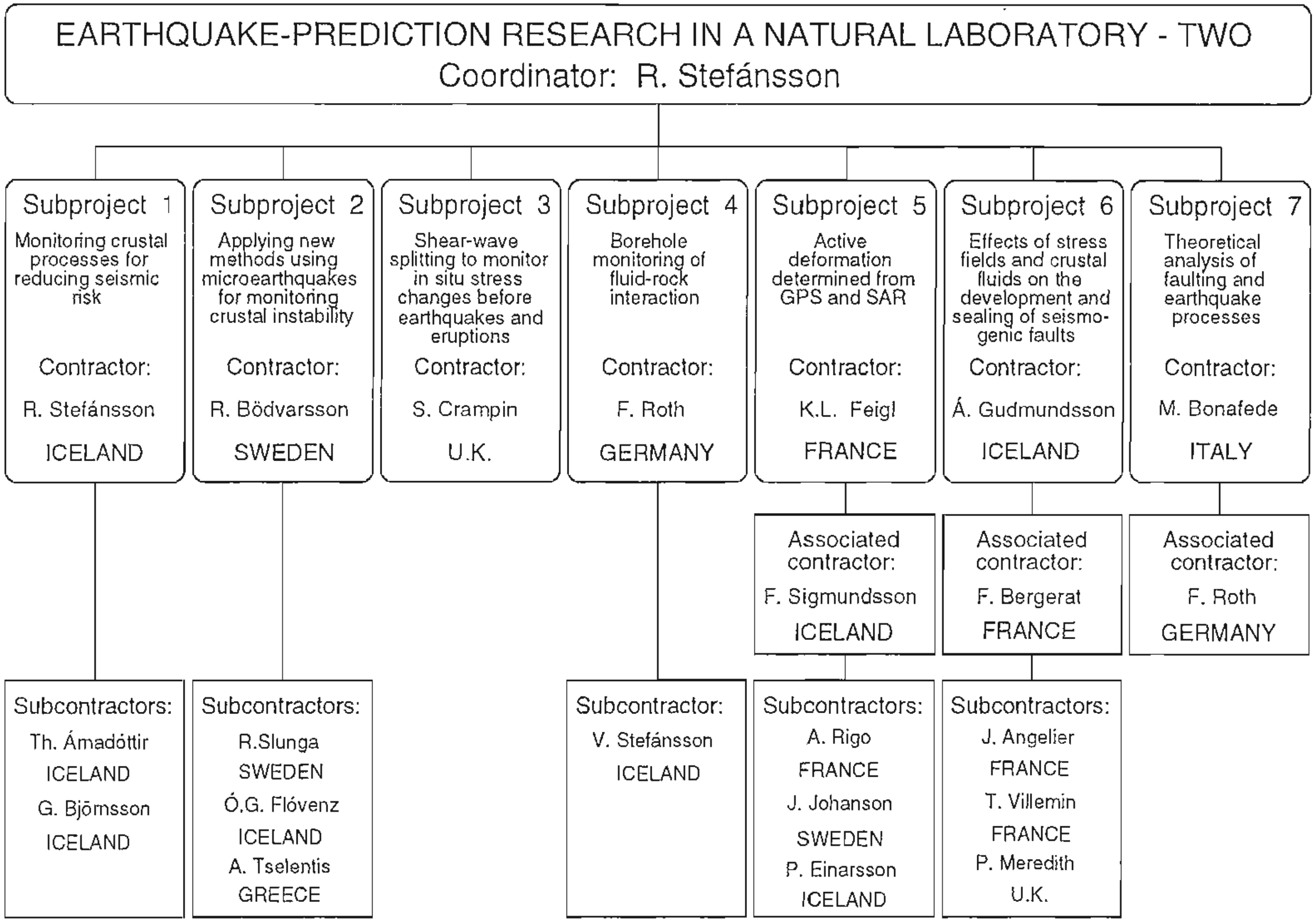

Figure 7: Subprojects and participants.

Figure 8: *Participants responsible for tasks listed in Chapter 2.*

Chapter 7

The partnership

7.1 Subproject 1: Monitoring crustal processes for reducing seismic risk

Contractor:

Ragnar Stefánsson (**partner 1, coordinator**)
Department of Geophysics, Icelandic Meteorological Office, Reykjavík, Iceland

Subcontractor:

Thóra Árnadóttir
Free-lance scientist

Subcontractor:

Grímur Björnsson
Icelandic Energy Authority, Reykjavík, Iceland

Ragnar Stefánsson is also a coordinator for the project as a whole. The Icelandic Meteorological Office, Department of Geophysics, is in a center position of the project. It builds and qualifies the common database. Most of the continuous monitoring, the basic seismic evaluations and upgrade of the alert system is carried out there. It applies or tests results and new methods from all the other partners for the seismic evaluation, for enhancing the alert system, and hazard assessment. Six of the staff members of the Icelandic Meteorological Office dedicate a significant part of their worktime to the project as detailed below.

Thóra Árnadóttir will cooperate in task 3, "Modelling of near field ground motions in catastrophic earthquakes in Iceland".

Grímur Björnsson and the Icelandic Energy Authority will cooperate in task 1 with integration in the database and monitoring of hydrological data from geothermal areas.

7.1.1 Department of Geophysics, Icelandic Meteorological Office

The Icelandic Meteorological Office (IMO) with its 95 staff members covers a wide range of scientific disciplines in meteorology and geophysics. Below is an overview on the role of the Icelandic Meteorolgical Office in reducing seismic risk.

In the Department of Geophysics, 11.5 persons are currently devoted to seismological research. Of these two are technical engineers, the others are scientists in the fields of seismology, geophysics and geology.

The main duties of the Department of Geophysics are monitoring of earthquakes and earthquake related changes and research based on instrumental as well as historical earthquake data. It operates the SIL network which consists of 33, 3-component seismic stations in the seismic zones of northern and southern Iceland, and a real-time evaluation system in Reykjavík. An alert system watching the seismic activity for different parts of the country is in automatic operation in the Department. Now the continuous monitoring of 7 borehole strainmeters is also included in the SIL system, as well as of 2 gravimeters to mention the most significant real-time monitoring.

The Department of Geophysics is the backbone of the successful SIL project for earthquake prediction research and the construction of the SIL system which is the main achievement of the SIL project. The Department has also lead other multinational research projects in Iceland. The borehole strainmeter project in the South Iceland seismic zone is one of these projects and of benefit for earthquake prediction research.

The research policy of the Department is focussed towards reducing seismic risk. It covers everything from general hazard assessment to the development of technology for short term alerts. The seismic system with its alert facilities and the strainmeter system is also significant for watching volcanoes and thus the Department is contributing significantly to volcanic research too, and to reducing volcanic risk.

The Department organized the XXV General Assembly of the European Seismological Commission in Reykjavík, September 9–14, 1996, in collaboration with the Ministry for the Environment and the University of Iceland. The Assembly was attended by 450 scientists in the fields of seismology, geophysics, geology, volcanology, engineering, etc.

The Department of Geophysics coordinates the ongoing PRENLAB project (EC project, seismic risk), but the present proposal is a continuation of and based on the results of the PRENLAB project.

Name: Ragnar Stefánsson

Citizenship:
Icelandic

Date of birth:
August 14, 1938, in Iceland

Education:
Fil. kand. (B.Sc.), Uppsala University 1961, mathematics and physics. Fil. kand. 1962, geodesy with geophysics. Fil. lic. (Ph.D.), Uppsala University 1966, Thesis: Methods of focal mechanism studies with application to two Atlantic earthquakes.

Career: 1962–1963 and since 1966 head of the Department of Geophysics, Icelandic Meteorological Office. At 3 occasions visiting researcher at the Department of Terrestrial Magnetism, Carnegie Institution of Washington. Fulbright scholar in the United States 1994. Chairman of the Icelandic National Committee for the mitigation of earthquake risk. Chairman of the steering committee of the Nordic SIL project 1987–1995. Project manager of the SIL project 1988–1995. Member of the European Advisory Evaluation Committee for Earthquake Prediction instituted by the Council of Europe. Vice-president of the European Seismological Commission.

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the 1991 eruption of Hekla from continuous borehole strain monitoring. *Nature* 365, 737–740.

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Other staff at the IMO working on Subproject 1:

Kristján Ágústsson:

1996: Fil. lic. from Uppsala University, Department of Geophysics.

1987–present: Geophysicist at the Icelandic Meteorological Office, maintainance and development of the strainmeter network and the alert system of the seismic network, analysis and interpration of strainmeter data.

Gunnar B. Gudmundsson:

1986: B.S. in geophysics from University of Iceland, Reykjavík.

1985–present: Geophysicist at the Icelandic Meteorological Office. Main work has been on the SIL network. In 1990, 1991 and 1994 organized and participated in OBS experiments in Iceland in colloboration with Hokkaido University, Japan.

Páll Halldórsson:

1979: Dipl. Phys. from University of Göttingen, Germany.

1979–present: Geophysicist at the Icelandic Meteorological Office. Main tasks are seismicity research and seismic hazard assessment.

Steinunn S. Jakobsdóttir:

1985: Cand. scient. in geophysics from University of Copenhagen. Thesis on interpretation of sonobuy-data from off coast East–Greenland.

1979–1984: Reasearch assistant at the Geological Survey of Greenland.

1985–1987: Geophysicist at the Geological Survey of Greenland.

1987–present: Geophysicist at the Icelandic Meteorological Office. Working mainly on the SIL network since 1988, building up and installing stations, developing and debugging software and running the network.

Sigurður Th. Rögnvaldsson:

1994: Ph.D. in seismology from Uppsala University.

1994–1995: Postdoctoral fellow at Nordic Volcanological Institute, Reykjavík.

1995–present: Reasearch position at the Icelandic Meteorological Office, partly financed by the Icelandic Science Foundation. Work on mapping active faults using relative location techniques and software development for the SIL network.

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Iceland. *Geophys. J. Int.* 123, 409–419.

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Employed by the PRENLAB project:

Einar Kjartansson:

1979: Ph.D. in geophysics from Stanford University, USA.

1979–1980: Research geophysicist at Gulf Research and Development Co.,USA.

1980–1982: Fellow at Nordic Volcanological Institute, Reykjavík.

1982–1984: Assistant professor of Geology and Geophysics, University of Utah, USA.

1985–1986: Senior research geophysicist, Entropic Processing Inc, Cupertion CA, USA.

1986-1996: Geophysicist, Icelandic Energy Authority

1996–present: Geophysicist at the Icelandic Meteorological Office.

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[1] Kjartansson, E. 1979. Constant Q–wave propagation and attenuation. *J. Geophys. Res.* 84, 4737–4748. (This paper has been reprinted in two books that Society of Exploration Geophysicists has published on seismic attenuation and rock physics).

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Free–lance scientist:

Name: Thóra Árnadóttir

Citizenship:
Icelandic

Date of birth:
December 17, 1963, in Iceland

Education:
1986 B.S. geophysics, University of Iceland, Reykjavík.
1989 M.A. geophysics, Princeton University, Princeton, New Jersey, USA.
1993 Ph.D. geophysics, Stanford University, California, USA.

Career: Summer 1985: Research assistant at the Science Institute, University of Iceland, Reykjavík.
Summer 1986: Field assistant in GPS measurements in Iceland.
1986–1988: Research assistant, Dept. of Geosciences, Princeton University, USA.
1989–1993: Research assistant, Dept. of Geophysics, Stanford University, USA.
Summer 1989: Research volunteer at the U.S. Geological Survey Hawaii Volcano Observatory, Hawaii, USA.
1994–1995: Research fellow, Dept. of Geology, Victoria University, New Zealand.
1996–present: Research associate, Dept. of Geosciences, Princeton University, USA.

My research focuses on inversion of geodetic and seismic data to study earthquake sources. In particular, I use a nonlinear optimization method to determine the fault geometry from measured crustal deformation, and model the slip distribution on the fault and stresses induced by earthquakes. The geodetic method I have mostly used to measure crustal deformation, is the Global Positioning System (GPS). In the past, I have collected and modelled data from the 1989 Loma Prieta, California, earthquake, the 1994 Arthur's Pass, New Zealand, earthquake, and the 1989 Kilauea south flank earthquake, Hawaii, USA.

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[5] Árnadóttir, T., P. Segall & P. Delaney 1991. A fault model for the 1989 Kilauea south flank earthquake from leveling and seismic data. *Geophys. Res. Lett.* 18, 2217–2220.

7.1.2 Icelandic Energy Authority (IEA)

The Icelandic Energy Authority is an independent government organization under the Ministry of Industry and Energy. It advises the Icelandic government on energy policy by performing research and planning commensurate with satisfying the nation's energy needs. The Icelandic Energy Authority has been active in the fields of exploration, development and utilization of energy sources for forty years both at home and abroad. In Iceland, the Icelandic Energy Authority works closely with the energy utilities developing the geothermal and hydropower potential of Iceland.

The IEA covers all aspects of geothermal investigations and is furthermore one of few organizations in the world covering such a wide spectrum of activities. It operates several laboratories such as petrologic laboratory for mineral analysis, chemical laboratory for rock, water and gas analysis and laboratories for development, maintenance and calibration of geophysical instruments and well logging equipment.

A geothermal training programme, jointly sponsored by the Government of Iceland (80%) and the United Nations University (20%) is run by the Icelandic Energy Authority. More than 130 specialists chiefly from the developing countries have received postgraduate training in the programme since 1978.

The staff of the Icelandic Energy Authority counts about 95 persons.

Name: Grímur Björnsson

Citizenship:
Icelandic

Date of birth:
June 7, 1960, in Iceland

Education:
1980–1984: University of Iceland, B.S. in geophysics.
1985–1987: University of California, Berkeley, U.S.A., M.Sc. in reservoir physics.

Career: Present Position: Reservoir physicist in the Geothermal Logging and Reservoir Physics Division at the Icelandic Energy Authority. Work includes numerical modelling of single– and two–phase flow in geothermal reservoirs and boreholes, well logging and testing, hydrological interpretation of well tests and program writing. Monitoring internal changes in high-temperature reservoirs due to production. Supervising geothermal research and production monitoring for a few district heating systems in Iceland. Storing the collected data in an Oracle relational database. Summarize and draw geographical and potential field data by using various mapping tools. Several consultancy missions to El Salvador and Djibouti regarding geophysical surveys and geothermal reservoir engineering studies. Instructor at the United Nations geothermal training program, Iceland. Part time lecturer in geothermal reservoir physics and engineering. Supervising students in prepairing and writing their final reports.

References relevant to the proposal:
[1] Björnsson G. 1987. A multi–feedzone, geothermal wellbore simulator. MS thesis at University of California, Berkeley. Lawrence Berkeley Laboratory report no. LBL–23546, 102 p.

[2] Björnsson G. & B. Steingrímsson 1992. Fifteen years of temperature and pressure monitoring in the Svartsengi high–temperature geothermal field in SW–Iceland. *Geothermal Resources Council TRANSACTIONS* 16, 627–633.

[3] Björnsson G. & G. Axelsson 1994. Feasibility study for the Thelamörk low-temperature system in N-Iceland. Nineteenth Workshop on Geothermal Reservoir Engineering, Stanford, California, 9 p.
[4] Axelsson G., G. Björnsson, Ó.G. Flóvenz, H. Kristmannsdóttir & G. Sverrisdóttir 1995. Injection experiments in low-temperature geothermal areas in Iceland. Proceedings of the World Geothermal Congress 1995, Florence, Italy, Vol. 3, 1991-1996.

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

Contractor:

Reynir Bödvarsson (**partner 2**)
Department of Geophysics, Uppsala University, Sweden

Subcontractor:

Ragnar Slunga
Department of Geophysics, Uppsala University, Sweden

Subcontractor:

Ólafur G. Flóvenz
Icelandic Energy Authority, Reykjavík, Iceland

Subcontractor:

Akis Tselentis
Seismological Laboratory, University of Patras, Greece

Subcontractor Ragnar Slunga plays a key role in in this project. Most of the microearthquake analysis software used is developed by him. He will be employed by the project as a part-time professor supervising the students working within the project.

Ólafur G. Flóvenz is the scientific leader at the Icelandic Energy Authority (IEA). IEA is involved in a project where a dense network of seismic stations will be installed in a geothermal area. The data from this network and also other data from this project will be available to our project.

Professor Akis Tselentis is the director of the seismological unit at Patras University. Within this project we plan to implement the scientific and technical knowhow gained by the PRENLAB project into a new seismic network in Patras.

7.2.1 Department of Geophysics, Uppsala University

The Section of Solid Earth Physics (SEPU), Uppsala University, forms together with the Section of Seismology, the Department of Geophysiscs with a total of 30 employees. SEPU is specialized in studies of the lithospheric system employing a variety of geophysical techniques: reflection and refraction seismology, magnetotellurics including controlled sources, and potential fields. Recent projects include the deep drilling project in Siljan and reflection seismic studies in the Caledonides in Norway and Sweden.

SEPU has been involved in magnetotelluric research for a decade. The research has focussed on studies of the lithosphere and experience has been obtained from various geological environments. SEPU has been concerned with various aspects of magnetotelluric instrument development. SEPU has assisted with technical and interpretational support to a project on earthquake prediction research in Greece.

Name: Reynir Bödvarsson

Citizenship:

Icelandic

Date of birth:

December 2, 1950, in Iceland

Education:

1974–1976: Electrical engineering at New Mexico Institute of Mining and Technology, Soccoro, New Mexico, USA and North Carolina State University, Raleigh, North Carolina, USA.
1977–1980: Computer science at University of Uppsala, Sweden.

Career: 1970–1973: Engineer at Science Institute, University of Iceland.
1980–present: Research engineer, Department of Geophysics, Uppsala University.
1980–1982: Principle investigator for the project: General Data Acquisition System for Geophysical Measurements. This project was funded by the National Swedish Board for Technical Development.
1982–1984: Principle investigator for the project "Development of Geophysical Data Acquisition". This project was funded by the Swedish Natural Science Research Council.
1984–1986: Responsible for field data digitization and record production of the Swedish part of the EUGENO-S project. This project was funded by grants from national funding agencies in Sweden, Denmark Germany, Great Britain, Switzerland, Finland and Poland.
1987–1996: Principal investigator for the Swedish participation in the SIL project. The Swedish participation in the SIL project is funded by the Swedish Natural Science Research Council and the Section of Solid Earth Geophysics at Uppsala University. Pointed by the SIL steering commitee to be responsible for the design of the SIL data acquisition system.

References relevant to the proposal:

[1] Bödvarsson, R. 1988. Design of the data acquisition system for the South Iceland Lowland (SIL) project. Vedurstofa Íslands, 18 pp.
[2] Bödvarsson, R. & S.Th. Rögnvaldsson 1992. The SIL acquisition system, a new tool for earthquake prediction research. In: *Natural Disasters 92*, proceedings of the International Conference on Preparedness and Mitigation for Natural Disasters, 28–29 May, 1992, Reykjavík, Iceland. Association of Chartered Engineers in Iceland, 81–90.
[3] Stefánsson, R., R. Bödvarsson, R. Slunga, P. Einarsson, S. Jakobsdóttir, H. Bungum, S. Gregersen, J. Havskov, J. Hjelme & H. Korhonen 1993. The SIL project, background and perspectives for earthquake prediction in the South Iceland seismic zone. *Bull. Seism. Soc. Am.* 83, 696–716.
[4] Slunga, R., S.Th. Rögnvaldsson & R. Bödvarsson 1995. Absolute and relative locations of similar events with application to microearthquakes in South Iceland. *Geophys. J. Int.* 123, 409–419.
[5] Bödvarsson, R., S.Th. Rögnvaldsson, S.S. Jakobsdóttir, R. Slunga, & R. Stefánsson 1995. The SIL data acquisition and monitoring system. *Seism. Res. Letters* 67, 35–46.

Name: Ragnar Slunga

Citizenship:

Swedish

Date of birth:

July 10, 1943, in Sweden

Education:

1955–1963: Hal Haparanda.
1963–1964: Swedish Army.
1964–1968: Royal Technical University, Stockholm.

Career: 1975–1982: Principal investigator at FOA for seismic risk assessment for the Swedish nuclear power plants at Forsmark, Oskarshamn, Ringhals, and Barsebäck.
1979–1985: Scientific investigator for the Swedish digital seismic network for regional earthquakes (22 stations in southern Sweden and Denmark).
1986–1989: Principal investigator for the Swedish digital seismic network covering south–eastern Sweden and northern Sweden (totally 18 stations).
1985–1989: Principal investigator for the seismic measurements and analysis during the hydrofracturings and water circulations within the Swedish Hot Dry Rock Project (500 m depth in granite).
1989: Principal investigator for the seismic measurements and analysis during the hydrofracturing within the deep borehole at Siljan (Gravberg), (5000–6000 m deep borehole for gas).
1987–1995: Member of the steering comittee of the Nordic SIL project in Iceland.
1988–1995: Principal investigator for implementing and developing seismologicalanalysis of microearthquakes within the SIL project.
1989–1993 and 1996–present: Part–time professor in tectonophysics at Uppsala University.

References relevant to the proposal:

[1] Slunga, R. 1988. Frictional sliding and the crustal stresses, In: A. Boden & K.G. Eriksson (editors), *Deep Drilling in Crystalline Bedrock*, vol 2, 444–453.
[2] Slunga, R. 1991. The Baltic Shield earthquakes. *Tectonophysics* 189, 323-331.
[3] Rögnvaldsson, S.Th. & R. Slunga 1993. Routine fault plane solutions for local networks: A test with synthetic data. *Bull. Seism. Soc. Am.* 83, 1232–1247.
[4] Rögnvaldsson, S.Th. & R. Slunga 1994. Single and joint fault plane solutions for microearthquakes in South Iceland. *Tectonophysics* 237, 73–86.
[5] Slunga, R., S.Th. Rögnvaldsson & R. Bödvarsson 1995. Absolute and relative locations of similar events with application to microearthquakes in South Iceland. *Geophys. J. Int.* 123, 409–419.

7.2.2 Icelandic Energy Authority

See Subproject 1, section 7.1.2

Name: Ólafur G. Flóvenz

Citizenship:

Icelandic

Date of birth:

May 22, 1951

Education:

1976: B.S. in geophysics from University of Iceland, Reykjavík.
1979: Cand. real. in applied geophysics from University of Bergen, Norway.
1985: Dr. scient. from University of Bergen, Norway.

Career: Present position: Director of Energy Research Division, Icelandic Energy Authority.
1985–1996: Head of Geophysical Department, Icelandic Energy Authority, geothermal division and project manager of geothermal exploration and exploitation for the Akureyri municipal district heating system in North–Iceland.
1995–present: Member of the Joule and Thermie program committes of the EU's 4th framework programme.
1988: Participation in planning of transient electromagnetic measurements in the Asal rift in Djibouti and interpretation of the TEM-data obtained by a field crew from the Icelandic Energy Authority.
1979–1985: Geophysicist at the Icelandic Energy Authority. In charge of geophysical exploration (both field work and interpretation) in various geothermal research projects.
1982–present: Project manager of geothermal exploration and geothermal drilling for the Akureyri municipal district heating system, North–Iceland.
1982–present: Lecturer in applied geophysics, and geothermal prospecting technique at University of Iceland.
1979: Representative for the Department of Industry, Icelandic offshore seismic reflection survey and the interpretation of the data at the Western Geophysical office in London.
1976–1978: In charge of geophysical exploration (both field work and interpretation) in geothermal reconnissance survey of the North–West Peninsula in Iceland and eastern Iceland.

References relevant to the proposal:

[1] Flóvenz, Ó.G. 1985. Application of subsurface temperature measurements in geothermal prospecting in Iceland. *J. Geodynamics* 4, 331–340.
[2] Flóvenz, Ó.G. 1985. Electrical and seismic structure of the upper crust in Iceland. *Dr. scient.* thesis, University of Bergen, 98 p.
[3] Flóvenz, Ó.G. & K. Gunnarsson 1991: Seismic crustal structure in Iceland and the surrounding areas. *Tectonophysics* 189, 1–17.
[4] Flóvenz, Ó.G. & K. Sæmundsson 1993. Heat flow and geothermal processes in Iceland. *Tectonophysics* 223, 123–138.
[5] Bjarnason, I.Th., W. Menke, Ó.G. Flóvenz & D. Caress 1993. Tomographic image of the spreading center in southern Iceland. *J. Geophys. Res.* 98, 6607–6622.

7.2.3 Seismological Laboratory, University of Patras

Name: Akis Tselentis

Citizenship:

Greek

Date of birth:

September 5, 1955, in Zaire

Education:

Dipl. in electronics, Polytechnic of Zurich 1976.
B.Sc. (honours) in physics, Athens University 1977.
M.Sc. in applied geophysics, Leeds University, U.K. 1978.
Ph.D. in engineering geophysics, Imperial College, London 1980.
DIC in geological sciences, Imperial College, London 1980.
FSTP in engineering seismology, Tokyo University 1988.

Career: 1979–1980: Research scientist at Bullard Labs, Cambridge, U.K.
1981–1983: Research scientist at Athens University, Greece.
1984–1985: Senior geophysicist, at Institute of Geology (IGME).
1985–1987: Professor of signal processing at the National Aeronautical Military Academy of Sciences.
1987–1989: Visiting researcher employed by EC at the Earthquake Research Institute of Tokyo University.
1989–present: Associate professor of seismology and geophysics at Patras University. Also director of the Seismological Unit.

References relevant to the proposal:

[1] Tselentis G–A. 1989. Stress transfer and non linear stress accumulation at the North Anatolian Fault, Turkey. *Pure and Applied Geophysics* 132, 699–710.
[2] Tselentis G–A. 1990. Interstation seismic wave attenuation by autoregressive deconvolution. *Pure and Applied Geophysics* 133, 429–446.
[3] Tselentis G–A. 1993. Geoscan–An algorithm for hard rock tomographic analysis. In: Proceedings of the 2nd National Geotechnical Conference, Vol. 1, 285–292.
[4] Tselentis G–A. 1993. Depth-dependent seismic attenuation in W. Greece. *Tectonophysics* 225, 523–528.
[5] Tselentis G–A. 1993. Shallow attenuation in the West Corinth–Patras rift. *Bull. Seism. Soc. Am.* 83, 603–619.

7.3 Subproject 3: Shear–wave splitting to monitor in situ stress changes before earthquakes and eruptions

Contractor:

Stuart Crampin (**partner 3**)
Department of Geology and Geophysics, University of Edinburgh, United Kingdom

Stuart Crampin pioneered seismic anisotropy and, with Sergei Zatsepin, is now developing an anisotropic poro-elastic (APE) model for microscale deformation which appears to match observations of shear–waves: variations in shear–waves can be directly interpreted in terms of stress variations before earthquakes and eruptions. This opens the way to detailed monitoring of stress beneath Iceland.

7.3.1 Department of Geology and Geophysics, University of Edinburgh

The Department with about 35 academic staff (including some 15 geophysicists) and about 70 research students is the largest earth science department in U.K. universities and is a leading research institute.

The Department (in collaboration with BGS) will analyze three-component seismograms, particularly from the closely-spaced subset of the SIL network for seismic shear-wave splitting. The contractor Stuart Crampin, moved to the University from BGS five years ago and there is still close collaboration between the Department and BGS. Crampin and colleagues at the University and BGS pioneered much of the development of shear–waves and shear–wave splitting in over 180 research papers; and are thus well qualified to interpret shear–wave data from SIL.

The Department contains and has access to a large range of computers and computer hardware and software. These include PC's and small workstations, and Europe's largest parallel computer, the Cray T3D.

Name: Stuart Crampin

Citizenship:
British

Date of birth:
October 22, 1935, in England

Education:

1959: B.Sc., mathematics, University of London.
1965: Ph.D., geophysics, University of Cambridge.
1978: Sc.D., publications in geophysics, University of Cambridge.

Career: 1963–65: Research fellow, Seismological Institute, University of Uppsala, Sweden.

1965–92: Principal scientist, senior principal scientist (individual merit), and deputy chief scientist (individual merit), at the British Geological Survey.

1992–present: Professor of seismic anisotropy, Department of Geology and Geophysics, University of Edinburgh.

Pioneered theoretical, numerical, observational, and interpretational development of seismic anisotropy in over 180 research papers in refereed international journals. Was amongst the first to recognize the significance of shear–wave splitting for monitoring cracked rocks. Directed the Turkish Dilatancy Projects (TDP1 in 1979, TDP2 in 1980, and TDP3 in 1984) which first positively identified shear–wave anisotropy above earthquakes, and was amongst the first to recognize shear–wave anisotropy in sedimentary basins. As a result of these studies, the significance of microcrack– and fracture–induced anisotropy is now widely recognized in both academic and industrial seismology.

In 1988 found and directed the Edinburgh Anisotropy Project (supported by a consortium of up to 11 oil Companies) developing processing techniques for extracting anisotropy parameters from shear–wave records.

Organized and helped to organize a series of International Workshops on seismic anisotropy in Suzdahl, USSR, 1982; Moscow, USSR, 1986; Berkeley, USA, 1988; Edinburgh, U.K., 1990; Banff, Canada, 1992; and Trondheim, Norway, 1994.

Currently, with Sergei V. Zatsepin, developing an (a)nisotropic (p)oro–(e)lasticity (APE) model for the deformation of cracked porous rock. This is believed to be a fundamental new understanding of rock deformation with important implications and applications.

References relevant to the proposal:

[1] Crampin, S. 1981. A review of wave motion in anisotropic and cracked elastic-media. *Wave Motion* 3, 343–391.

[2] Crampin, S. 1994. The fracture criticality of crustal rocks. *Geophys. J. Int.* 118, 428–438.

[3] Crampin, S. & S.V. Zatsepin 1995. Production seismology: the use of shear waves to monitor and model production in a poro–reactive and interactive reservoir. In: Expanded abstracts from the 65th Ann. Int. SEG Meeting, Houston, 199–202.

[4] Crampin, S. & S.V. Zatsepin 1996. 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. ISSN 9979–60–235–X, 318–323.

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

7.4 Subproject 4: Borehole monitoring of fluid–rock interaction

Contractor:

Frank Roth (**partner 4**)
GeoForschungsZentrum, Potsdam, Germany

Subcontractor:

Valgardur Stefánsson
Icelandic Energy Authority, Reykjavík, Iceland

Subcontractor Valgardur Stefánsson, is essential, because he provides the borehole and has logging tools, very important for the investigations, that GFZ does not have. He also has a large data base on rock physical properties of Icelandic rocks, essential for the interpretation of the logs and will provide logistic support to our common work.

7.4.1 GeoForschungsZentrum (GFZ), Potsdam

The GFZ is a new science center placed in Potsdam, just outside of Berlin, in the state Brandenburg, one of the five new states of the Federal Republic. It comprises all sciences of the solid earth, from geodesy via geophysics, geology and mineralogy to geochemistry in a multidisciplinary research association. Its main tasks are:

- Basic research in geosciences on global subjects.
- Joint projects together with universities and other research institutions in national and international cooperation.

Main fields for the research work of the GFZ during the next years will be:

- Kinematics and potential fields of the earth
- Mobile zones of the lithosphere
- Plate margins – deformations and mass movements
- The genesis of granite and crustal evolution
- Earthquakes and volcanism

The research work is done in 22 sections organised in five divisions named:

1 Kinematics and Dynamics of the Earth
2 Physics of the Earth and Disaster Research
3 Structure and Evolution of the Lithosphere
4 Material Properties and Transport Processes
5 Rock Mechanics and Management of Drilling Projects

Division 1 "Kinematics and Dynamics of the Earth" comprises the following sections:

1.1 Kinematics and Neotectonics
1.2 Recent Stress Field of the Earth
1.3 Gravity Field and Figure of the Earth
1.4 System Theory and Modelling
1.5 Remote Sensing

Division 2 "Physics of the Earth and Disaster Research" comprises the following sections:

2.1 Earthquakes and Volcanism
2.2 Applied Disaster Research
2.3 Deep Electro-Magnetic Sounding/Geomagnetic Fields
2.4 Seismology/Seismic Tomography
2.5 Deep Seismic Sounding

Division 3 "Structure and Evolution of the Lithosphere" comprises the following sections:

3.1 Structure, Evolution and Geodynamics
3.2 Dynamics of Tectonic Processes
3.3 Sedimentation and Basin Analysis
3.4 Modelling of Geoprocesses

Division 4 "Material Properties and Transport Processes" comprises the following sections:

4.1 Experimental Petrology and Geochemistry
4.2 Material Properties and Transport Processes
4.3 Genesis of Ore Deposits
4.4 Physical Properties of Minerals and Rocks

Division 5 "Rock Mechanics and Management of Drilling Projects" comprises the following sections:

5.1 Operational Support Group ICDP and Borehole Measurement Technologies
5.2 Geoscientific Instrumentation
5.3 Rock Mechanics and Stress Field

Name: Frank Roth

Citizenship:
German

Date of birth:
July 23, 1951

Education:
1972–1979: Physics and mathematics at Bonn University.
Diplom (M.Sc.) June 1979 in physics, second subject mathematics, thesis on experimental particle physics.
Dissertation 1979–1983 in geophysics at the Institute of Geophysics, University of Kiel, Germany. The Ph.D. was formally finished in January, 1994. Thesis title "Surface deformations and crustal stresses in areas of high seismicity: A model describing temporal variations" (in German; surface displacement, strain and stress due to point dislocations in a layered, inelastic half-space, theory and application to an earthquake in Colombia and to the North Anatolian fault zone).

Career: Research fellow January to July 1984 at the Institute of Geophysics, ship of the German State Seismological Bureau, Beijing, P. R. China. Max-Planck-Society studies on earthquake prediction research in China. Work in a research August 1984 to December 1985 in the Turkish-German project Earthquake Research Project at the western end of the North-Anatolian fault zone, especially in the active seismic experiment for monitoring travel time changes of seismic waves (including seismic field measurements in Turkey).

1986–1991: University assistant at the Institute of Geophysics, Ruhr-University-Bochum, Germany; work on an own project on the modelling of subsurface displacement and tilt to be measured in boreholes, funded by the German Research Foundation in the framework of the German Continental Deep Drilling Program (KTB); work on dislocation theory models applied to the stress field of the North-Anatolian fault zone, the Xian-shui-he fault zone, Sichuan, China and stress measurements in boreholes; introduction of opening cracks as a source in layered (in-)elastic half-spaces; boundary element analysis of the interaction of cracks; applying pattern recognition to seismicity; computation of synthetic seismograms using the reflectivity method; work on vector processors and SUN work stations.

Habilitation May 1992, with the "Habilitation thesis" (in German): "Dislocation theory modeling of processes on faults". It contains a review on the theoretical connections between the seismological description of transient displacement due to seismic sources, static deformations of the earth's crust and the fracture mechanics approach to the extension of cracks, further the treatment of subsurface deformations in a layered half-space due to double-couple sources and due to opening cracks, applications to stresses on single faults as well as to the interaction of faults in Germany (Upper Rhine graben) and South China (Panxi paleorift).

Since June 1, 1992, Leader of Section 5.3 "Borehole Logging" in Department 5 "Disaster Research" of the GeoForschungsZentrum, Potsdam. Forming of a logging team for deep wells (down to 7000 m) with caliper tools, dipmeters, borehole televiewers, etc. Cooperation with the Institute of Geophysics, University of Karlsruhe, in a research project on the tectonic stress field in eastern Europe in the framework of the International Lithosphere Project, especially the World Stress Map project. Co-investigator in a German Research Foundation (DFG) project in 1992/93 and main proposer in the continuing project for 1994/95.

Teaching at Bochum and Leipzig University. Lectures on "Introduction to Geophysics" (1 year), "Modeling of Deformation on Faults", "Borehole Geophysics"; seminaries on earthquake prediction research, on processes at faults and on key experiments in the KTB project, guiding of several exercises in seismic source theory, inversion theory, laboratory experiments on seismic waves, geomagnetics etc., field experiments on refraction seismics, magnetics and geoelectrics, guidance of laboratory reports of students (graduate level).

References relevant to the proposal:

[1] F. Roth 1988. Modeling of stress patterns along the western part of the North Anatolian Fault Zone. *Tectonophysics* 152, 215–226.

[2] F. Roth 1989. A model for the present stress field along the Xian-shui-he fault belt, NW Sichuan, China. In: M.J. Berry (editor), Earthquake hazard assessment and prediction. *Tectonophysics* 167, 103–115.

[3] F. Roth 1990. Subsurface deformations in a layered elastic half-space. *Geophys. J. Int.* 103, 147–155.

[4] F. Roth 1993. Deformations in a layered crust due to a system of cracks – modeling the effect of dike injections or dilatancy. *J. Geophys. Res.* 98, 4543–4551.

[5] F. Roth 1994. New methods using dislocation theory. In: Proceedings of the 8th Internat. Symp. on Recent Crustal Movements (CRCM '93) of IUGG and IAG, Local Organizing Committee for the CRCM '93, Kobe, December 6-11, 1993, 265–274 (special issue of *J. of the Geodetic Soc. of Japan*).

7.4.2 Icelandic Energy Authority

See Subproject 1, section 7.1.2.

Name: Valgardur Stefánsson

Citizenship:
Icelandic

Date of birth:
1939, in Iceland

Education:
Dr. of Science in nuclear physics from University of Stockholm in 1973.

Career: Joined the Icelandic Energy Authority in 1973 as exploration geophysicist. From 1976 to 1985 he was the head of the Geothermal Logging Department.
In 1979-1985 he was deputy director of the Geothermal Division of the Icelandic Energy Authority.
In 1985-1990 he was an interregional advisor on geothermal energy at the Energy Branch, Division of Natural Resources and Energy, Department of Technical Cooperation for Development, United Nations in New York.
Since 1990 he has been the head of the Reservoir Engineering Department of the Icelandic Energy Authority. He has been scientific project manager of several main high temperature geothermal projects in Iceland, including the Krafla and Nesjavellir fields.
He has been consultant in various geothermal projects in Kenya, Russia, Croatia, Georgia, Ethiopia and Central America.

References relevant to the proposal:
[1] Stefánsson, V. & B. Steingrímsson 1980. Geothermal logging I: an introduction to techniques and interpretation. *Report OS80017/JHD09*, National Energy Authority, 117 pp.
[2] Jónsson, G. & V. Stefánsson 1982. Density and porosity logging in the IRDP-hole. *J. Geophys. Res.* 87, 6619–6630.
[3] Stefánsson, V., Á. Gudmundsson & R. Emmerman 1982. Gamma ray logging in Icelandic rocks. *The Log Analyst XXIII* 6, 11–16.
[4] Stefánsson, V., G. Axelsson & O. Sigurdsson 1982. Resistivity logging of fractured basalt. In: Proceedings of the 8th Workshop on Geothermal Reservoir Engineering, Stanford University, 189–196.
[5] Nielsen, P. H., V. Stefánsson & H. Tulinius 1984. Geophysical logs from Lopra-1 and Vestmanna-1. In: O. Berthelsen, A. Noe-Nygaard & J. Rasmussen (editors), *The Deep Drilling Project 1980–1981 in the Faroe Islands.* Foroya Frodskaparfelag, 115–136.

7.5 Subproject 5: Active deformation determined from GPS and SAR

Contractor:

Kurt L. Feigl (**partner 5**)
Centre National de la Recherche Scientifique (CNRS), Toulouse, France

Associated contractor:

Freysteinn Sigmundsson (**partner 6**)
Nordic Volcanological Institute, Reykjavík, Iceland

Subcontractor:

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

Subcontractor:

Jan Johanson
Onsala Space Observatory, Chalmers University of Technology, Gothenburg, Sweden

Subcontractor:

Páll Einarsson
Science Institute, University of Iceland, Reykjavík, Iceland

CNRS (K. Feigl and A. Rigo) and NVI (F. Sigmundsson) will be responsible for the SAR interferometric analysis of radar data. When the project begins both CNRS and NVI will have a running version of the DIAPASON software for interferometric analysis of SAR images. This software, developed by D. Massonnet at Centre National d'Etudes Spatiales in France, will be used for the radar analysis. CNRS will acquire the relevant radar data, NVI will provide the Digital Elevation Model (DEM) required for the analysis. The analysis will be conducted in collaboration.

The Science Institute, University of Iceland (P. Einarsson) will provide information on active faults in the South Iceland seismic zone in the form of a digitized fault map. This map will be used for the interpretation of the SAR images, and to relate deformation to distribution of faults and seismicity within the seismic zone.

The NVI (F. Sigmundsson) will be responsible for the maintenance of 3 GPS receivers in the South Iceland Seismic Zone at least 8 months per year at semi-permanent stations. The GPS data will be analysed at NVI and at the Onsala Space Observatory.

At the Onsala Space Observatory (J. Johanson) data from the GPS stations within the South Iceland seismic zone will be included in joint data analysis of about 50 GPS stations in the "Northern Hemisphere", using both the GIPSY and the Bernese Software. In these network solutions the Iceland stations will be "connected" to stations on Greenland, North America, Fennoscandia and Continental Europe. This network will also be combined with the more sparse, but yet, global IGS network. This will put the Iceland stations in to a global reference frame, allowing the determination of the absolute plate motion applied to the South Iceland seismic zone.

All the participants in the subproject, K. Feigl, F. Sigmundsson, P. Einarsson, J. Johanson, and A. Rigo will collaborate on the initial interpretation of the deformation data, as well as other members from the participating institutions.

7.5.1 Centre National de la Recherche Scientifique (CNRS)

Groupe de Recherche en Geodesie Spatiale (GRGS) is an inter–departmental organization of which the French space agency (Centre National d'Etudes National, CNES) and the national research council (Centre National de la Recherche Scientifique, CNRS) are both members. Historically, this is the research organization in France responsible for geophysical applications of space geodesy (e.g. DORIS, TOPEX/POSEIDON, SLR, etc.). It is one of only a few laboratories in the world to combine the expertise in producing radar interferograms with a geophysical background in modeling crustal deformation. It is thus in a privileged position to undertake this project. With the proposed budget, it will possess the computational resources required for the production and analysis of the necessary radar interferograms.

Name: Kurt L. Feigl

Citizenship:
U.S.A. and France

Date of birth:
January 30, 1962, in Sweden

Education:
B.S. in geology and geophysics, summa cum laude, Yale University, 1985.
Ph.D. in geophysics, Massachusetts Institute of Technology, 1991.

Career: Research technician, R/V R. D. Conrad, Lamont–Doherty Geological Observatory, Columbia University, USA 1985-1986.
Research associate, Institut de Physique du Globe de Paris, 1991–1992.
Research scientist, Centre Nationale de la Recherche Scientifique, Toulouse 1992–present.

References relevant to the proposal:

[1] Feigl, K.L., D.C. Agnew, Y. Bock, D. Dong, A. Donnellan, R.W. King, B.H. Hager, T.A. Herring, D.D. Jackson, T.H. Jordan, S. Larsen, K.M. Larson, M.H. Murray, Z. Shen & F. H. Webb 1993: Space geodetic measurement of crustal deformation in central and southern California, 1984-1992, *J. Geophys. Res.* 98, 21677–21712.

[2] Massonnet, D., M. Rossi, C. Carmona, F. Adragna, G. Peltzer, K. Feigl & T. Rabaute 1993. The displacement field of the Landers earthquake mapped by radar interferometry. *Nature* 364, 138–142.

[3] Massonnet, D., K.L. Feigl, M. Rossi & F. Adragna 1994. Radar interferometric mapping of deformation in the year after the Landers earthquake. *Nature* 369, 227–230.

[4] Feigl, K.L., A. Sergent & D. Jacq 1995. Estimation of an earthquake focal mechanism from a satellite radar interferogram: application to the December 4, 1992 Landers aftershock. *Geophys. Res. Lett.* 22, 1037–1048.

[5] Massonnet, D. & K.L. Feigl 1996. Radar interferometry and its application to changes in the Earth's surface. *Rev. Geophys.*, submitted.

Name: Alexis Rigo

Citizenship:
French

Date of birth:
August 23, 1963, in France

Education:
Magistère Interuniversitaire des Sciences de la Terre, Université Paris 6, 1990.
DEA de Géophysique Interne, Université Paris 7, 1990.
Doctorat en Géophysique Interne, Université Paris 7, 1994.

Career: Lecturer, Institut de Physique du Globe de Paris, 1993–1994.
Research consultant in seismic hazard, Coyne & Bellier, Gennevilliers, France, 1995.
Research scientist, Centre National de la Recherche Scientifique, Toulouse, 1995–present.

References relevant to the proposal:

[1] Armijo R., B. Meyer, G.C.P. King, A. Rigo & D. Papanastassiou 1996. Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean, *Geophys. J. Int.* 126, 11–53.

[2] Rigo, A., H. Lyon-Caen, R. Armijo, A. Deschamps, D. Hatzfeld, K. Makropoulos, P. Papadimitriou & I. Kassaras 1996. A microseismic study in the western part of the Gulf of Corinth (Greece): Implications for large-scale normal faulting mechanisms. *Geophys. J. Int.* 126, 663–688.

[3] Bernard, P., P. Briole, B. Meyer, H. Lyon-Caen, J.M. Gomez, C. Tiberi, C. Berge, D. Hatzfeld, C. Lachet, B. Lebrun, A. Deschamps, F. Courboulex, C. Laroque, A. Rigo, D. Massonnet, P. Papadimitriou, J. Kassaras, D. Diagourtas, K. Makropoulos, G. Veis, E. Papazisi, C. Mitsakaki, V. Karakostas, E. Papadimitriou & D. Papanastassiou 1996. The Ms=6.2, June 15, 1995 Aigion earthquake (Greece): Results of a multidisciplinary study. *J. Seismology*, submitted.

[4] Rigo, A., C. Olivera, A. Souriau, S. Figueras, H. Pauchet, A. Grésillaud, & M. Nicolas 1996. The February 1996 earthquake sequence in the eastern Pyrenees: First results. *J. Seismology*, submitted.

[5] Baker, C., D. Hatzfeld, H. Lyon-Caen, E. Papadimitriou & A. Rigo 1996. Earthquake mechanisms of the Adriatic Sea and Western Greece. *Geophys. J. Int.*, submitted.

7.5.2 Nordic Volcanological Institute (NVI)

The Nordic Volcanological Institute (NVI) is a multinational organization sponsored by the Nordic countries, Denmark, Finland, Iceland, Norway and Sweden. The NVI was founded in 1973 and has now 14 salaried researchers. The institute focuses on basic research in volcanology and related topics. One field of special emphasis is research on active crustal deformation at plate boundaries, both at volcanoes and in seismic zones. This research field has been pursued at the institute for more than 20 years, relying e.g. on geodetic techniques. The technigues currently used include optical levelling and automatic tilt measurements, electronic distance measurements (EDM), Global Positioning System (GPS) geodesy, and Satellite Radar Interferometry (SAR). The institute has three Trimble 4000 SST GPS receivers, partly at the disposal of this project. The Bernese GPS software, Version 4.0, is used for analysis. of GPS data. The NVI should soon have a copy of the DIAPASON software, developed by D. Massonnet at Centre National d'Etudes Spatiales in France, that will be used for SAR interferometric analysis of radar images.

Name: Freysteinn Sigmundsson

Citizenship:

Icelandic

Date of birth:

July 22, 1966, in Iceland

Education:

1985–1988: University of Iceland, B.S. degree 1988, geophysics.
1988–1989: University of Colorado at Boulder, USA.
1989–1990: University of Iceland, M.S. degree 1990, geophysics.
1990–1992: University of Colorado, Ph.D. degree 1992, geophysics.

Career: 1988–1989: University of Colorado, research assistant. Deformation monitoring in the Long Valley Caldera, and research on the application of the Global Positioning System for tectonic studies.

1989–1990: University of Iceland, research assistant. Research on post-glacial rebound and rheology in Iceland.

1990–1992: University of Colorado, research assistant. Research on crustal deformation in sub-aerial parts of the world-oceanic rift system and application of the Global Positioning System for tectonic studies.

1992–present: Nordic Volcanological Institute, research geophysicist. Principal field of work: Research on crustal deformation related to volcanic and seismic activity using the Global Positioning System (GPS), Satellite Radar Interferometry (SAR), optical levelling and automatic tiltmeters.

References relevant to the proposal:

[1] Sturkell, E., F. Sigmundsson, P. Einarsson & R. Bilham 1994. Strain accumulation 1986–1992 across the Reykjanes Peninsula plate boundary, Iceland, determined from GPS measurements. *Geophys. Res. Lett.* 21, 125–128.

[2] Sigmundsson, F., P. Einarsson, R. Bilham & E. Sturkell 1995. Rift-transform kinematics in South Iceland: Deformation from Global Positioning System measurements, 1986–1992. *J. Geophys. Res.* 100, 6235–6248.

[3] Sigmundson, F. 1996. Crustal deformation at volcanoes. In: F. Barberi & R. Casale (editors), Proceedings of the Course the Mitigation of Volcanic Hazards, European School of Climatology and Natural Hazards, Vulcano, Sicily, 12–18 June 1994. European Commission, ECSC-EC-EAEC, Brussels.

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

[5] Vadon, H. & F. Sigmundsson 1997. Crustal deformation from 1992–1995 at the Mid-Atlantic Ridge, SW Iceland, mapped by satellite radar interferometry. *Science* 275, 194–197.

7.5.3 Onsala Space Observatory (OSO)

The research group on Space Geodesy and Geodynamics at the Onsala Space Observatory has been involved in the development of the Very-Long Baseline Interferometry (VLBI) technique for precise determination of baseline vectors in application to the measurement of plate tectonics and earth orientation from the start in the early 1960's. They have been involved in a number of long-term international research projects, most notably NASA's Crustal Dynamics Program during 1980's and the follow-on Dynamics of the Solid Earth program. The latter application highlights the use of GPS and VLBI for the measurement of postglacial rebound and related changes of the sea level.

Onsala Space Observatory has started its GPS activities in 1986. A CIGNET (now IGS) tracking station has been in operation since 1987. Research and development on the GPS technique for precise determination of geodetic positions with special emphasis on antennas and atmospheric wave propagation. During 1993 in a joint effort, OSO and the National Land Survey of Sweden created a permanent array of 21 GPS stations evenly distributed throughout the country. Since August 1993 the data that are continuously observed in the array are being processed at OSO and solutions are obtained on a daily basis. Since 1996 a more extensive network is routinely analyzed. The group has acquired expertise with several GPS software packages. The Bernese Software as well as the GIPSY software developed at Jet Propulsion Laboratory, USA are used daily.

Name: Jan Johanson

Citizenship:
Swedish

Date of birth:
September, 1960, in Sweden

Education:
1985: M.Sc. degree (civ. ing) in electrical and computer engineering at Chalmers University of Technology, Gothenburg, Sweden.
1992: Ph.D. at Chalmers University of Technology.

Career: 1985–1992: Research assistent at Onsala Space Observatory, Chalmers University of Technology.
1992–1993: Visiting scientist (postdoctoral fellow) at Harvard-Smithsonian Center for Astrophysics Cambridge, Mass., USA.
1993–present: Postdoctoral scientist/assistant professor at Onsala Space Observatory, Chalmers University of Technology.
1994: Visiting scientist at Harvard–Smithsonian Center for Astrophysics Cambridge, Mass., USA.
President IAG/IUGG Special Study Group on site dependent effects in high–precision satellite navigation (SSG 1.158).
Chairman of NKG WG on permanent geodetic stations.

References relevant to the proposal:

[1] Scherneck, H.-G. 1991. A parametrized solid earth tide model and ocean tide loading effects for global geodetic baseline measurements. *Geophys. J. Int.* 106, 677–694.
[2] Elósegui, P., J.L. Davis, R.T.K. Jaldehag, J.M. Johansson, A.E. Neill & I.I. Shapiro 1995. Geodesy using the Global Positioning System: The effects of signal scattering on estimates of site position. *J. Geophys. Res.* 100, 9921–9934.
[3] BIFROST Project, R.A. Bennett, T.R. Carlsson, T.M. Carlsson, R. Chen, J.L. Davis, M. Ekman, G. Elgered, P. Elósegui, G. Hedling, R.T.K. Jaldehag,

P.O.J. Jarlemark, J.M. Johansson, B. Jonsson, J. Kakkuri, H. Koivula, G.A. Milne, J.X. Mitrovica, B.I. Nilsson, M. Ollikainen, M. Paunonen, M. Poutanen, R.N. Pysklywec, B.O. Rönnäng, H.-G. Scherneck, I.I. Shapiro & M. Vermeer 1996. GPS measurements to constrain geodynamic processes in Fennoscandia. *EOS Trans. American Geophys. Union* 77, 337–339.

[4] Jaldehag, R.T.K., J.M. Johansson, B.O.Rönnäng, P. Elósegui, J.L. Davis, I.I. Shapiro & A.E. Neill 1996. Geodesy using the Swedish Permanent GPS Network: Effects of signal scattering on estimates of relative site positions. *J. Geophys. Res.* 101, 17,841–17,860.

[5] Jaldehag, R.T.K, J.M. Johansson, J.L. Davis & P. Elósegui 1996. Geodesy using the Swedish Permanent GPS Network: Effects of snow accumulation on estimates of site positions. *Geophys. Res. Letters* 23, 1601–1604.

7.5.4 Science Institute, University of Iceland

The University of Iceland is a state university with 5000 students in 9 departments: law, medicine, dentistry, theology, philosophy, social sciences, engineering, natural sciences, and economics. The Department of Natural Sciences encompasses the subjects physics, mathematics, computer science, chemistry, biology and geology, and has 800 students. B.S. and M.S. degrees are offered in these subjects. Yearly number of physics students (including geophysics) is 5-10. The Science Institute is a research institute of the Department of Natural Sciences, but with a separate budget. It has divisions of mathematics, physics, geophysics, geology, chemistry, and computer science. Most of its funds come from the government budget, but a substantial part comes from grants and contracts. The Geophysics Division has a staff of 14: 2 professors, 4 senior research scientists, 3 research scientists, 3 technicians and 2 research assistants. Main research areas are seismology, crustal movements, glaciology, paleomagnetism, geomagnetism, mass spectrometry, and geothermal research. The division runs a geomagnetic observatory (Leirvogur), 20 seismographs throughout the country, and a mass spectrometer. The Geophysics Division has conducted research on seismicity and crustal movements for almost 30 years. Studies of the South Iceland seismic zone go back to 1974, with emphasis on seismicity, crustal deformation, radon precursors and mapping of recent earthquake faults.

Name: Páll Einarsson

Citizenship:
Icelandic

Date of birth:
March 27, 1947, in Iceland

Education:
University of Göttingen, Germany, 1967–70. Major in physics, minors in mathematics and chemistry. Vordiplom in physics 1970.
Columbia University, New York, USA, 1970–75. Major in seismology, minors in general geology, physics and structural geology. M.Phil. degree in 1974, Ph.D. degree in 1975.

Career: Graduate research assistant, Lamont-Doherty Geological Observatory, USA, 1970–75.

Teaching assistant, Columbia University, USA, 1974–1975.
Research scientist, Science Institute, University of Iceland, 1975–1977.
Senior research scientist, Science Institute, University of Iceland, 1977–1994.
Head of the Geophysics Division and member of the Board of Directors of the Science Institute, 1983–87.
Member of the University Senate, U.I., 1986–1990.
Lecturer in the Department of Natural Sciences, U.I., 1975–1994, teaching courses in geophysics, physics, seismology, tectonics and volcanology.
Professor of geophysics, U.I., 1994.

References relevant to the proposal:

[1] Einarsson, P., S. Björnsson, G. Foulger, R. Stefánsson & Th. Skaftadóttir 1981. Seismicity pattern in the South Iceland seismic zone. In: D. Simpson & P. Richards (editors), *Earthquake Prediction - An International Review*, Am. Geophys. Union, M. Ewing Series 4, 141–151.
[2] Einarsson, P. & J. Eiríksson 1982. Earthquake fractures in the districts Land and Rangárvellir in the South Iceland seismic zone. *Jökull* 32, 113–120.
[3] Einarsson, P. 1991. Earthquakes and present-day tectonism in Iceland. *Tectonophysics* 189, 261–279.
[4] Sigmundsson, F., P. Einarsson, R. Bilham & E. Sturkell 1995. Rift–transform kinematics in South Iceland: Deformation from Global Positioning System measurements, 1986 to 1992. *J. Geophys. Res.* 100, 6235–6248.
[5] Erlendsson, P. & P. Einarsson 1996. The Hvalhnúkur fault, a strike-slip fault mapped within the Reykjanes Peninsula oblique rift, Iceland. In: B. Thorkelsson (editor), *Seismology in Europe*. Papers presented at the XXV ESC General Assembly, September 9–14, 1996, Reykjavík, Iceland. ISBN 9979-60-235-X, 498–504.

7.6 Subproject 6: Effects of stress fields and crustal fluids on the development and sealing of seismogenic faults

Contractor:

Ágúst Gudmundsson (**partner 6**)
Nordic Volcanological Institute, Reykjavík, Iceland

Associated contractor:

Francoise Bergerat (**partner 8**)
Laboratorie de Tectonique Quantitative, Université Pierre et Marie Curie, CNRS, Paris, France

Subontractor:

Jacques Angelier
Laboratorie de Tectonique Quantitative, Université Pierre et Marie Curie, CNRS, Paris, France

Subontractor:

Thierry Villemin
Université de Savoie, France

Subontractor:

Philip Meredith
Department of Geological Sciences, University College, London, U.K.

7.6.1 Nordic Volcanological Institute

The Nordic Volcanological Institute (NVI) is a multinational organization sponsored jointly by the Nordic countries, Denmark, Finland, Iceland, Norway and Sweden. The NVI was founded in 1973 and has now 14 salaried researchers. The institute focuses on basic research in volcanology, with special emphasis on volcanotectonics and crustal deformation of active volcanoes as well as their histories, petrology and geochemistry.

The institute is well equipped for volcanological studies. In addition to the usual equipment for studies in geochemistry and petrology (including a microprobe), NVI has several GPS instruments and access to a large range of computers and computer hardware and software, including the boundary-element analysis system BEASY.

Name: Ágúst Gudmundsson

Citizenship:

Icelandic

Date of birth:

November 26, 1953, in Iceland

Education:

B.S. in general geology, University of Iceland, 1977.
B.S. (honours) in structural geology, University of Iceland, 1978.
M.Sc. in structural geology and rock mechanics, Imperial College, London, 1979.
Ph.D. as an external student, University of London, 1984.

Career: He was a part-time teacher at the Sund College in Reykjavík, 1974–1978 and again 1986–1987, and a full-time teacher 1979–1985. He has lectured on geology, astronomy, computer sciences and mathematics. He worked as a field geologist for the Icelandic Energy Authority 1977–1978 and again during the summer of 1982. During the spring semester of 1985, he lectured on rock mechanics and fracture mechanics at the Department of Physics, University of Iceland. He was a research fellow at the Nordic Volcanological Institute, 1985–1987, and a research scientist at the same institute from 1987. He was the president of the Geoscience Society of Iceland 1994–1996.

References relevant to the proposal:

[1] Gudmundsson, Á., K. Fjäder & T. Forslund 1994. Dikes, minor faults and mineral veins associated with a transform fault in North Iceland. *J. Struct. Geol.* 16, 109–119.

[2] Gudmundsson, Á. 1995. Infrastructure and mechanics of volcanic systems in Iceland. *J. Volcanol. Geotherm. Res.* 64, 1–22.

[3] Gudmundsson, Á. & B. O. Längbacka 1995. Extensional tectonics in the vicinity of a transform fault in North Iceland. *Tectonics* 14, 294–306.

[4] Gudmundsson, A., 1995. Ocean-ridge discontinuities in Iceland. *J. Geol. Soc. London* 152, 1011–1015.

[5] Gudmundsson, A., F. Bergerat & J. Angelier 1996. Off-rift and rift-zone paleostresses in Northwest Iceland. *Tectonophysics* 255, 211–228.

7.6.2 Laboratorie de Tectonique Quantitative, Université Pierre et Marie Curie, CNRS

This laboratory has a long experience in tectonic studies, focusing on quantitative studies such as paleostress reconstructions using fault-slip data sets. Since 1987 Jacques Angelier and Francoise Bergerat from this Laboratory have carried out volcano-tectonic studies in Iceland, including fracture studies in the rift zone, paleostress reconstructions, and studies within the on-land parts of the Tjörnes fracture zone in North Iceland.

Name: Francoise Bergerat

Citizenship:
French

Date of birth:
January 18, 1949

Education:
Baccalauréat Sciences Expérimentales, Paris, 1966.
Maitrise de Géologie, University of Pierre and Marie Curie, 1971.
D.E.A. de Géologie Structurale, University of Pierre and Marie Curie, 1972.
Doctorat de 3ème cycle en Géologie Structurale, University of Pierre and Marie Curie, 1974.
Doctorat d'Etat és-Sciences, University of Pierre and Marie Curie, 1985.

Career: She joined the CNRS (The French National Research Centre) in 1982 as a research scientist and became a research director, at the same institute, in 1989. Deputy-Director of the "Parisian Center of Geology" CNRS Research Federation since 1996.

References relevant to the proposal:

[1] Bergerat, F., J. Angelier & T. Villemin 1990. Fault systems and stress patterns on emerged oceanic ridges: a case study in Iceland. *Tectonophysics* 179, 183–197.

[2] Bergerat, F., L. Csontos, G. Tari & L. Fodor 1991. Evolution of the stress field in the Carpathe-Pennonian area during the Neogene. *Tectonophysics* 199, 73–92.

[3] Bergerat, F. 1994. Tectonic evolution of the Greenland–Scotland ridge during the Paleogene: New constraints. *Geology* 22, 653–656.

[4] Bergerat, F. & P. Martin 1996. Paleostresses inferred from macro- and microfractures in the Balazuc-1 borehole (G.P.F. programme). Contribution to the tectonic evolution of the Cévennes border of the SE Basin of France. *Marine and Petroleum Geology* 13, 671–684.

[5] Bergerat, F., J. Angelier, O. Dauteuil & T. Villemin 1997. Tension-shear relationships in extensional fissure swarms, axial rift of northeastern Iceland: morphological evidence. *J. Struct. Geol.*, in press.

Name: Jacques Angelier

Citizenship:
French

Date of birth:
March 2, 1947

Education:
Baccalauréat de Sciences Expérimentales, Aix Marseille, 1964.
Maitrise és Sciences de Géologie, Faculté des Sciences de Paris, 1968.
D.E.A. de Géologie Structurale, Université Pierre et Marie Curie 1970.
Doctorat de 3e cycle en Géologie Structurale, Université Pierre et Marie Curie, 1971.
Doctorat d'Etat és Sciences, Université Pierre et Marie Curie, 1979.

Career: He was a teacher (assistant) at the University of Pierre et Marie Curie, Paris from 1970 to 1971 and at the University of Orleans from 1971 to 1976 (first as "assistant" and then as "maitre-assistant"). He was a "maitre-assistant" at the Université Pierre et Marie Curie from 1976 to 1981 and became a professor at the same university in 1981. Head of the "Tectonics" CNRS Laboratory for the period 1997–2000.

References relevant to the proposal:

[1] Angelier, J. 1984. Tectonic analysis of fault slip data sets. *J. Geophys. Res.* 89, 5835–5848.

[2] Angelier, J. 1989. From orientation to magnitudes in paleostress determinations using fault slip data. *J. Struct. Geol.* 11, 37–50.

[3] Angelier, J. 1990. Inversion of field data in fault tectonics to obtain the regional stress III. A new rapid direct inversion method by analytical means. *Geophys. J. Int.* 103, 363–376.

[4] Angelier, J., J. M. Dupin & W. Sassi 1993. Homogeneous stress hypothesis and actual fault slip: a distinct element analysis. *J. Struct. Geol.* 15, 1033–1043.

[5] Angelier, J. 1994. Paleostress trajectory maps based on the results of local

determinations: the LISSAGE program. *Computers and Geosciences* 20, 161–191.

7.6.3 Université de Savoie

The Laboratoire de Géodynamique des Chaînes Alpines (LGCA) (Laboratory of Alpine Belt Geodynamic) is a laboratory of both the University of Savoy (Chambéry) and University Joseph Fourier (Grenoble). The LGCA is also a associated Laboratory of the Centre National de la Recherche Scientifique (ESA CNRS n°5025). The LGCA has a staff of about 25 academic people, and 40 reseach students.

The main fields of reseach at the LGCA during the next years are as follow:

- Sedimentology and lithospheric deformation.
- Tectonic, magmatic and metamophic evolution of the lithosphere during convergence processes.
- Characterization, measure and modelization of recent and present-day deformation. This group is made of 7 permanents and 15 research students. Special attention will be payed to natural risk due to earthquakes (fault propagation) and slope instabilities (cliff evolution).

The LGCA contains and has access to a lot of computers and softwares, a large range of photogrammetric and geodesic instruments, equipments for analogue experiments in rock mechanics.

Name: Thierry Villemin

Citizenship:
French

Date of birth:
September 10, 1958

Education:
Bachelor's degree in natural sciences, Pierre and Marie Curie University, Paris, 1980.
Master's degree in natural sciences, Pierre and Marie Curie University, Paris, 1981.
Biology and geology agrégation examination, 1982.
Ph.D. in geology, Pierre and Marie Curie University, Paris, 1986.

Career: He was a full time teacher from 1984–1986. In 1986 he obtained a temporary employment of senior lecturer at the Pierre and Marie Curie University, Paris and gave lectures in geology. In 1990 he has obtained a permanent employment of senior lecturer at the University of Savoie. Now he gives lectures in structural geology, tectonics, teledetection and geodesy. He makes research on fracture mechanics and fracture patterns at the Laboratory of alpine belts geodynamic (CNRS associated Laboratory).

References relevant to the proposal:

[1] Bergerat, F., J. Angelier & T. Villemin 1990. Fault systems and stress patterns on emerged oceanic ridges: a case study in Iceland. *Tectonophysics* 179,

183–197.
[2] Bergerat, F., J. Angelier & T. Villemin 1992. Déformations cassantes dans la partie émergée d'une zone transformante océanique: la zone de fractures de Tjornes (Islande). *C. R. Acad. Sci., Paris* 315, 1011–1018.
[3] Gudmundsson, Á, F. Bergerat, J. Angelier & T. Villemin 1992. Extensional tectonics of southwest Iceland. *Bull. Soc. Géol. France.* 163, 561–570.
[4] Villemin, T., F. Bergerat, J. Angelier & C. Lacasse 1994. Brittle deformation and fracture patterns on oceanic rift shoulders: the Esja peninsula, SW Iceland. *J. Struct. Geol.* 16, 1641–1654.
[5] Villemin, T., J. Angelier & S. Choon 1994. Fractal distribution of fault extents and offsets: implications on brittle deformation evaluation: the Lorraine coal Basin (NE France). In: C.C. Barton & P.R. Lapointe (editors), *Fractals in the earth Sciences*, Plenum Press, 205–226.

7.6.4 Department of Geological Sciences, University College, London

The Rock & Ice Physics Research Unit at the University College, London (UCL) is based on the research activities and interests of Philip Meredith (director), Stan Murrell, Peter Sammonds and David Scott. The Unit currently comprises 20 members, and its main research objectives include the fracture behaviour of rocks, fluid-rock interaction, the determination of crustal stress fields by observations and experiments in boreholes, deformation and strength of crustal rocks, syn-deformational measurements of acoustic properties of rocks, including P- and S-wave velocities, attenuation and acoustic emission.

Name: Philip Meredith

Citizenship:
British

Education:
B.Sc. in mining engineering, Imperial College, London, U.K.
Ph.D. in geophysics, Imperial College, London, U.K.

Career: From 1983–1985 he was NERC postdoctoral research fellow at Imperial College and from 1985–1988 special fellow at University College, London. At the University College he was lecturer in rock physics from 1988–1992, reader in rock physics from 1992–1995, director of the Rock & Ice Physics Laboratory from 1989-1995 and deputy head of Department from 1994–1995. He was Monbusho visiting professor at the Research Institute for Fracture Technology, Tohoku University in Japan, in 1992. He has published more than 70 research publications (excluding abstracts) since 1981.

References relevant to the proposal:
[1] Meredith, P. & B. K. Atkinson 1987. The theory of subcritical crack growth with applications to minerals and rocks. In: B.K. Atkinson (editor), *Fracture Mechanics of Rock.* Academic Press, London, 111–166.
[2] Meredith, P. & B.K. Atkinson 1987. Experimental fracture mechanics data for rocks and minerals. In: B.K. Atkinson (editor), *Fracture Mechanics of Rock.* Academic Press, London, 477–525.
[3] Sammonds, P.R., P.G. Meredith & I.G. Main 1992. Role of pore fluids in the generation of seismic percursors to shear fracture. *Nature* 359, 228–230.

[4] Hatton, C.G., I.G. Main & P.G. Meredith 1994. Non-universal scaling of fracture length and opening displacement in the Krafla fissure swarm, NE Iceland. *Nature* 367, 160-162.
[5] C. Jones, P. Meredith & S.A.F. Murrell 1996. Thermally induced seismicity, microcrack damage and fluid permeability in basalts. 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, 83–88.

7.7 Subproject 7: Theoretical analysis of faulting and earthquake processes

Contractor:

Maurizio Bonafede (**partner 7**)
Department of physics, University of Bologna, Italy

Associated contractor:

Frank Roth (**partner 4**)
GeoForschungsZentrum, Potsdam, Germany

7.7.1 Department of Physics, University of Bologna

The Department of Physics, University of Bologna is divided in 8 research branches (sectors), one of which is the sector "Geophysics", with 8 professors 4 permanent and several non-permanent research assistants. Geophysical disciplines are taught to undergraduate students in physics and geology; a Ph.D. curriculum in geophysics is also available.

Main research fields in solid earth geophysics include:

- Gravitation: Experiment on the detection of non–Newtonian terms in the gravity force (5–th force) employing a superconductor gravimeter.
- Physical modelling of geodynamic processes, including plate tectonics, post–glacial rebound, interaction with earth rotation, fault mechanics and volcanic processes.
- Advanced statistical methods applied to establish phenomenological relationships between geophysical observations and seismic and volcanic events, including precursory events.
- Modelling tsunami generation and propagation following landslides, earthquakes and volcanic eruptions.
- Space geodesy (mainly GPS) applied to monitor the deformation field in tectonically active areas in Italy and the Mediterranean.
- Seismic and gravimetric prospecting for local studies.

Name: Maurizio Bonafede

Citizenship:

Italian

Date of birth:

April 23, 1949

Education:

Degree in physics, University of Bologna, 1972.
Postdoctoral diploma in space science, University College, London, 1974.

Career: Full professor of physics of the solid earth, University of Bologna.
Teaching — undergraduate:
Mathematics (University of Ancona 1976–1977, University of Bologna 1977–1983), seismology (University of Ancona 1977-1983), physics (University of Bologna 1983-88), physics of the solid earth (University of Bologna 1988 to present).

Teaching — postgraduate:
Mechanics of continua (Ph.D. in physics 1987-1988), partial differential equations (Ph.D. in physics 1989-1993).
Convenor and chairman of EUG and EGS symposia, workshops and schools.
Editor of Acta Vulcanologica, associate editor of Annali di Geofisica and Physics and Chemistry of the Earth, and guest editor of Terra Nova, vol. 4.
Member of the Directive Council of Osservatorio Vesuviano (Napoli). Member of the Scientific Council of Gruppo Nazionale per la Vulcanologia. Member of Scientific Council of Istituto Nazionale di Geofisica.
Proposer and co-investigator in several research projects funded by the Italian National Research Council (CNR) and Ministry of Scientific and Technological Research (MURST) since 1977. Contractor within the previous phase of EC Programme Environment and Climate.
The research activity is mainly concerned with the physical and mathematical modelling of geodynamic processes (interaction between lithosphere and asthenosphere), ground deformation (induced by fluid migration, seismic and volcanic activity), fracture mechanics (dyke injection, rheology of fault regions, aftershocks), precursory phenomena (piezomagnetic effect).

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7.7.2 GeoForschungsZentrum, Potsdam

See Subproject 4, section 7.4.1 for information on GeoForschungsZentrum and Frank Roth.

Chapter 8

Financial information

A summary of the costs of the project is given in Table 1 on the following page.

Table 1. *Summary of the costs of the project. Breakdown of costs for each partner is in Annex.*

	Full cost	Additional cost	Total cost	Contributed	EC funding requested
Partner 1 Icelandic Meteorological Office, Reykjavík, Iceland					
Contractor: Ragnar Stefánsson (Subproject 1)	X		686,000 ECU	439,000 ECU	247,000 ECU
Partner 2 Uppsala University, Sweden					
Contractor: Reynir Böðvarsson (Subproject 2)		X	139,000 ECU		139,000 ECU
Partner 3 University of Edinburgh, U.K.					
Contractor: Stuart Crampin (Subproject 3)		X	130,000 ECU		130,000 ECU
Partner 4 GeoForschungsZentrum, Potsdam, Germany					
Contractor: Frank Roth (Subproject 4)		X	72,200 ECU		72,200 ECU
Associated contractor: Frank Roth (Subproject 7)		X	33,800 ECU		33,800 ECU
Partner 5 CNRS, Toulouse, France					
Contractor: Kurt L. Feigl (Subproject 5)	X		110,000 ECU	64,000 ECU	46,000 ECU
Partner 6 Nordic Volcanological Institute, Reykjavík, Iceland					
Contractor: Ágúst Gudmundsson (Subproject 6)		X	120,000 ECU		120,000 ECU
Associated contractor: Freysteinn Sigmundsson (Subproject 5)		X	35,000 ECU		35,000 ECU
Partner 7 Department of Physics, University of Bologna, Italy					
Contractor: Maurizio Bonafede (Subproject 7)		X	31,000 ECU		31,000 ECU
Partner 8 Université Pierre et Marie Curie, CNRS, Paris, France					
Associated contractor: Francoise Bergerat (Subproject 6)	X		136,032 ECU	81,032 ECU	55,000 ECU
Total:			1,493,032 ECU	584,032 ECU	909,000 ECU

Chapter 9

Exploitation plans

The results of this project should be exploited for reducing seismic risk in Europe and for further development of the scientific and technical achievements. The results obtained will be disseminated as soon as they are reached, in journals, at scientific meetings, and in open yearly reports to the EC.

The results will be used in Iceland as a basis for preparing better hazard assessment maps and for application in alert systems, especially the already existing alert system operated at the Icelandic Meteorological Office. The partners of this project consider it significant that the scientific results, technology and knowhow developed during the project will be exploited for similar purposes in other earthquake prone countries. Initiatives have been taken towards implementation of the scientific and technical knowhow gained in the PRENLAB project into a new seismic network in Patras, Greece, as a part of this project.

There are several software programs used within this project by various groups which have acquired license for using them. Also there are a few software programs developed at an earlier stage by the participants which are patented. Apart from this, the use of advanced technology developed under the project is free under the condition of referring to the authors and using it with the authors' knowledge.

Chapter 10

Ongoing projects and previous proposals

The project proposed here is a direct continuation of the project *Earthquake-Prediction Research in a Natural Laboratory (PRENLAB)*, EC project, contract no. ENV4-CT96-0252. That project started March 1, 1996 and will finish its term on February 28, 1998.

The present proposal *Earthquake-Prediction Research in a Natural Laboratory - Two (Earthquake Prediction Natlab-2)*, is a new project with a new work content, proposed to start on March 1, 1998.

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Breakdown of costs for each partner

Partner 1 Icelandic Meteorological Office, Reykjavík, Iceland

Subproject 1: Monitoring crustal processes for reducing seismic risk
Contractor: Ragnar Stefánsson (coordinator)

	Total cost	Requested
Personnel:		
Salaries of the existing personnel		
devoted to the project	355,000 ECU	
Contractor (50%)		
Scientists (425%)		
Technical engineer (50%)		
Salaries of a new personnel	138,500 ECU	138,500 ECU
2 scientists (200%)		
Equipment:		
Mobile seismometers with accessories (3)	36,900 ECU	19,600 ECU
Work stations	33,900 ECU	4,500 ECU
Modems and accessories	3,000 ECU	1,200 ECU
External services:		
Development of SIL software	4,000 ECU	4,000 ECU
Installation of hardware	4,700 ECU	4,700 ECU
Travel and subsistence:		
Travels to project meetings and international		
conferences for the contractor (4)	8,600 ECU	8,600 ECU
Travels to international conferences		
for other personnel (6)	12,900 ECU	12,900 ECU
Other costs:		
Vault construction for mobile seismic stations	15,500 ECU	15,500 ECU
Operation cost of the mobile seismic stations	20,900 ECU	20,900 ECU
Overheads:	52,100 ECU	16,600 ECU
Total:	686,000 ECU	247,000 ECU
Contribution requested (36%):		247,000 ECU

$\boxed{\text{Partner 2}}$ Uppsala University, Sweden

Subproject 2: Applying new methods using microearthquakes for monitoring crustal instability
Contractor: Reynir Bödvarsson

	Requested
Personnel:	98,000 ECU
Equipment:	3,000 ECU
Travel and subsistence:	17,000 ECU
Consumables and computing:	2,000 ECU
Overheads (20% on personnel):	19,000 ECU
Total:	139,000 ECU
Contribution requested:	139,000 ECU

Partner 3 University of Edinburgh, United Kingdom

Subproject 3: Shear-wave splitting to monitor in situ stress changes before earthquakes and eruptions
Contractor: Stuart Crampin

	Requested
Personnel:	
20% project manager: Stuart Crampin	
(Entirely supported by contract work)	20,000 ECU
50% post doctoral fellow (Helen J. Rowlands)	40,000 ECU
75% research assistant (not yet appointed)	28,000 ECU
Travel and subsistence: 2 x 7-day visit to Iceland per annum for discussions; 1 x 1-day visit to Brussels per annum; 2 European conferences	10,000 ECU
Computing and consumables: Peripheral hardware, software licences, miscellaneous stationary, express charges, etc.	10,333 ECU
Overheads (20%):	21,667 ECU
Total:	130,000 ECU
Contribution requested:	130,000 ECU

Partner 4 GeoForschungsZentrum, Potsdam, Germany

Subproject 4: Borehole monitoring of fluid-rock interaction
Contractor: Frank Roth

	Requested
Personnel:	
Salaries for 1 scientist, experienced in logging (half-time; 1 year)	21,500 ECU
External services/subcontracts:	
3 additional log suits from subcontractor IEA	7,400 ECU
1 shipping of the logging-truck to Iceland	6,500 ECU
Hiring crane and car during 3 logging campaigns	6,000 ECU
Travel and subsistence:	
1 travel for 2 scientists to Iceland for 5 days (meetings)	2,400 ECU
3 travels incl. subsistence for 5 persons for 7 days from Germany to Iceland (logging campaigns)	14,000 ECU
Overheads:	14,400 ECU
Total:	72,200 ECU
Contribution requested:	72,200 ECU

Subproject 7: Theoretical analysis of faulting and earthquake processes
Associated contractor: Frank Roth

	Requested
Personnel:	
Salaries for 1 scientist (half-time, 1 year)	21,500 ECU
Travel and subsistence:	
2 travels for 1 scientist to Iceland for 5 days (meetings)	2,700 ECU
Consumables and computing:	
Tapes, disks, (plotting-)paper, etc.	2,800 ECU
Overheads (20%):	6,800 ECU
Total:	33,800 ECU
Contribution requested:	33,800 ECU

Partner 5 Centre National de la Recherche Scientifique (CNRS), Toulouse, France

Subproject 5: Active deformation determined from GPS and SAR
Contractor: Kurt L. Feigl

	Total cost	Requested
Personnel:	17,054 ECU	
Equipment: 2/5 cost of a computer, SUN Ultra 1 Sparc	20,000 ECU	8,000 ECU
External services: Subcontractor Science Institute, University of Iceland, digitized fault map	12,000 ECU	12,000 ECU
Travel and subsistence: Meetings and conferences	6,000 ECU	6,000 ECU
Consumables and computing:	4,000 ECU	2,000 ECU
Other costs: Radar data from European Space Agency: 20 frames at 600 ECU/frame	12,000 ECU	12,000 ECU
Overheads:	38,946 ECU	6,000 ECU
Total:	110,000 ECU	46,000 ECU
Contribution requested:		46,000 ECU

Partner 6 Nordic Volcanological Institute, Reykjavík, Iceland

Subproject 6: Effects of stress fields and crustal fluids on the development and sealing of seismogenic faults
Contractor: Ágúst Gudmundsson

	Requested
Personnel: Research scientist, 8 months salary	25,000 ECU
Travel and subsistence: Including fieldwork	18,000 ECU
Subcontractors:	
Thierry Villemin	27,500 ECU
Philip Meredith	20,000 ECU
Consumables and computing:	9,500 ECU
Overheads (20%):	20,000 ECU
Total:	120,000 ECU
Contribution requested:	120,000 ECU

Subproject 5: Active deformation determined from GPS and SAR
Associated contractor: Freysteinn Sigmundsson

	Requested
Personnel: Part-time assistant to maintain GPS receivers and data transfer	5,000 ECU
External services: Subcontractor Onsala Space Observatory, GPS analysis	8,000 ECU
Travel and subsistence: Meetings and conferences, and travel in Iceland	7,000 ECU
Consumables and computing: Including 3 GPS antennas	10,500 ECU
Overheads (20%): (Not on subcontract amount)	4,500 ECU
Total:	35,000 ECU
Contribution requested:	35,000 ECU

Partner 7 Department of Physics, University of Bologna, Italy

Subproject 7: Theoretical analysis of faulting and earthquake processes
Contractor: Maurizio Bonafede

	Requested
Personnel: One research assistant for 2 years	20,000 ECU
Travel and subsistence: Workshops, meetings and conferences	3,000 ECU
Consumables and computing:	2,833 ECU
Overheads (20%):	5,167 ECU
Total:	31,000 ECU
Contribution requested:	31,000 ECU

Partner 8 Université Pierre et Marie Curie, CNRS, Paris, France

Subproject 6: Effects of stress fields and crustal fluids on the development and sealing of seismogenic faults
Associated contractor: Francoise Bergerat

	Total cost	Requested
Personnel:	38,428 ECU	
Travel: fieldwork	36,000 ECU	36,000 ECU
Equipment: 3D software	8,500 ECU	8,500 ECU
Consumables:	8,500 ECU	8,500 ECU
Other costs:	6,500 ECU	
Overheads:	38,104 ECU	2,000 ECU
Total:	136,032 ECU	55,000 ECU
Contribution requested:		55,000 ECU