The South Iceland earthquakes 2000
a challenge for earthquake prediction research

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CONTENTS

1 INTRODUCTION

In June 2000 two earthquakes with magnitude 6.6 (Ms) occurred in the central part of the South Iceland seismic zone (SISZ). They were immediately followed by seismic activity along zones of approximately 100 km length. This activity occurred after 88 years of relative quiescence in the 70 km long EW transform zone in SW-Iceland (Figure 1). Earthquakes in this region have, according to historical information, at some occations caused collapse of the majority of houses in areas encompassing 1000 km^2 and pose a significant threat to inhabitants of this area, a relatively densely populated farming region. Despite intensive surface fissuring caused by the earthquakes and measured accelerations reaching 0.8 g, the earthquakes in 2000 caused no serious injuries and no structural collapse. The relatively minor destruction led 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 warning, including the right epicenter and size of the second earthquake, was issued beforehand. Preliminary observations which were made of the earthquakes as well as of associated preseismic and postseismic processes, will be described in this paper. Among significant observational systems recording the events is the SIL-system. SIL stands for South Iceland Lowland, i.e. the test area for the SIL-project described in Stefánsson et al. 1993. The SIL-system is especially aimed at retrieving real-time information carried by microearthquakes (Böðvarsson et al 1999). Other significant observational systems include strong motion instruments, continuous GPS measurements, borehole strainmeters and hydrological observations in boreholes. Earlier survey-mode GPS measurements were repeated after the earthquakes, and detailed analysis of extensive surface fissures was carried out. InSAR images were collected to observe coseismic evidence and to compare with preseismic and postseismic deformation. We estimate that no more than one fourth of the available moment in the zone was released in the two earthquakes that occurred in 2000 and even larger earthquakes may occur in the zone during the next few decades.

2 THE SOUTH ICELAND SEISMIC ZONE

According to the NUVEL 1A plate model (DeMets et al. 1994) the direction of the divergent motion across the plate boundary of the Eurasian relative to the N–American plate in Iceland is N103°E at a velocity of 1.85 cm/year. If all of this motion is taken up by the SISZ, which is oriented almost due EW, the relative left-lateral motion across SISZ would be approximately 1.8 cm/year and a NS opening component across the zone could be around 0.4 cm/year. Historically most of the earthquakes in this EW left-lateral shear zone have had right-lateral motion on NS striking faults as observed on the surface. Faults due to known historical earthquakes are found side by side at less than 5 km distance from each other (Einarsson 1991; Einarsson et al. 1981; Stefánsson et al. 1993). There are indications that the seismic cycle, i.e. the time period of strain build-up and of break-up (strain release) of the whole SISZ is 140 years. This suggestion was based on historical seismicity and tectonic considerations (Stefánsson and Halldórsson 1988). Volcanic pulsations in the most active volcanic zone (EVZ) of Central Iceland, inferred

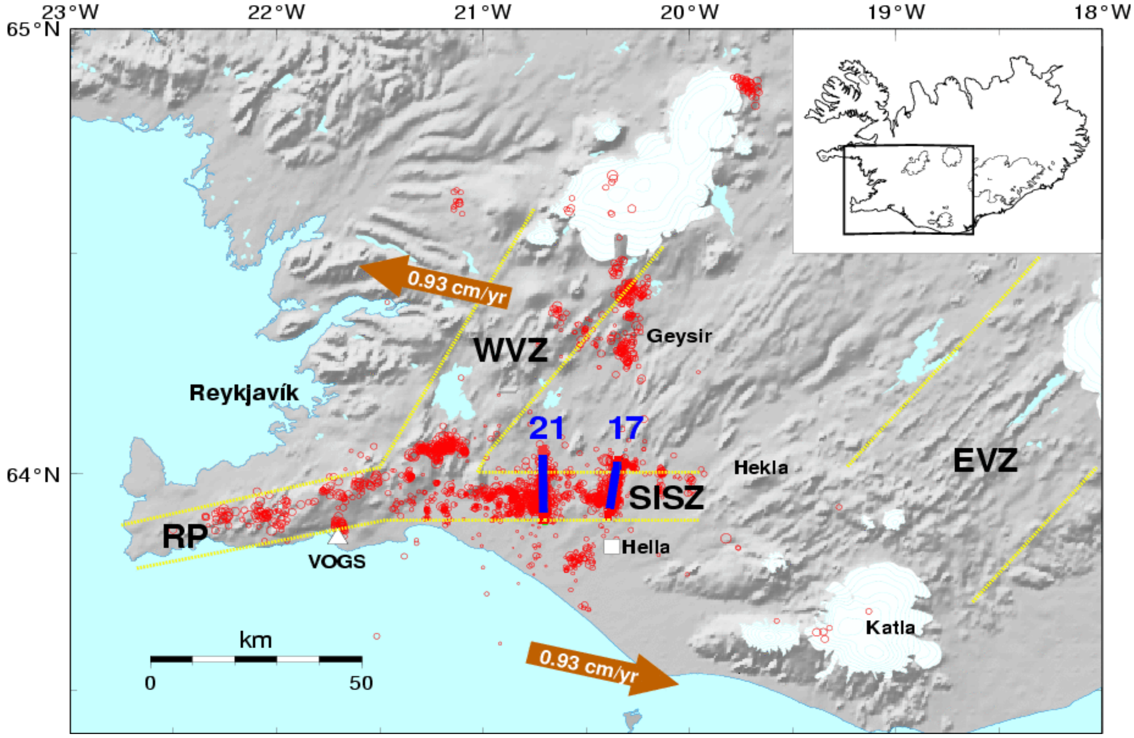

Figure 1. *The southwestern part of Iceland. Iceland as a whole is shown in the upper right corner. Dotted yellow lines denote the western volcanic zone (WVZ) and the presently more active eastern volcanic zone (EVZ). The South Iceland seismic zone (SISZ) is indicated as well as its prolongation in the Reykjanes peninsula (RP). The direction of the relative plate motion is shown by arrows. The faults of the two large earthquakes that ruptured on June 17 and 21 are indicated by 17 and 21 respectively. The epicenters of small shocks following the large earthquakes (red dots) show the extent of the seismically activated area.*

from tephrastratigraphic studies coincide with this estimate of the seismic cycles (Larsen et al. 1998). On the basis of the estimated magnitudes (Ms) of historical earthquakes, the total seimic moment release during a 140 year period is approximately 10^{20} Nm (Halldórsson 1987; Stefánsson and Halldórsson 1988). Assuming that the seismogenic crust in the 70 km long zone is only 10 km thick (Stefánsson et al. 1993; Tryggvason et al. 2002) and total displacement across the zone is 1.85 cm/year, the maximum moment build-up over a 140 year period would be $6.5 * 10^{19}$ Nm. There is a discrepancy in the results of the calculations above in such a way that slightly more moment seems to be released in earthquakes than accumulated from plate motion. It would be more natural to expect the opposite, as some of the strain energy could be released aseismically. One explanation could be that the cumulative moment of the historical earthquakes has been overestimated. Another possibility is that the thickness of the elastic/brittle crust is underestimated. The thickness is estimated from the depth limit of microearthquake activity. But it has also been suggested that a part of the strain energy build-up comes from a local sources, due to fluid-induced expansion near the bottom of the seismogenic crust (Stefánsson and Halldórsson 1988; Stefánsson 1999a; Stefánsson 1999b).

3 THE JUNE 17 EARTHQUAKE

According to the Icelandic Meteorological Office (IMO) the origin time of the June 17 earthquake was 15:40:40.94 GMT, the hypocenter at 63.97°N, 20.37°W, and a hypocentral depth of 6.3 km. The aftershocks indicate an 11-12 km long rupture extending from the surface to 10 km depth. Assuming that the upper 1 km of the rupture does not contain considerable energy to be released in the earthquake the fault width is taken to be 9 km (Figure 2). The aftershocks indicate that the fault strikes N7°E and dips 86° towards the east. Surface fissures showing right-lateral motion on an underlying fault coincide with and are found along the entire fault (Einarsson et al. 2000). Our model for the earthquake mechanism agrees very well with the USGS Rapid Moment Tensor Solution which has a nodal plane striking N4°E and dip of 84° to the east. The moment calculated by USGS is $6.0 * 10^{18}$ Nm, assuming a best-fitting double-couple solution. The preliminary magnitudes estimated by the National Earthquake Information Center (NEIC) in USA were mb=5.7 and Ms=6.6. Preliminary modeling of local measurements by volumetric strainmeters, assuming rigidity 36 N/m^2, indicate variable slip as shown in Figure 2, and a moment of $4.8 * 10^{18}$ Nm (Alan Linde and Kristján Ágústsson 2000, personal communication; Stefánsson et al. 2000). Assuming uniform slip along the fault the rupture dimension suggested by aftershocks, and the moment estimated by USGS, an average right-lateral displacement of 1.5 m is inferred. Two minutes after the main shock an earthquake of local magnitude 5 (mb) occurred 6 km to the southwest of the main shock epicenter, not along a continuation of the main shock fault, but to the west of it. Studying the spatial distribution of the aftershocks (i.e. aftershocks within a couple of kilometers from the fault) the following observations are noticable (Figure 2). The observations suggest that the earthquake initiated in the center of the rupture which appears to have extended down to 10 km. This is slightly deeper, but comparable to the depth of the brittle/ductile boundary inferred from earlier microearthquake studies: around 8 km in this part of the SISZ (Stefánsson et al. 1993; Tryggvason et al. 2002). A few early aftershocks occurred at 12 km depth, well into what usually is considered the ductile zone. This suggests that ductility depends on strain rate which of course is expected to be high immediately after and near a large earthquake. The concentration of aftershocks at the southern and northern end of the rupture, reflect high stresses where the fault movement stopped. A similar effect is observed at the bottom of the fault, where ductile motion is expected following the earthquake. A concentration of aftershocks close to the hypocenter of the main shock is also noticeable. Further conclusions about these peculiarities require a more thorough investigation of a large amount of aftershocks of magnitudes down to zero, including joint hypocenter location by cross correlation of similar signals and, based on it, reevaluation of the microearthquake mechanisms.

4 THE SECOND LARGE EARTHQUAKE OCCURRING THREE DAYS LATER

The IMO determined origin time of the June 21 earthquake was 00:51:46.95 GMT, the hypocenter was at 63.98°N, 20.71°W, and a hypocentral depth of 5.1 km. The aftershocks indicate a vertical fault, 15 km long, striking N2°W extending from the surface to 8 km depth (Figure 3).

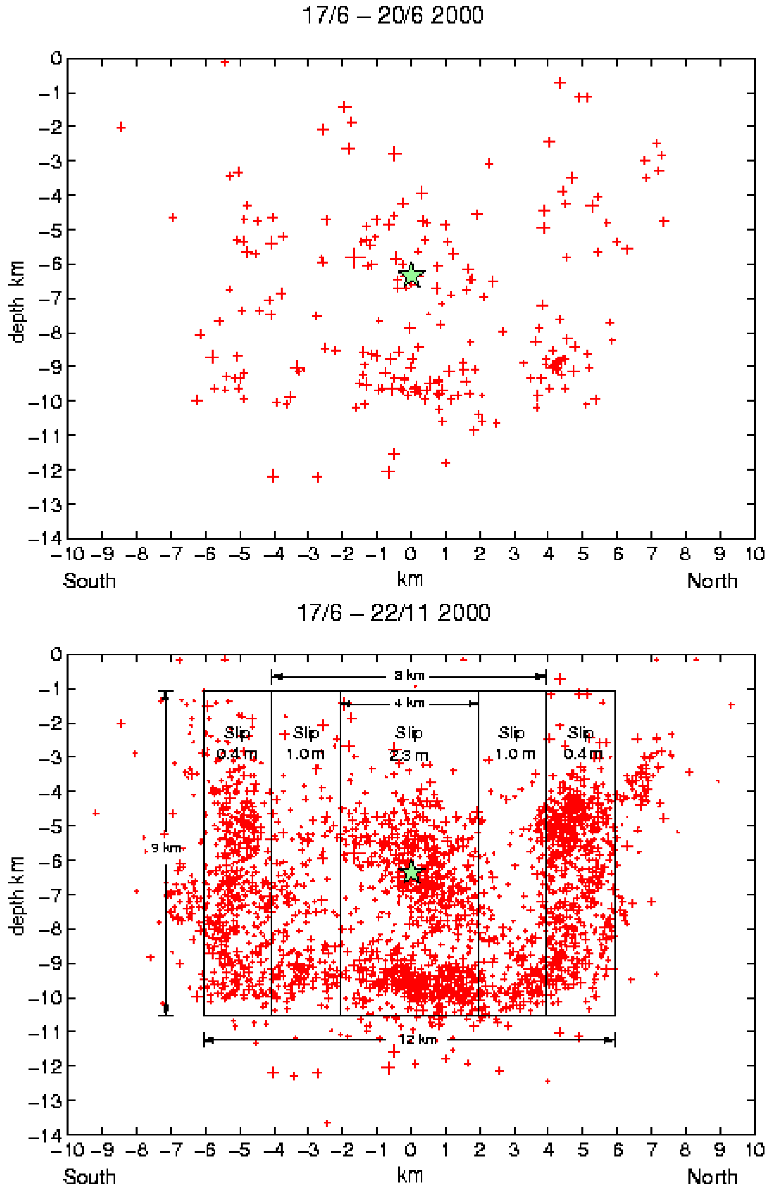

Figure 2. *Aftershocks of the June 17 earthquake within 3 km of the fault plane are shown along with a tentative slip model. The frame at the top shows aftershocks during the first 32 hours. The second frame shows the aftershocks until December 10, 2000, and a rupture model to fit observations from local volumetric strainmeters, with variable right-lateral slip on a 12 km long fault (Stefánsson et al. 2000; Alan Linde and Kristján Ágústsson personal communication).*

Surface fissures indicating general right-lateral motion (Einarsson et al. 2000) coincide with and are found all along the main fault as it is reflected in the aftershocks. Related ENE-WSW fault with left-lateral motion was also observed near the southern end of the main fault. The USGS Rapid Moment Tensor Solution gives a moment of $5.2 * 10^{18}$ Nm, assuming a best fitting double-couple solution. Preliminary magnitudes by NEIC were mb=6.1 and Ms=6.6. The strainmeter observations were not good enough to provide an independent estimate of the moment. Assuming uniform right-lateral slip

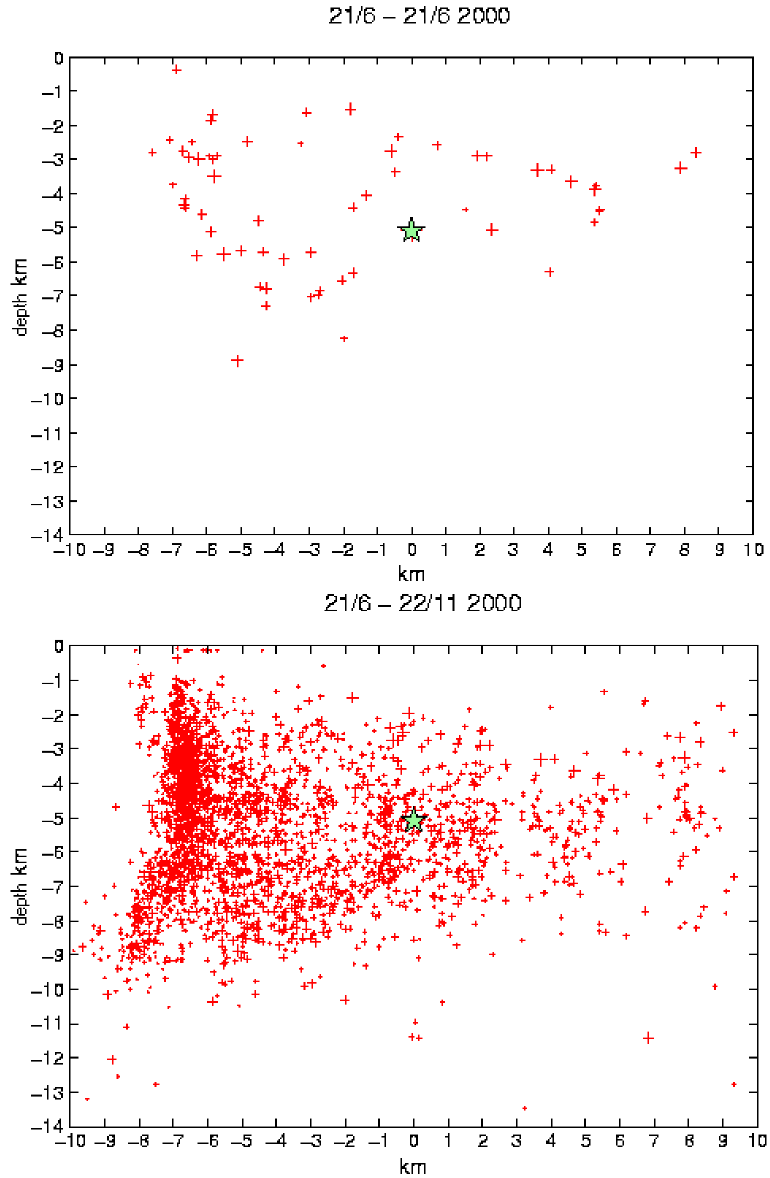

Figure 3. *The figure shows the aftershocks of the June 21 earthquake, within 3 km of the fault plane. The frame at the top shows aftershocks during the first 32 hours. The second frame shows the aftershocks until December 10, 2000.*

as indicated by the surface fissures, fault size indicated by the aftershocks and the moment of USGS, a 1.2 meter right-lateral coverage slip of the main fault is implied.

5 COSEISMIC EVIDENCE FOR THE TWO EARTHQUAKES FROM GPS AND INSAR

GPS measurements during and soon after the earthquake sequence were compared with GPS measurements of 1995 and 1999 to study the surface deformation. Model estimation based on these are in good agreement with the seismic modelling above (Árnadóttir et al. 2001). The same is true for InSAR observations based on comparing satellite images a few years before the earthquakes (Pedersen et al. 2001). Coulomb stress changes in the SISZ due to the two earthquakes (Árnadóttir et al. 2003) have been estimated based on distributed slip model derived from joint inversion of InSAR and GPS data (Pedersen et al. 2003). Among results of this study is that static stress change caused by the June 17 earthquake is enough to promote failure on the June 21 fault.

6 STRESS TRANSFER TO LARGE DISTANCES ALONG SEISMIC ZONES

Within less than a minute to a few hours seismic activity began in several areas up to 90 km to the west and to the north of the June 17 main shock. (Figure 1). 3 earthquakes of magnitude 4.5-5 occurred on the Reykjanes peninsula, one at 60 km distance, 27 seconds after the mainshock and two at 80-85 km distance, 30 seconds and 5 minutes respectively after the main shock (Kristín S.Vogfjörð 2002, personal communication).

The IMO runs a network of continuous GPS (CGPS) stations in the southern part of Iceland (Árnadóttir et al. 2000). At the time of the earthquakes 3 CGPS were in operation 70-100 km to SE and 4 in operation 30-60 km to W of the earthquake epicenters (Figure 4). Most of the stations show coseismic signals (Geirsson 2003; Figure 4) which are larger than expected from earthquakes as modelled above, assuming an elastic halfspace environment, which seems to be justifiable in modelling strain fields as can be expected from the individual large events. The observed CGPS signals can be explained by general left-lateral motion of a few centimeters across the SISZ and RP plate boundary and a significant component of NS expansion across this boundary (Figure 4). The relative displacement recorded on June 17 between VOGS, which is located south of the westward prolongation of SISZ, and REYK, which is located to the north of this plate boundary, is of special interest (Figure 1 and Figure 4). VOGS moved 2 cm east and 1 cm south within a few hours of the main ahock (Figure 4). An alternative explanation for this large signal movement of VOGS could be that the large signal was caused locally by combination of seismic and aseismic motions. There was intense seismic activity along a NS fault close to VOGS immediately following the 17 June earthquake. The other GPS signals may of course have been modified by comparable local strain release events (mostly aseismic) triggered by the main shocks. In spite of such possible modifications of the signal the most likely explanation is an aseismic/seismic strain episode in a huge area following the June 17 earthquake.

By comparing InSAR images before and after the June 2000 earthquakes deformation was detected 80-85 km west of the June 17 main earthquake comparable to what would be expected from a N-S right-lateral magnitude (moment) 6 earthquake in that location, i.e. one meter slip on a 5 km long and 7 km wide fault (Clifton et al. 2003; Pagli et al. 2003). As the largest earthquake at this location was magnitude 5 (Mb) this was largely an aseismic event.

The seismic activity, the displacements of CGPS stations and the deformation detected by InSAR probably indicate fast redistributions of strains along the EW elongated SISZ and RP zones, the plate boundary, up to 100 km to the west of the June 17 main shock, reflected in displacements on faults and rifts close to fracture criticality. In some cases the displacements are directly caused by dynamic triggering. Similar effects are

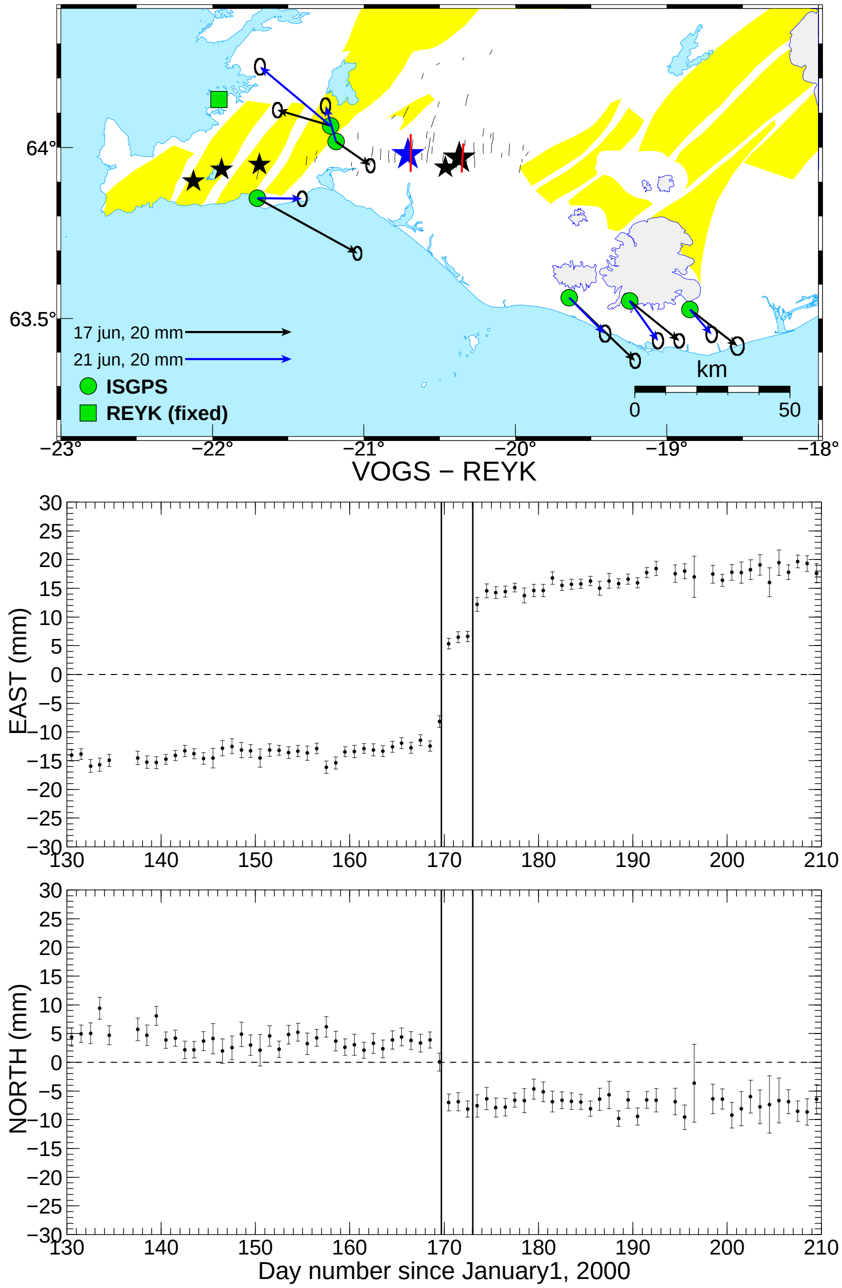

Figure 4. *Above: Observed horizontal coseismic displacements related to the June 17 (black arrows) and the June 21 (blue arrows) earthquakes, assuming that REYK is fixed. Large black star notes the location of the June 17 main event and smaller black stars denote subsequent earthquakes in the magnitude range 4.5-5. The large blue star denotes the epicenter of the June 21 earthquake. Red lines indicate the faults of the two large earthquakes. Below: Time series of east and north components of displacement of VOGS relative to REYK covering the time of occurrence of the two large earthquakes, denoted by vertical lines. (Geirsson 2003).*

observed seismically to the north of the June 17 earthquake (Figure 1) where postseismic stresses also triggered earthquakes at sites close to fracture criticality.

7 THE EFFECTS OF THE EARTHQUAKES

The earthquakes were felt within 200 km distance from their epicenters. They caused intensive surface fissures along the faults with opening of around one meter at various places. Several accelerometers were operated in the near field. The highest measured maximum acceleration was 84% g in the June 21 earthquake (Þórarinsson et al. 2002). In spite of these strong surface effects no serious injuries were caused to people. The area where the effects of the earthquakes were most severe is a sparsely populated farming area. The villages closest to the epicenters are village Sólheimar (100 inhabitants), 5 km to the north of the June 21 fault, where the maximum acceleration was 71% g in the June 21 earthquake, and the the village Hella (600 inhabitants), 10 km to the south of the June 17 earthquake where the maximum acceleration was 47% g. No houses collapsed in the area but several houses were, however, so badly damaged that they had to be demolished. Several incidents of broken pipelines were reported (Þórarinsson et al. 2002).

Following both mainshocks hydrothermal activity increased substantially over a large area around the two faults (Björnsson et al. 2001). Geysir, the great geyser, which lends its name to all the geysers in the world, is located 30 km to the north of the faults. It was reactivated after the earthquakes after having been more or less dormant for more than half a century. Water level changes in boreholes, observed immediately after the earthquakes, agree very well with the observed mechanisms of the earthquakes, with raised water level in the areas of compression and lowered levels in regions of extension. The shape of the signals reflects an impulse occurring immediately at the origin times of the two large earthquakes, with a relaxation tail of a few months. The magnitude of the signals was typically 0.1 to 1 bar, but may have exceeded 10 bars in a few cases close to the main earthquake faults. Signals were observed up to a distance of 75 km from the epicenters (Björnsson et al. 2001)

8 HAZARD ASSESSMENT AND LONG–TERM PREDICTIONS

A time-dependent hazard assessment or long–term prediction was made 15 years ago for the area, suggesting that there was more than 80% probability that large earthquakes would occur in the SISZ during the next 25 years. It was predicted that the earthquakes would probably start at the eastern part of the seismic zone, with an event of magnitude 6.3 to 7.5, but during the next days or months a sequence of earthquakes would follow further west in the seismic zone (Einarsson 1985). Later revisions of magnitudes and hazard assessments assume that the largest possible earthquake in this zone could not exceed magnitude 7.2 (Ms) (Halldórsson 1987; Stefánsson and Halldórsson 1988). Based on these later estimates, the time-dependent hazard assessment just before the earthquakes was: 98% probability of a magnitude 6 earthquake during the next 25 years and lower probability for a larger one.

9 PREDICTION OF EPICENTER AND SHORT–TERM PRECURSORS OF THE JUNE 17 EARTHQUAKE

For various reasons it was expected that the next SISZ earthquake would occur in the epicentral area of the June 17 earthquake. This was stated most clearly in 1988 as follows: "... there are strong indications that the next large earthquake of size approaching 7 in this zone will take place near longitude 20.3°–20.4°W" (Stefánsson and Halldórsson 1988), i.e. on the EW oriented SISZ at around 64°. This was based on a lack of strain release in historical earthquakes since the year 1700 in a narrow area (Halldórsson 1987; Stefánsson and Halldórsson 1988). A similar but less pronounced a gap was also indicated for a narrow area around 20.7°W. Some years later it was pointed out that these gaps coincided with a long–term concentration of microearthquake activity in the seismic zone (Stefánsson et al. 1993). It was never stated definitely if the microearthquake activity was expressing aseismic strain release or if it was reflecting high stresses in preparation of a large earthquake, although the latter was assumed to be more likely. The question has apparently now been answered by nature. As there is a tendency in the seismic history for earthquake sequences to start east of the center of the zone and to trigger earthquakes farther west, it was also expected that any subsequent large earthquake would most probably occur to the west. On the basis of historical intensitites and known earthquake faults, it was also expected that the fault planes of the earthquakes would have NS strike.

While the June 17 earthquake occurred in the area identified as the probable location of the next large earthquake in the SISZ, no short-term precursory signals were recognized before it occurred. In hindsight, however, several changes can be recognized, changes that were possibly premonitory. These include:

1) Several microearthquakes (ML=0-1) clustered at depth along the fault of the impending earthquake, weeks and days before its occurrence (Figure 5). This was a significant change compared to the less clustered microearthquake activity that had been observed during the previous 10 years.

2) In a geothermal borehole at Flúðir 10 km to the north of the NS striking fault plane (Figure 5), short-term water level drop, of not less than 5 m, was alarmed 24 hours before the earthquake. Unfortuneately this signal is not seen in the preserved recorded trace averaging water level on 15 minutes intervals. During a 5 years of continuous operation this was the first such an alarm (Björnsson et al. 2001). Most probably the alarm was a short-lived low pressure pulse related to the preparatory phase of the earthquake.

Both these changes were possibly related to relocation of strains towards the impending rupture, possibly related to dislocation in the deeper and ductile part of the seismic zone. Also mechanism of slow rupture initiation, as described by Dietrich 1986, and Roy and Marone 1996, may apply in this case.

Several other observed changes, listed below, prior to the earthquake may possibly also be related to a crustal process leading to it:

1) The volcano Hekla (Figure 1), 30–35 km east of the epicenter, has been anomalously active since 1970, last erupting at the end of February 2000. An eruption with similar mechanism occurred in 1991. In that case a flurry of small earthquakes followed in the SISZ during days and weeks (Stefánsson et al. 1993). There are also earlier examples of this effect which probably is caused by transfer of strain energy along a

seismically active zone where local spots are close to fracture criticality, even if the area is not ready for a large earthquake. Thus it was considered noticeable that small earthquakes did not occur in the zone following the February 2000 eruption. After the large earthquakes occurred in the zone it is tempting to suggest that this lack of earthquakes is comparable to periods of quiescence sometimes reported before large earthquakes. It remains to be studied what is the mechanism of stress transfer in the region and how this may explain the flurry of small earthquakes frequently observed as well as the lack of it this time. Better understanding of this may lead to the application of such a quiescence as a precursor.

2) A slight but persisting increase in seismicity was observed in the SISZ area early in 1995-1996 (Guðmundsson et al. 2001). On a long-term scale the seismic rate in the SISZ was slightly increasing since that time. This may have been linked to dyke intrusions in Vatnajökull area, 150 km towards northeast in the eastern volcanic zone, preceding the large Vatnajökull eruption in October 1996. Such a mechanism was proposed (Stuart Crampin 2000, personal communication; Volti and Crampin 2003) to explain increased stress in the area indicated by shear-wave splitting. There were also marked and possibly related changes in seismic rates at different parts of the zone, especially during the last 1-2 years before the earthquake. Automatic fault plane solutions of microearthquakes showed anomalous variations during 3 months before the earthquakes, 20 km to the west of these, and inside the SISZ (Stefánsson et al. 2000).

3) Radon anomalies, i.e. anomalously low values and positive spikes were observed in radon from geothermal water wells in the area during 1-5 months before the earthquakes (Einarsson et al. 2003).

4) Anomalous strain signals were observed in May and June at borehole strainmeter stations, 3 and 20 km respectively from the epicenter of the June 17 earthquake.

5) There was some increase in shear-wave splitting time in microearthquakes of local origin, a few weeks before the earthquake (Stuart Crampin 2000, personal communication; Volti and Crampin 2003).

These observations of possible premonitory changes have been reported by scientists at the Icelandic Meteorological Office, the National Energy Authority, the Science Institute, University of Iceland and the University of Edinburgh. They are now the subject of further studies and modelling to try to understand how they might be related to the earthquakes.

10 SHORT–TERM WARNING FOR THE JUNE 21 EARTHQUAKE

It was considered possible that another earthquake of similar size would follow the June 17 mainshock. This was realized 80 hours later. But before that, i.e. 26 hours before the magnitude 6.6 earthquake of June 21, as special warning was issued by IMO to the state and the local civil defence services. In the warning it was stated that the most likely hazard area (Figure 6) of a probable impending earthquake would be as indicated in the figure, i.e. within 1 km of the NS fault line on which the earthquake occurred.

The warning was based on evaluation by IMO seismologists of time and space distribution of microearthquake activity. It was also based on the understanding of the tectonics of the area and the knowledge of the historical seismicity described briefly earlier in this paper. Indications based on seismic history as well as on recent observations

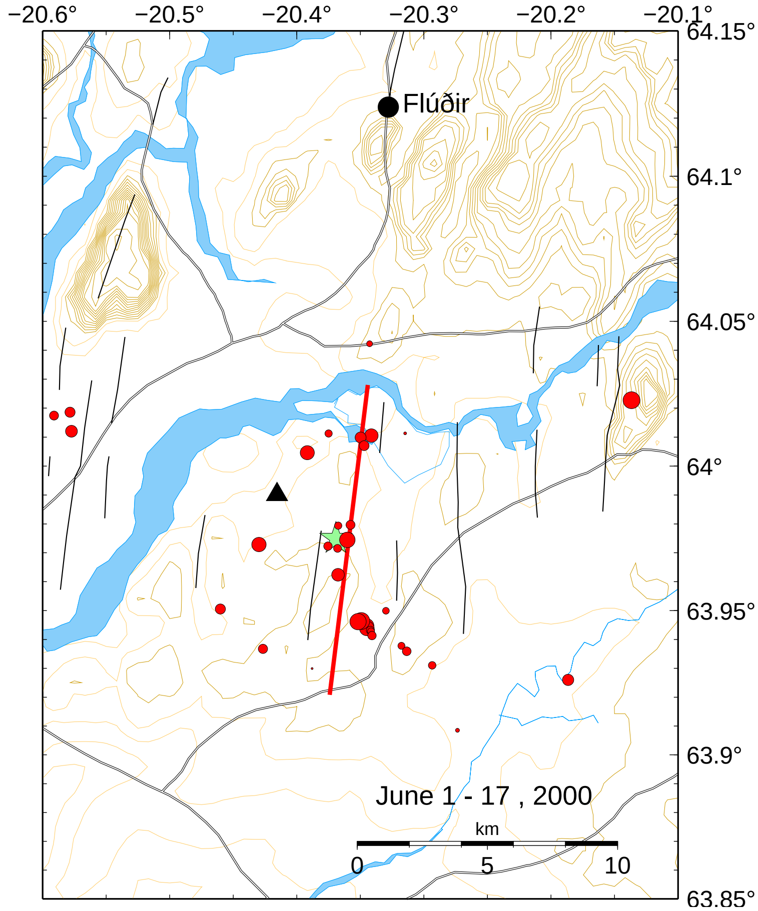

Figure 5. *The area near the June 17 earthquake. The epicenter is shown by a green star and the rupture is indicated with a red NS striking line. The NS striking black lines indicate old earthquake faults. Red dots show microearthquakes (36 in number, ML=-1 to 1), during a period of 17 days before the earthquake. Hydrological changes were observed at the village Flúðir.*

that large seismic events tend to migrate approximately with a velocity of 5 km/day were also taken into account. The actual velocity between the 2 epicenters was 4.9 km/day.

11 PERSPECTIVES FOR FUTURE LARGE EARTHQUAKES IN THE SISZ

As discussed earlier the moment released in the two large earthquakes of 2000 is estimated to be $1.2 * 10^{19}$ Nm, while the the moment built up and released during a 140 year earthquake cycle has been estimated to be 0.7–$1 * 10^{20}$ Nm, where the higher value is based on the estimated size of historical earthquakes. Assuming that the lower value is more realistic, as the historical earthquake magnitudes may have been overestimated, and taking into account that only 100 years have apparently elapsed of the 140 year cycle (Stefánsson and Halldórsson 1988), the moment build-up before the earthquakes would have been $5 * 10^{19}$ Nm. This means that only a fourth of the stored moment would have been released in the two large earthquakes in 2000. The remaining moment is probably

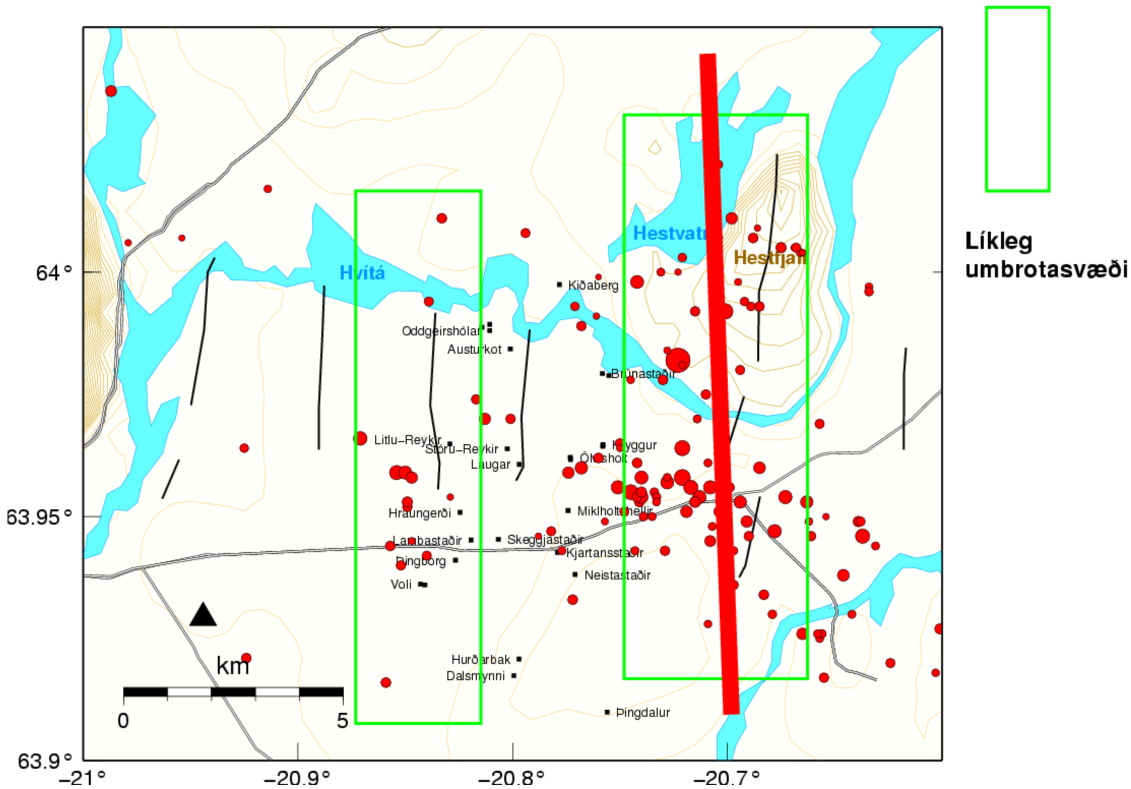

Figure 6. *The map that was sent to the Iceland Civil Defence 26 hours before the earthquake on June 21. Red dots indicate the location of small earthquakes, which were the basis for the immediate warning. Green boxes show probable hazard areas (in Icelandic: Líkleg umbrotasvæði). An accompanying telephone report explained that an earthquake of similar size or slightly smaller than the first earthquake was to be expected to occur within either of the green boxes, more likely within the larger one. A strictly defined time window was not given, but the advice was given to prepare for that an earthquake with the expected size and location would occur "anytime soon". The red NS line, which was put afterwards onto the warning map, indicates the fault plane of the June 21 earthquake.*

mostly stored in the easternmost part of the SISZ, where the largest earthquakes are to be expected as the elastic/brittle crust is thickest there. Judging from historical observations and the general understanding of tectonics outlined above, the build-up of strain from around 1900 to year 2000 has not been enough to produce a magnitude 7 earthquake in the easternmost part of the zone. We suggest, however, that further build-up of strain, in addition to what remains after the recent earthquakes will be enough to rupture the strong crust there within the next few decades. The above reasoning is based on a simple model of moment build-up, assuming steady plate motions with shearing deformation across a homogeneous SISZ, however, with increasing thickness and strength from west to east. The total release of stress in such a simplified zone would have the tendency to delay until it starts at the easternmost, strongest part and trigger subsequent earthquakes further west during a relatively short time frame.

Although there is some historical support for this hypothesis, both history and the recent events show deviations from such a simple model. The deviations may result from stress heteorogeneities within the zone causing fracture criticality to be reached locally, before stresses reach the fracture criticality of the zone as a whole.

It has also been proposed that strain build-up for earthquakes in this area is not only due to general plate motion, but also has a local build-up of stress, possibly caused by intrusion of fluids near the bottom of the seismogenic crust (Stefánsson and Halldórsson 1988) Considering this, it is suggested that it is still possible in the present cycle that an earthquake of a comparable size to the recent earthquakes may also occur farther west, either before a possible magnitude 7 earthquake in the easternmost part, or triggered by stress transfer by such an earthquake.

12 THE SIGNIFICANCE OF THE TWO EVENTS FOR EARTHQUAKE RESEARCH

Development of high level monitoring facilities as well as progress in understanding regional crustal processes were of significance in coping with the year 2000 earthquakes, both in providing useful hazard assessments and warnings as well as in collecting data for future research. A significant milestone was the SIL-project (1988-1995), building the high-level seismic SIL-system. It was a concerted effort of the Nordic countries toward earthquake prediction research in the SISZ (Stefánsson et al. 1993). The PRENLAB and PRENLAB-2 projects of the European Union 1996-2000 (Stefánsson et al. 1999) were also significant in this development. PRENLAB stands for Earthquake-Prediction Research in a Natural Laboratory. The SIL-project as well as the PRENLAB projects were based on a physical approach to earthquake prediction research, in collection of data and in their multidisciplinary approach to earthquake prediction research. At the same time emphasis has been on automatic or fast evaluation of observations with the goal of ultimately providing short-term warnings. Increased earth activity, seismic and volcanic, has also spurred the recent efforts to build up a continuously recording GPS network in addition to the GPS campaigns carried out repeatedly during the last decade. InSAR technology has been applied with good results to monitor volcanic areas as well as seismic and interseismic deformations in the fault zones. Volumetric strain measurements have been ongoing since 1980 in and near the SISZ especially to monitor short-term strain changes, with especially good results related to volcanic eruptions (Linde et al. 1994) Measurements of water level (pressure) in boreholes in hydrothermal fields with deep roots have been initiated during the last few years as a part of monitoring strain changes in the crust. Continuous monitoring of water level in some boreholes in the SISZ was in preparation before the earthquakes and has gradually come in operation after the earthquakes. A network of strong motion instruments was installed in Iceland during the last decade, especially in the SISZ. The multidisciplinary earthquake data that have been collected for the two recent earthquakes in the SISZ - the seismic and intensity data, deformation data and hydrological data are of enormous significance for ongoing research aiming at understanding and for modelling earthquake release processes in the SISZ. The study and modelling based on historical seismicity as well as on mapping of earthquake faults will be revised in the light of the new data. The data collected and the ongoing research have a focus on mitigating seismic risk in general, and on more complete and more secure warnings for earthquakes, both in this zone and worldwide.

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