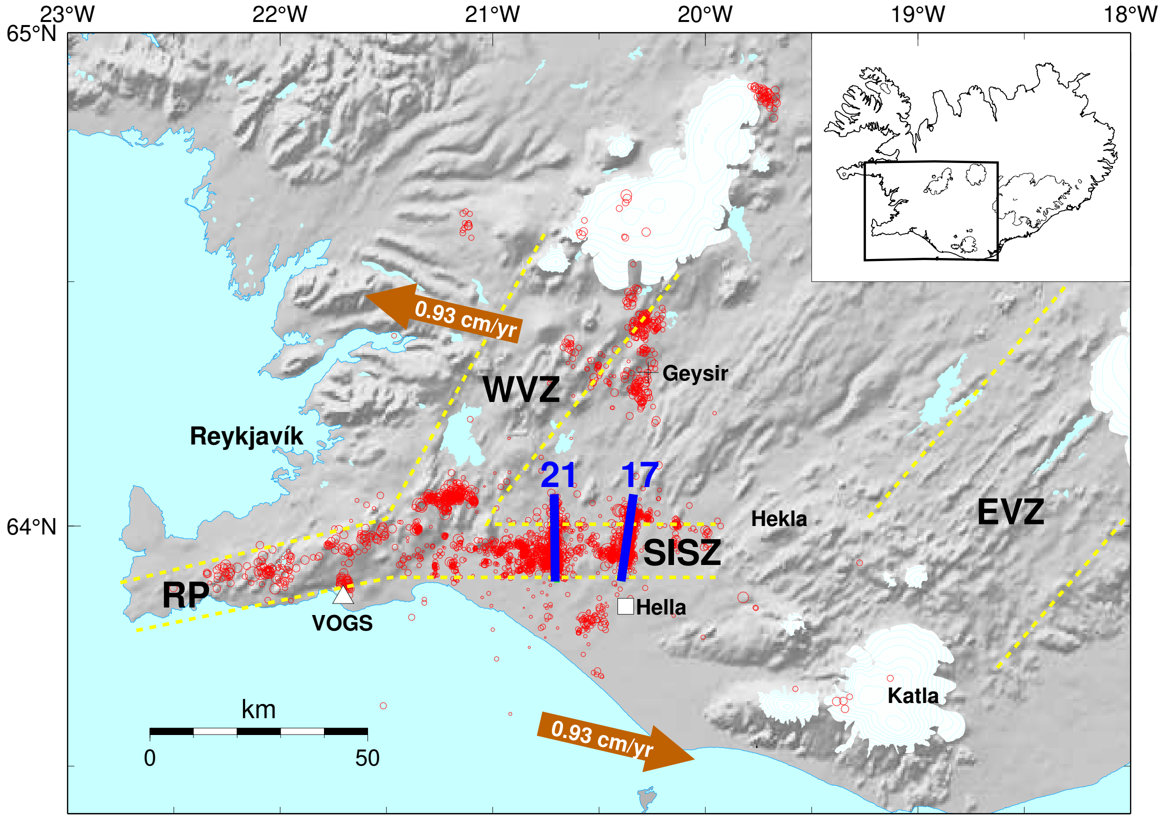

Figure 4. *The figure shows the southwestern part of Iceland. Iceland as a whole is shown in the upper right corner. Dotted yellow lines denote the western volcanic zone (WVZ) and the presently more active eastern volcanic zone (EVZ). South Iceland seismic zone (SISZ) is indicated as well as its prolongation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

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

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

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

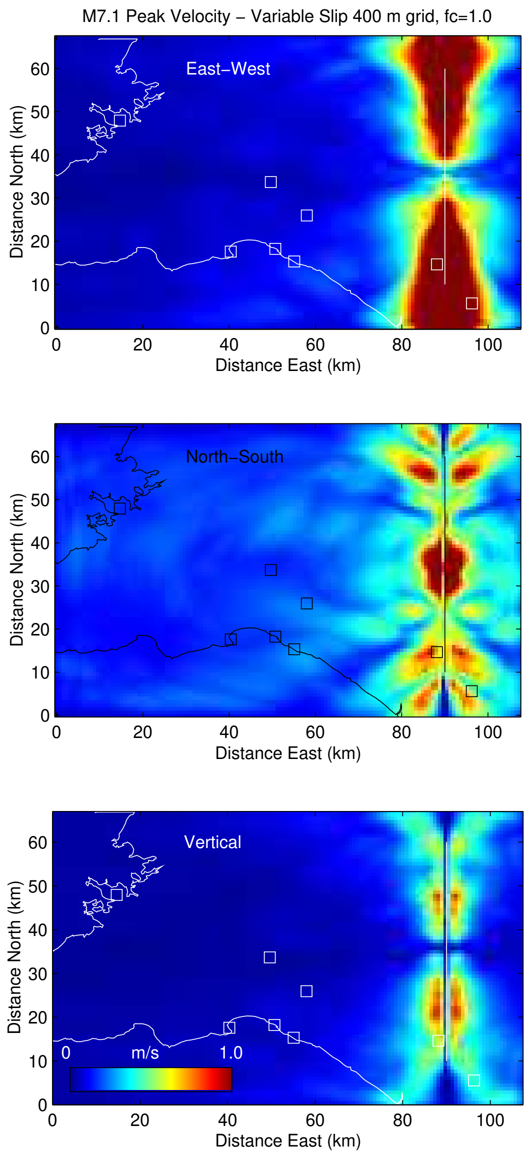

Figure 5. *Peak velocities for a model with variable slip distribution. The top panel shows the E-W component, the center panel shows the N-S component, and the bottom panel shows the vertical component. The color scale extends from 0 m/s (dark blue) to 1.0 m/s (red). The N–S line shows the surface trace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

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

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

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

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

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

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

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

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

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

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

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

- **Slungawarning:**

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

- **SAG:**

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

- **Monitoring rock stress tensor:**

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

- **Subcrustal mapping of faults:**

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

3.1.5.2 An early warning system and an early warning database

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

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

3.1.5.3 Warnings for hazards in practice

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Contractor:

Reynir Böðvarsson
Department of Geophysics
Uppsala University
Villavägen 16
S–752 36 Uppsala
Sweden
Tel: +46–471–182378
Fax: +46–471–501110
E–mail: rb@geofys.uu.se

Researcher:

Ragnar Slunga
Department of Geophysics
Uppsala University
Villavägen 16
S–752 36 Uppsala
Sweden
Tel: +46–471–182378
Fax: +46–471–501110
E–mail: ragnar@geofys.uu.se

Researcher:

Björn Lund
E–mail: bl@geofys.uu.se
Department of Geophysics
Uppsala University

Researcher:

Zaher Hossein Shomali
E–mail: hs@geofys.uu.se
Department of Geophysics
Uppsala University

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

3.2.1 Real-time mass evaluation of relative locations

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

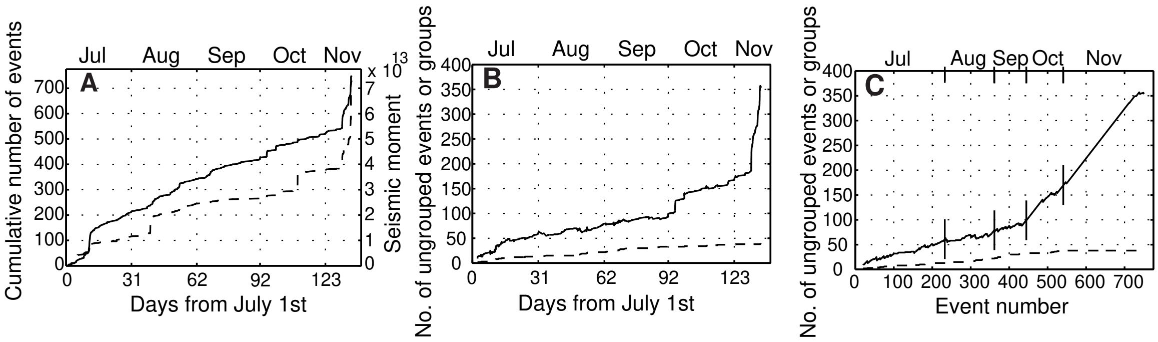

Figure 6. *Correlation results in Ölfus, July 1 to November 13, 1998. A) Plotted versus time in days is the cumulative number of events (solid line, scale to the left) and the cumulative scalar seismic moment (dashed line, scale to the right). B) Number of ungrouped events (solid line) and the number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

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

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

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

3.2.3 Real-time inversion of stress tensor

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

3.2.4 References

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

Contractor:

Stuart Crampin
Department of Geology and Geophysics
University of Edinburgh, Grant Institute
West Mains Road, Edinburgh EH9 3JW
United Kingdom
Tel: +44-131-650-4908
Fax: +44-131-668-3184
E-mail: scrampin@ed.ac.uk

Researcher:

Theodora Volti
Department of Geology and Geophysics
University of Edinburgh, Grant Institute
West Mains Road, Edinburgh EH9 3JW
United Kingdom
Tel: +44-131-650-8533
Fax: +44-131-668-3184
E-mail: tvolti@ed.ac.uk

3.3.1 Task 1: Continuous monitoring of shear-wave splitting

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

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

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

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

3.3.1.1 Temporal variations in time-delays

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

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

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

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

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

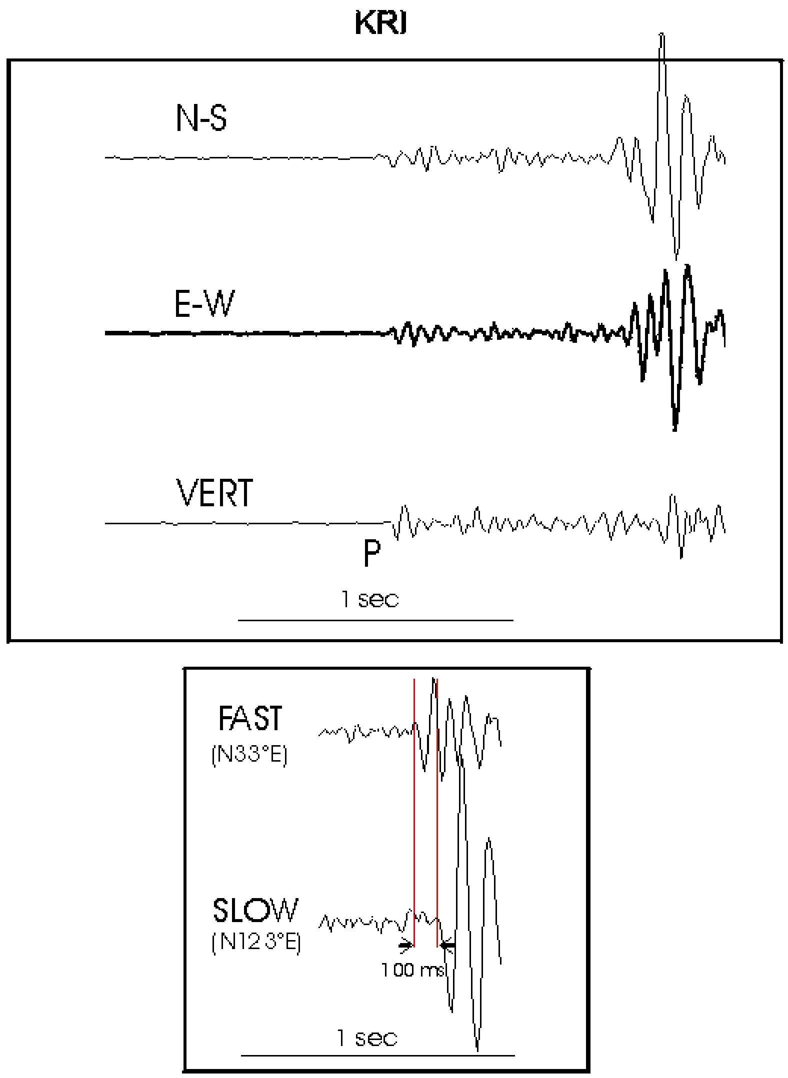

Figure 7. *Example of shear-wave splitting at station KRI. The upper diagram shows the three recorded components. On the bottom the rotated N-S and E-W components show the time-delay between the two shear-wave arrivals. (Event occurred at 03:02:40:6, April 9, 2000, at 5.7 km depth, 4.5 km from KRI).*

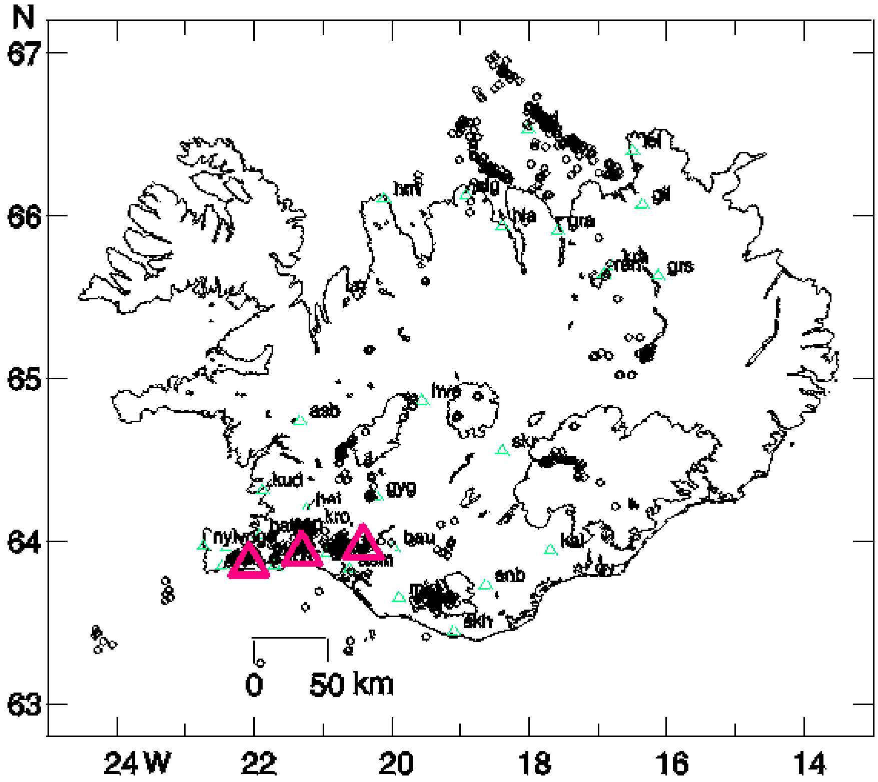

Figure 8. *Map of Iceland showing all earthquakes with $M \geq 2$, during the period March 1998 – June 2000. The small green triangles show the majority of SIL stations, whereas the stations KRI, BJA and SAU (from left to right) are shown with large red triangles.*