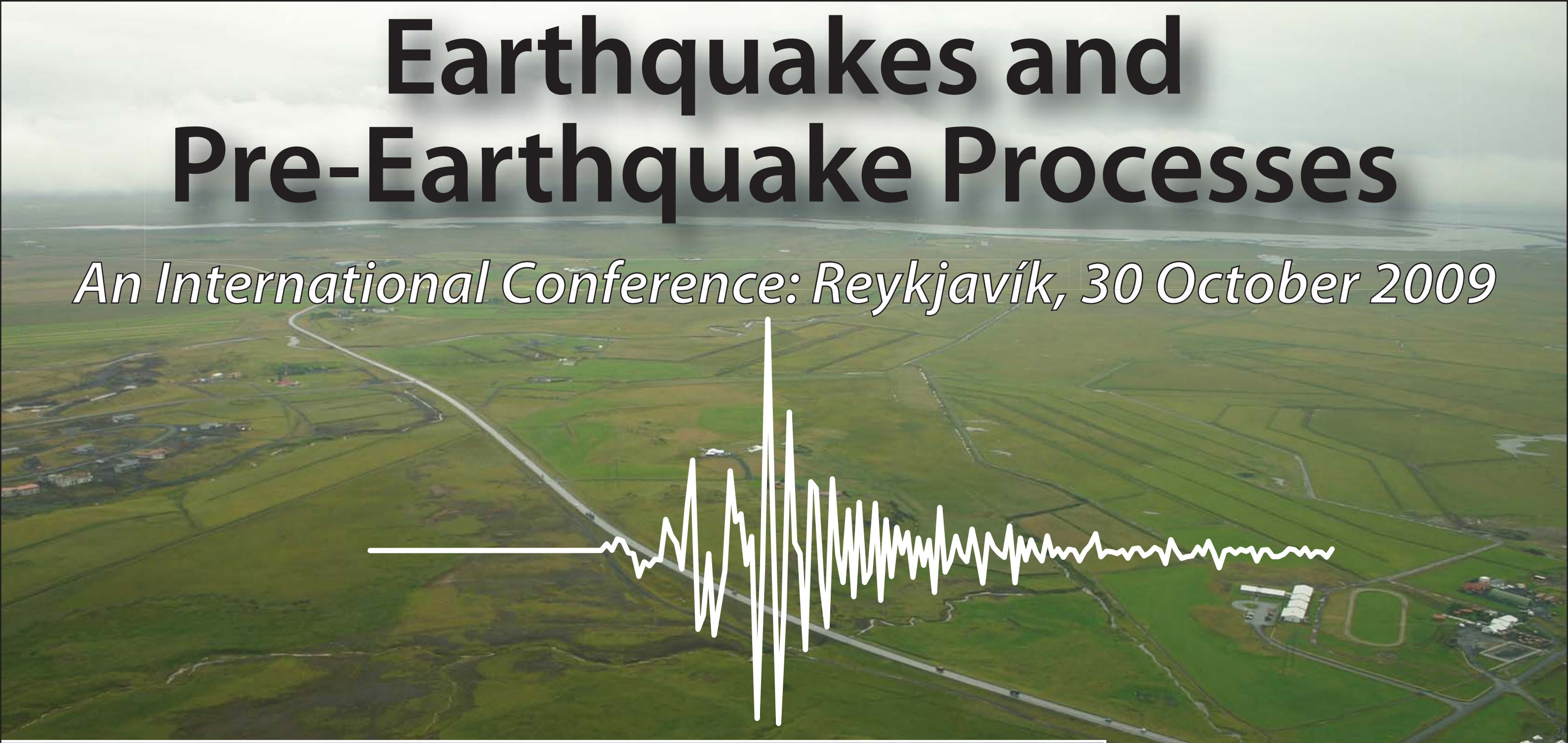
Earthquakes and Pre-Earthquake Processes

An International Conference: Reykjavík, 30 October 2009



ABOUT THE COVER

On 29 May 2008 at 15:45:58 UTC a strong earthquake occurred in south-west Iceland (upper image), causing moderate structural damage to nearby towns. Based on attenuation of peak ground-velocity with distance, the Icelandic Meteorological Office estimated a local magnitude of 6.3. The rupture initiated near to Mt. Ingólfsfjall (lower images) on a 10-km-long, N-S-trending fault, which immediately triggered slip along a parallel, 19-km-long fault, 4 km west. Building damage was highest close to the western fault (middle image). The waveform trace is a 1 Hz record of the earthquake from a borehole strainmeter at Geldingaá, ~97 km from the epicentre of the mainshock. Photographer: Matthew J. Roberts

Earthquakes and Pre-Earthquake Processes

An International Conference

Orkugarður, Reykjavík, Iceland
30 October 2009

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Conference web-site: http://en.vedur.is/earthquakes-and-volcanism/conferences/jsr-2009

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PREFACE

This year marks the centennial anniversary of earthquake monitoring in Iceland. In addition, it is the thirtieth anniversary of borehole strain measurements, twenty years since the first station in the present SIL seismic network was installed, and the tenth anniversary of Iceland's continuous GPS network. To mark these milestones, the Icelandic Meteorological Office, in collaboration with the University of Iceland, the University of Akureyri, Reykjavík University, Iceland Geosurvey, and Uppsala University, hosted an international conference on earthquakes, pre-earthquake processes and earthquake prediction research. The conference took place on 30 October 2009 in Reykjavík, Iceland. The conference was held in memory of Sigurður Th. Rögnvaldsson – a geophysicist who passed away on 25 October 1999. Sigurður was a very promising seismologist.

Oral and poster presentations were given on: (i) the history of seismological observations in Iceland; (ii) the development of earthquake research and earthquake prediction research; and (iii) measurement and research endeavours that promote and improve earthquake prediction. A one-day excursion to the source areas of the 2000 and 2008 earthquakes in south-west Iceland was convened on 31 October 2009. The meeting provided an opportunity to discuss past and future collaboration in earthquake prediction research.

Steinunn S. Jakobsdóttir

On behalf of the local organising committee

CONFERENCE SCHEDULE

08:00	*Registration and poster set-up*

ORAL PRESENTATIONS

08:30	*Steinunn S. Jakobsdóttir and others* Opening address
08:55	*Ragnar Stefánsson* From earthquake prediction research to useful warnings ahead of earthquakes
09:20	*Ragnar Slunga* Microearthquakes, stresses, crustal stability, and earthquake warnings
09:45	*Reynir Bödvarsson* Development history and future potential of the SIL system
10:10	*Coffee and posters*
10:50	*Halldór Geirsson and others* Summary of results from over 10 years of continuous GPS observations in Iceland
11:15	*Kristine M. Larson* High-rate GPS: applications to earthquakes and volcanoes
11:40	*Freysteinn Sigmundsson and others* Magma chambers and intrusions in Icelandic crust – constraints from volcano geodesy
12:05	*Björn Lund and others* How may glacial rebound influence the seismic activity in Iceland?
12:30	*Lunch and posters*
14:00	*Ari Tryggvason and others* Relative locations in 3D velocity models
14:25	*Þóra Árnadóttir and others* Geodetic constraints on the earthquake cycle in the South Iceland Seismic Zone
14:50	*Páll Einarsson* Mapping of Holocene surface ruptures in the South Iceland Seismic Zone
15:15	*Coffee and posters*
15:50	*Jeremy Zechar and others* Improving time-varying seismic hazard assessment: Iceland as a CSEP testing region
16:15	*Josef Horalek and others* Source mechanisms and their time and space variations as a tool for revealing a role of crustal fluids in the Bohemia / Vogtland earthquake swarms
16:40	*Luca Lenti and others* Recorded microseismicity due to seismically-induced cracks and collapses within a karstified rock mass
17:05	*Kristín Vogfjörð and others* Interpreting seismic signals from Icelandic volcanoes
17:30	*Robert White and others* Anatomy of melt intrusion at 15-18 km depth beneath Upptyppingar, Iceland
17:55	*Discussion and refreshments*

POSTER PRESENTATIONS

Ásta Rut Hjartardóttir and Páll Einarsson
The Kerlingar fault, north east Iceland, a Holocene normal fault east of the divergent plate boundary
Bryndís Brandsdóttir and others
Automated location of the May 2008 South Iceland aftershocks using coalescence microseismic mapping
Einar Kjartansson and others
Seismic and tsunami early warning in Iceland
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The first seismograph in Iceland: a Mainka-type instrument first deployed in 1909
Hossein Shomali and others
A duration-energy procedure for rapid estimate of earthquake magnitude using early part of P waveforms
Judicael Decriem and others
Geodetic observations of the 29 May 2008 south Iceland earthquake
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The HYDRORIFT experiment
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Stress and strain along an oblique plate boundary, the Reykjanes peninsula in SW Iceland
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Thirty years of borehole strainmeter measurements in Iceland
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Geothermal seismic noise at Ölkelduháls
Ólafur Guðmundsson and Roland Roberts
Ambient seismic noise correlation in two dimensions
Páll Einarsson and others
Radon monitoring in the South Iceland Seismic Zone
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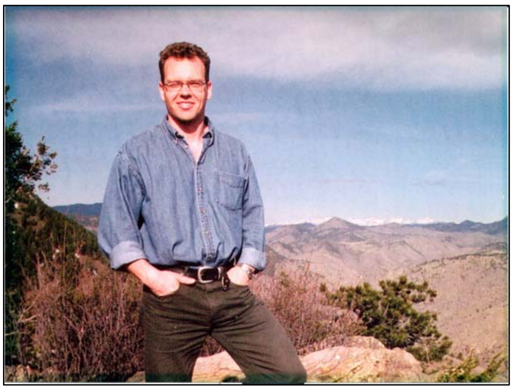
Improved radon monitoring network for earthquake precursor studies in seismic areas
Sigurlaug Hjaltadóttir and others
Relocated microearthquakes used for mapping active faults at depth in Iceland
Steinunn S. Jakobsdóttir and others
A deep-seated magmatic intrusion at Upptyppingar, Iceland, during 2007 and 2008
Tomás Fischer and others
Triggering mechanisms of the West Bohemia / Vogtland earthquake swarms

IN MEMORIAM: SIGURÐUR TH. RÖGNVALDSSON



Sigurður Thorlacius Rögnvaldsson was born in Reykjavík in January 1964. He was married to Nanna Lind Svavarsdóttir and they have two children: Svanhvít Sif, born in 1988, and Ari Thorlacius, born in 1995. Sadly Sigurður died in a car accident in October 1999.

Sigurður graduated from the Menntaskólinn við Hamrahlíð junior college in 1982 and received his BS degree in geophysics from the University of Iceland in 1987. During his undergraduate years, Sigurður worked summers at the Icelandic Energy Authority, carrying out electromagnetic resistivity survey and other fieldwork for geothermal prospecting.

Sigurður continued his geophysics studies in Sweden at the University of Uppsala. He finished a *Fil. lic.* degree in 1992 and a Ph.D. degree in 1994. His supervisors were Ragnar Slunga and Reynir Böðvarsson. His thesis research focused on developing and testing geophysical algorithms implemented as part of the South Iceland Lowland (SIL) digital seismic network for analysis of earthquake data. In collaboration with Ragnar Slunga, his most important contributions were in automatic estimation of fault-plane solutions for micro-earthquakes by inverting observed polarities and spectral amplitudes of P- and S-waves, and in relative locations of micro-earthquakes. Sigurður's research thus demonstrated that micro-earthquakes contain information about large-scale tectonic processes.

During his student years in Uppsala, Sigurður travelled to Mozambique where he organised and supervised resistivity measurements for mapping groundwater levels. Sigurður also participated in refraction measurement campaigns in Poland and Sweden.

Upon graduation Sigurður first held a postdoctoral position at the Nordic Volcanological Centre in Reykjavík, and then moved to the Geophysical Department of the Icelandic Meteorological Office (IMO) in the autumn of 1995. At IMO, Sigurður participated in the deployment and day-to-day maintenance of the SIL system as well as its development. The map on the IMO web site showing daily seismic activity was implemented by Sigurður during a seismic crisis in Hengill in 1998; it is an example of his creativity and effort to visualise SIL earthquake data.

Sigurður participated in several Icelandic and international research projects after his return to Iceland, but the focal point of his research continued to be analysing micro-seismicity in Iceland, building on his doctoral work in Uppsala. These studies included mapping of faults in the Tjörnes fracture zone, the South Iceland seismic zone, and the Hengill region using relative relocations and earthquake focal mechanisms. Mapping of seismically active faults at depth using relative relocations of micro-earthquakes provides important information on the seismo-tectonics of a region, and the method is now used in geothermal exploration.

Sigurður's contributions to the field of seismology during his short career demonstrate the enthusiasm that he held for the subject. He was a great colleague and a true friend - always ready to help, whether the problem involved deciphering convoluted computer codes, delving into the mysteries of the SIL system, making presentable documents using *LaTeX*, or discussing life, the universe and everything.

RELATIVE LOCATIONS IN 3D VELOCITY MODELS

Ari Tryggvason, **Reynir Bödvarsson, Björn Lund, and Hossein Shomali**

Swedish National Seismic Network, Uppsala University, Uppsala, Sweden

Abstract

By comparing travel times station by station from similar events, located reasonably close to each other, important information on the location of these events relative to each other can be derived. This may be obtained with either the "normal" travel time picks, or after cross correlation of waveforms recorded at the same stations. The former procedure is commonly referred to as "joint hypocentral locations". When relative travel times based on waveform correlations are used, the term "relative event locations" is commonly used. Another term referring to the above procedures is "double difference" locations. In most instances "double difference" event locations imply what we here have referred to as joint hypocentral locations, even though sometimes relative travel-times based on waveform correlations are used. In this case the event locations are to be considered as relative locations using the above definitions. If both travel time picks and relative times based on waveform correlations are used when solving for the locations, it is important that the data are weighted properly. Whereas normal travel time picks may be accurate to the order of the sampling interval, relative travel-times based on waveform correlation techniques may be significantly better – a not unrealistic estimate of the accuracy may be one tenth of the sampling interval. The accuracy obtained of course depends on the data quality, but also on the technique used for waveform correlation. For a group of similar events, all events may be correlated to each other, or a "master event" is selected and all events in a group are correlated to this event. The point of performing joint or relative locations is the improved accuracy compared to normal single event locations that is obtained in the hypocentral parameters. For relative event locations the relative position of individual earthquakes may be known to within 10 m. The absolute location of the events (or the entire group of events if one wish) is commonly far less accurately known, even though the consensus is that it is improved compared to single event locations. It has been shown that the relative event locations are not very dependent of the velocity model used. For the absolute locations (or the group location), however, the locations are much more dependent on the velocity model used. Even if the one-dimensional (1D) velocity model that is used for the locations is as good as one can possibly expect it to be, the real world is rarely 1D. Neither are earthquakes occurring everywhere with the same probability. Earthquakes are thus unusual phenomena, and it is not uncommon that earthquakes occur also where the velocity structure is uncommonly heterogeneous. In such heterogeneous regions, to compute accurate absolute event locations, a three-dimensional (3D) representation of the velocity structure is needed. This is commonly not done, except in the application of "double difference tomography", in which a 3D velocity model is inverted for along with the relative event locations. In this presentation we examine the effects of unknown 3D velocity variations may have on the absolute locations, even if joint (or relative) event locations are used. We also suggest how relative event locations in 3D models may be implemented in the routine analysis of events.

THE KERLINGAR FAULT, NORTH EAST ICELAND, A HOLOCENE NORMAL FAULT EAST OF THE DIVERGENT PLATE BOUNDARY

Ásta Rut Hjartardóttir and **Páll Einarsson**

Institute of Earth Sciences, University of Iceland

Abstract

The Kerlingar fault is located in the easternmost part of the deformation zone of the Northern Volcanic Rift Zone; about 14 km east of Grímsstaðir, NE Iceland (Figure 1). The total length of the fault is at least 30 km, although its surface manifestation is divided into at least 7 segments. It is an eastward-dipping normal fault, with a throw of ~4 m, as measured in Holocene deposits. The general orientation of the fault is ~NNW, and it is gently curved so the northern end is more westerly oriented than the southern part. Very few earthquakes have been detected in this area in the last decades. Our calculations indicate, however, that the maximum size of an earthquake originated at this fault might be about M_{ω}=6.7. The role of this fault is unclear. It is unusually long, and has an orientation and dip direction that differs from other structures in the area. The fault is located north of the Kverkfjöll fissure swarm. We suggest that the existence of the fault may be in some relation to its location at the end of the fissure swarm, or that it is in some way related to stress transfer in relation to activity of the Húsavík fault zone, as the fault is located in direct continuation of that fault zone.

Figure and Tables

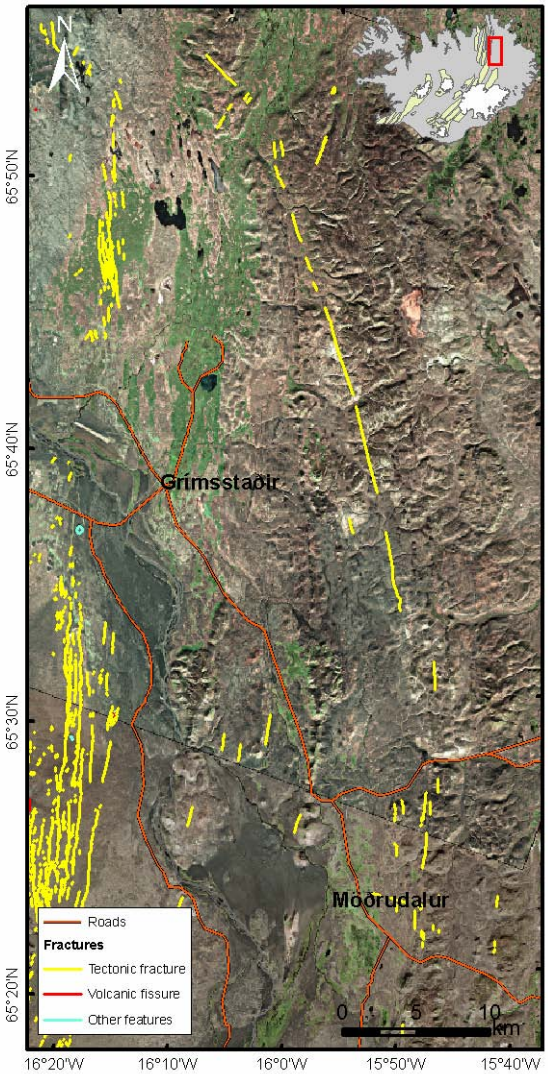


Figure 1: The Kerlingar fault, east of Grímsstaðir. The background is from SpotImage©.

HOW MAY GLACIAL REBOUND INFLUENCE SEISMIC ACTIVITY IN ICELAND?

Björn Lund (1), Peter Schmidt (1), and Þóra Árnadóttir (2)

1. Department of Earth Sciences, Uppsala University, Uppsala, Sweden; 2. Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

Abstract

The current warming trend started in the 1890s in Iceland, and the Icelandic ice caps have been generally retreating since then. The total volume of ice lost by Vatnajökull since 1890 is estimated at 435 km^3, equivalent to a 50 m thick layer over the entire glacier. Ice loss data from the other major Icelandic glaciers is scarcer, but they all indicate significant retreat since 1890. Using a model for the ice loss history of the Icelandic ice caps from 1890 to 2004, and a 3D finite element Earth model, we calculate the response of the Earth to the current deglaciation. The modelled uplift is compared to GPS data from countrywide campaigns in 1993 and 2004. These data show a broad region of rapid uplift in central Iceland, with velocities of up to 25 mm/yr, which our models reproduce well when all major ice caps in south-central Iceland are included. Our best-fit 1D Earth model has a 10 km elastic layer on top of a 30 km viscoelastic layer with viscosity 1e20 Pa s, overlying a viscoelastic half-space with viscosity 1e19 Pa s (Árnadóttir *et al.*, 2009). The inferred viscosity is higher than found by some previous studies that considered more spatially limited data sets.

We explore how 3D structures such as laterally varying lithosphere thickness, inclusion of a low-viscosity ridge system and lateral viscosity variation, all present in the complex structure of Iceland, affect the resulting uplift. Preliminary results indicate that data coverage near the glacial rims, or even better on nunataks, are essential to resolve such structures.

We use the modelled stress fields to investigate the effect of deglaciation on the stability of faults. Although the stresses can be readily used to calculate increasing or decreasing fault stability using e.g. the Coulomb Failure Stress (CFS) criterion, we show that such inferences need to take the background stress field into account. Utilizing simple models of the background stress field we show how seismicity is promoted in some areas and demoted in other. The affected areas are primarily below the ice caps and near their rims. The region between the Vatnajökull and Hofsjökull glaciers is particularly interesting as the glacially induced stresses are relatively large there and will interact with both the rift related and the local volcanic stress fields. We model this interaction at different depths to study the effect on fault stability and thus possible earthquake activity.

Reference

Árnadóttir, T., Lund, B., Jiang, W., Geirsson, H., Björnsson, H., Einarsson, P. and Sigurdsson, T., 2009, Glacial rebound and plate spreading: results from the first countrywide GPS observations in Iceland, Geophys. J. Int., 177, 691-716.

AUTOMATED LOCATION OF THE MAY 2008 SOUTH ICELAND AFTERSHOCKS USING COALESCENCE MICROSEISMIC MAPPING

Bryndís Brandsdóttir (1), Matthew Parsons (2), Ólafur Guðmundsson (3,4), Julian Drew (2), Ingi Þ. Bjarnason (1), and Robert S. White (2)

1. Institute of Earth Sciences, University of Iceland; 2. Cambridge University, England; 3. Reykjavík University, Iceland; 4. Uppsala University, Sweden

Abstract

While a dense array of seismic stations encompassing the earthquake source region will improve detection thresholds and minimize velocity model uncertainties and location errors, the accuracy of absolute earthquake locations is still being studied. Slunga *et al.* (1995) first investigated the sensitivity of differential arrival times to absolute earthquake locations within the South Iceland Seismic Zone, (SISZ) Iceland, recognizing relative location of micro-earthquakes to be a viable tool for mapping faults and fractures while retaining the absolute location of the earthquake sources among unknown variables. More recent synthetic tests have shown that the double-difference earthquake location method minimizes errors due to 3D variations in velocity structure and can, in principle, be used to determine the absolute locations of earthquakes (Waldhauser and Ellsworth, 2000; Menke and Schaff, 2004).

We applied a coalescence micro-seismic mapping method (CMM) for detection and localization of the aftershock sequence of the May 29, 2008 M6.1 and M6.0 Ölfus earthquakes (Hreinsdóttir *et al.*, 2009). This technique is both automatic and robust, and has been shown to give accurate absolute earthquake locations in spite of velocity model uncertainties (Drew *et al.*, 2005). Instead of using an interactive generalized inversion of travel time picks to derive a hypocenter and origin time of an event, the CMM method uses a short/long time average and continuous 3D polarization to detect P and S phases from the data stream and time-spatially maps the origin of each event before coalescing data from each sensor into a joint solution. The point of coalescence occurs at the same time and location, as might be predicted by inverting using travel time picks. Whereas the magnitude of each 4D map is a relative measure of the occurrence of a micro-seismic event the shape of the map describes the fit between modelled and measured data, and characterizes the uncertainty in the time and location estimate for the event.

More than 10,000 events, recorded on an 11 station temporal array were located during the period 30 May to 2 July, using the CMM method. Filtering based on signal-to-noise ratios and station numbers resulted in 7,643 usable event locations. The SIL system located more than 5,000 events during this period. In addition to the two main N-S faults, the aftershock distribution reveals several smaller parallel faults as well as conjugate NE-SW and ENE-WSW oriented faults Most hypocenters originate within the uppermost 9 km. Events on the Reykjafjall fault are concentrated at 1-5 km depth whereas aftershocks along the southern extension of this fault, in Flói, lie at 5-9 km depth. A comparison between CMM and SIL locations revealed a systematic westward shift of events by about 600 m, which we attribute to sparse SIL station distribution and marked 3D variations in upper crustal structure between the far-field SIL-stations located within the Western Volcanic Zone and the Tertiary, S-Iceland.

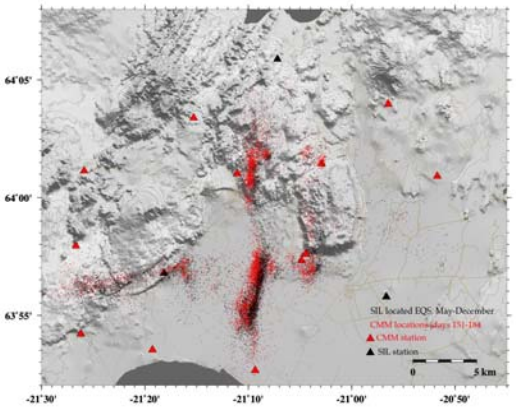


Figure 1: Aftershock distribution from the May 2008 Ölfus earthquakes. CMM located events (red) are shifted westwards compared to SIL locations (black).

References

Drew, J., D. Leslie, P. Armstrong, G. Michaud, 2005, Automated microseismic event detection and location by continuous spatial mapping, *Soc. Petroleum Engineers,* Abstract., 7 pp.

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SEISMIC AND TSUNAMI EARLY WARNING IN ICELAND

**Einar Kjartansson, Kristín S. Vogfjörd, Sigurlaug Hjaltadóttir,
Hjörleifur Sveinbjörnsson, Gunnar B. Gudmundsson, Sigthrúdur Ármannsdóttir,
Halldór Geirsson, Matthew J. Roberts, and Bergthóra S. Þorbjarnardóttir**

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Abstract

Tools for real-time analysis have been implemented at seismic stations in the SIL system in Iceland, as a part of the Icelandic Meteorological Office participation in the SAFER and TRANSFER projects. These tools include processes to support alert maps and Shake Maps, first steps towards fast magnitude determination based on dominant frequency, and the development of procedures to map faults in near real-time.

Data for alert maps and Shake Maps is obtained using a real-time process that monitors both ground velocity and acceleration in 4 separate frequency bands at each station: 4-50 Hz, 1-10 Hz, 0.25-2.5 Hz and 0.05-0.5 Hz. A reference level is maintained for horizontal and vertical components in each frequency band, such that it is exceeded a few times per hour. When signals exceed this level by more than 50%, a report is sent to the processing centre. When 5 or more stations send reports within a time interval of 20 seconds, alert maps are generated. The alert maps show observed values for each station, including peak ground velocity and arrival times for peaks in ground motion and first break

An attempt is also made to solve for the location of the event. The location solution is based on the assumption that time when the vertical component first exceeds the reference level by a certain amount indicate the arrival of the P wave from an earthquake.

All possible combinations of 3 stations are used to compute potential solutions; the location that yields the lowest sum of absolute residuals is then found. Once the location has been determined, conventional magnitude can be calculated, using recently refined magnitude-distance relations for Icelandic earthquakes. When a good fit is obtained for at least 5 stations, for both arrival times and amplitudes, and the magnitude indicated is greater than 2.0, a Shake Map is generated and placed online automatically. The Shake Maps are usually ready within 3 minutes of the earthquake. The maps can be accessed at http://hraun.vedur.is/ja/alert. This real-time analysis has been implemented on 56 stations in the SIL system. These tools have yielded accurate magnitude estimations for nearly all earthquakes that have been felt in the past 12 months. In order to get more accurate Shake Maps, data on near-surface seismic properties have been collected, and used to estimate the effect of site on seismic shaking. In addition to the parameters used for Shake Maps, estimates of dominant period for first 4 seconds after trigger on the vertical are computed, in real time. These may be used to estimate magnitude, before location has been determined as in the ElarmS methodology. In order to obtain more reliable results for earthquakes offshore North Iceland, data are obtained in near real-time through ORFEUS from station on Jan Mayen and Greenland. This data will be integrated into the near- real-time processing of data from the SIL stations. Mapping of faults in near real-time is performed by using double-difference relocation of automatically located micro-earthquakes, relative to a library of events already located with high precision. Thus, taking advantage of the tens of thousands of earthquakes in South Iceland that have been relatively located. Automation of the relocation process is under development. When completed, the process will enable near real-time delineation of activated faults by the distribution of micro-earthquakes.

MAGMA CHAMBERS AND INTRUSIONS IN ICELANDIC CRUST – CONSTRAINTS FROM VOLCANO GEODESY

Freysteinn Sigmundsson (1), Erik Sturkell (2), Rikke Pedersen (1), Andy Hooper (3), Halldór Geirsson (4), Páll Einarsson (5), Benedikt G. Ófeigsson (1), Þóra Árnadóttir (1), and Judicael Decriem (1)

1. Nordic Volcanological Centre, Institute of Earth Sciences, University of Iceland; 2. University of Gothenburg, Sweden; 3. Delft Technical University, Netherlands; 4. Icelandic Meteorological Office, Iceland; 5. Institute of Earth Sciences, University of Iceland

Abstract

Extensive crustal deformation studies have been conducted at Icelandic volcanoes for over four decades, utilizing levelling, electronic distance measurements, GPS geodesy, satellite radar interferometry (InSAR), and other techniques. The measurements have revealed a number of persistently deforming areas at central volcanoes, interpreted as a consequence of pressure variations in magma chambers, and more episodic deformation in relation to separate intrusions. In the Northern Volcanic Zone, deformation due to pressure variations in shallow magma chambers at the Krafla and Askja central volcanoes at about 3 km depth is well resolved. Pressure in both of these has been decreasing for the last two decades. At both Krafla and Askja volcanic systems, geodetic data have been interpreted in terms of additional sources at a depth of 16-22 km, although other interpretations cannot be excluded. In 2007-2008 a clear geodetic signal was recorded in relation to formation of a deep oblique sheet under Upptyppingar and Álftadalsdyngja, below the brittle-ductile transition. At Vatnajökull, the best-resolved magmatic deformation signal relates to inflation/deflation cycle of the Grímsvötn volcano, despite only a single observation site at Mt. Grímsfjall. The observations are explained by flow of magma in and out of a shallow magma chamber under the central part of the Grímsvötn caldera complex. Additionally, deformation of the Bárðarbunga volcanic system has been recorded, in relation to the 1996 unrest and Gjálp eruption. In South Iceland deformation data indicates pressure variations in magma chambers under Katla at a depth of a few kilometres. Analysis and inversion of InSAR data resolve a deep magma chamber under Hekla with a centre depth in the range of 15-20 km. At Eyjafjallajökull, two separate sill intrusions occurred in 1994 and 1999, and a new unrest episode began there in 2009. In SW-Iceland, the best-resolved magmatic signal is related to pressure increase under the Hrómundartindur volcanic system 1994-1999, interpreted as a result of magma accumulation. The seismic signatures associated with the observed inflation and deflation of magma chambers and the intrusions is highly variable, but combined interpretation of seismic and geodetic data, together with other available data, provides a powerful approach to understand unrest periods at volcanoes.

THE FIRST SEISMOGRAPH IN ICELAND: A MAINKA-TYPE INSTRUMENT FIRST DEPLOYED IN 1909

Gunnar B. Guðmundsson and Matthew J. Roberts

Monitoring and Forecasting Division, Icelandic Meteorological Office, Iceland

Abstract

Modern seismology began in 1880 when John Milne (1850−1913) and other British scientists working in Japan began to study earthquakes and to develop horizontal and vertical pendulum seismographs. In Germany, the astronomer E. von Rebeur-Paschwitz (1861−1895) built sensitive horizontal pendulums for measuring tidal tilt. In 1889 he correlated his measurements with an earthquake in Japan, thus making the first teleseismic observation. Realising that, through international cooperation, teleseismic observations of earthquakes would allow the Earth's structure to be revealed he proposed a world-wide network of seismic stations and an international institute to collect the data.

The International Permanent Commission for Earthquake Research was founded in 1899 during the Seventh International Geographical Congress in Berlin. The Icelandic geographer Þorvaldur Thoroddsen (1855−1921) participated in the congress, becoming a member of the Permanent Commission. The First international conference on seismology was held in Strasbourg in 1901, followed by a second meeting in 1903. During the second conference, the remit of the International Seismological Association (ISA) was defined, including membership, the structure of the Permanent Commission, and the establishment of a central bureau in Strasbourg. The statute of the ISA included financial provision for the installation of seismographs in countries qualifying for ISA support. At both conferences it was argued that a seismograph should be established in Iceland, particularly in light of damaging earthquake activity in Iceland in 1896.

It was not until 1907 at the ISA conference in the Netherlands that Iceland, with the support of the Icelandic government, was granted an ISA seismograph. It became the first internationally supported seismic station. The seismograph was a 135 kg bifilar cone pendulum, made by C. Mainka (1873−1943) at the central bureau in Strasbourg between 1907 and 1908.

The instrument − shipped to Iceland in 1909 − was a mechanically recording horizontal seismograph with air damping and a static magnification of 40 to 75. The seismograph was installed at the School of Navigation in Reykjavík in late 1909, and it was positioned to record the north-south component. The installation was performed by state engineer Thorvald Krabbe (1876−1953) and clockmaker Magnús Benjamínsson (1853−1942). The headmaster of the school, Páll Halldórsson (1870−1955), was responsible for running the seismograph. Seismograms from Iceland were sent to Strasbourg for analysis.

Another Mainka seismograph of the same design was installed in the same location around 1913 and was intended for east-west observations. Both seismographs remained in use until 1914, with later measurements made at the same site by the Icelandic Meteorological Office between 1925 and 1946. The instruments were then moved to IMO's office in Reykjavík in 1946. In 1954, the second seismograph was relocated to Akureyri and in 1955, the first seismograph was deployed to Vík in south-central Iceland to assist with seismic monitoring of the Katla volcano. It was replaced by the second instrument from Akureyri in 1964 and returned to Reykjavík, but its modern-day whereabouts are unknown. The second seismograph was decommissioned in 1974 and subsequently moved to the nearby Skógar museum, where it remains on display (Figure 1).

Figure 1: Photograph of a Mainka 135 kg horizontal pendulum, the second seismograph in Iceland and now on display at the Skógar Museum in southern Iceland. The inset photograph shows the contact clock from ISA, now at Icelandic Meteorological Office, which was used to time the measurements.

SUMMARY OF RESULTS FROM OVER 10 YEARS OF CONTINUOUS GPS OBSERVATIONS IN ICELAND

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Abstract

Iceland is located on the divergent plate boundary between the Eurasian and North American plates with frequent eruptions and drastic changes in ice-load due to climate changes, making it an excellent place for geodetic studies. Currently around 70 GPS stations in Iceland are continuously logging data. The Icelandic Meteorological Office (IMO) operates 58 of these stations along with many different collaborators. Of these, around 50 stations transmit data automatically at least once per day and an effort is being made to bring more sites on-line. During the past three years the sites have tripled in number. The primary purpose of the network is monitoring and research of crustal deformation, but the data have been used for a variety of different applications including GPS-meteorology and reference for high-resolution mapping.

Continuous GPS measurements in Iceland started in 1995 when the German institution "Bundesamt für Kartographie und Geodäsie" (BKG) installed a site in Reykjavik. The site is a part of the IGS (International GNSS Service) network and is among other things used for calculation of satellite orbits. BKG installed a station in south-east Iceland in 1997 (HOFN). Following intense seismic activity during 1994 – 1998 in the Hengill area in south-west Iceland, four sites were installed in the area in collaboration of IMO, the University of Iceland, and the Nordic Volcanological Centre (now a part of the Institute of the Earth Sciences at the University of Iceland) marking the initiation of the ISGPS network. The first site (VOGS) started collecting data on March 18, 1999. In 2006, when the network counted 20 sites, the Earth Science Institute of the University of Iceland and IMO received a grant to install a number of new sites in close cooperation with research groups outside of Iceland.

Plate spreading of about 2 cm per year usually dominates the horizontal site motion. The deformation is taken up on a 50-100 km wide zone following the plate boundary. Because of warming climate, the glaciers in Iceland are thinning and retreating, resulting in a widespread uplift with maximum uplift rates exceeding 2 cm per year. The strength of continuous GPS measurements lies in the time resolution and continuity of the observations. Annual load changes of the glaciers cause a sinusoidal signal of 2 cm peak to peak in the vertical component at the stations closest to the glaciers as an elastic response. The long-term uplift due to the retreat of the ice caps is controlled by viscoelastic, as well as elastic, response of the crust. The CGPS network captured co-seismic deformation due to two earthquake doublets in the south Iceland seismic zone, the first in 2000 and the second in 2008. In 2000, the deformation from each of the two M_w=6.5 earthquakes was well resolved as there were 3 days between the earthquakes. In 2008, the two M_w=6.1 earthquakes were separated only by 2-3 seconds. Normally the instruments collect data every 15 seconds, but a few sites collect data at 1 s intervals. These high-rate sites gave direct observations of displacement coda of seismic waves from the 2008 earthquakes for the first time in Iceland.

CGPS observations play an important part in research and monitoring of magma movements. During 2007 and 2008 a magma intrusion took place at a depth of 12 to 20 km in an area north of Vatnajökull ice cap. The deformation was observed at nearby CGPS sites, which were originally installed to monitor deformation due to load changes around one of the largest water reservoir in Iceland. Modelling of the surface deformation along with seismic observations made it possible to estimate the amount of magma intruded and monitor the time evolution of the intrusive event. Two localized uplift events have been ongoing in 2009; at Eyjafjallajökull in south-Iceland, and at Kleifarvatn on the Reykjanes peninsula.

Continuous GPS measurements along with seismic observations and other geodetic techniques have proven important for monitoring and research of crustal deformation processes in Iceland. Although the network is dense in many areas that have been active in the past decade, some areas deserve closer attention.

A DURATION–ENERGY PROCEDURE FOR RAPID ESTIMATE OF EARTHQUAKE MAGNITUDE USING EARLY PART OF P WAVEFORMS

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Abstract

Understanding the earthquake rupture process is the central-point in our understanding of fault systems and rapid magnitude determination. For example in an earthquake early warning system it is essential to be able quickly to determine the size and location of an earthquake. There are a number of procedures for rapid analysis of the magnitude of large earthquakes using seismic P wave portion of seismic waveforms at teleseismic distances. Because these procedures use only the P-wave portion of a seismogram thus the estimate of an event size is potentially available only a few minutes after the P waveform has been recorded at teleseismic distances, that is, in as little as 10–15 min after origin time (OT) at 30° great circle distance (GCD) and about 20 min after OT at 90° GCD.

We introduce a rapid and robust, energy-duration procedure, based on the Haskell, extended source model, to obtain an earthquake moment and a moment magnitude, M_{ED}. Using seismograms at teleseismic distances (30°–90°), this procedure combines radiated seismic energy measures on the P to S interval of broadband signals and source duration measures on high frequency, P-wave signals. The M_{ED} energy-duration magnitude is scaled to correspond to the Global Centroid-Moment Tensor (CMT) moment-magnitude, M_w^{CMT}, and can be calculated within about 20 min or less after origin time. In this study we present the application of the energy-duration methodology to a number of recent, large earthquakes (including 2007/09/12, Southern Sumatera earthquake, Mw^{CMT} 8.5 and 2004/12/2, Sumatra-Andaman mega-thrust earth- quake, Mw^{CMT} 9.0) using only SNSN (Swedish National Seismic Network) data.

IMPROVING TIME-VARYING SEISMIC HAZARD ASSESSMENT: ICELAND AS A CSEP TESTING REGION

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Abstract

Improving our ability to accurately forecast where and when the next damaging earthquake will likely occur is one of the key steps towards improving the earthquake resilience of modern societies. Model testing & validation is a critical next step in implementing time-varying probabilistic seismic hazard assessment (TV-PSHA). Progress in TV-PSHA has been impeded by the lack of an adequate experimental infrastructure, making it difficult to conduct scientific prediction experiments and model development under rigorous, controlled conditions, and even more difficult to evaluate forecasts using accepted criteria specified in advance. To remedy this deficiency, the Collaboratory for the Study of Earthquake Predictability (CSEP, www.cseptesting.org) is currently developing a community-supported, geographically-distributed laboratory with a computational infrastructure that is adequate to support a global program of research on earthquake predictability.

The CSEP EU Testing Center at ETH Zurich (eu.cseptesting.org) represents the European node of CSEP. It is funded in part through the EU project NERIES (www.neries-eu.org), and it will serve multiple testing regions within Europe. The first such region is in Italy, and experiments there are being sponsored by the Istituto Nazionale di Geofisica e Vulcanologia (INGV). For the Italian testing region, fully prospective testing of long-term (five- and ten-year) models started August 1 2009; 18 long-term models are participating. Models span the full range from purely statistical to mostly physics-based, and forecasts have been contributed by researchers from more than eight institutions across Europe. Model forecasts will be evaluated against earthquakes of magnitude at least 4 and 5 and above, as reported by INGV.

We propose that, because of the high seismicity and deformation rates, the excellent monitoring network, and the existence of several geophysical models, Iceland is ideally suited as a future testing region within the CSEP EU Testing Centre. Applying the wide range of existing models in Iceland should help improve our understanding of the physical processes underlying earthquakes in Iceland, and it may also lead us to generalisations regarding seismicity elsewhere. We have obtained seed funding from the Swiss National Science Foundation for the first phase of such a project. In collaboration with IMO scientists, we want to develop Iceland as a CSEP testing region within the next three years. This work will include (1) studies of earthquake network homogeneity and catalogue magnitude completeness; (2) calibration of a range of existing forecasting models to the seismic regions of Iceland; (3) evaluation of model forecasting ability based on retrospective testing and finally (4) implementation of fully prospective testing of models against a define authoritative data stream provided by IMO.

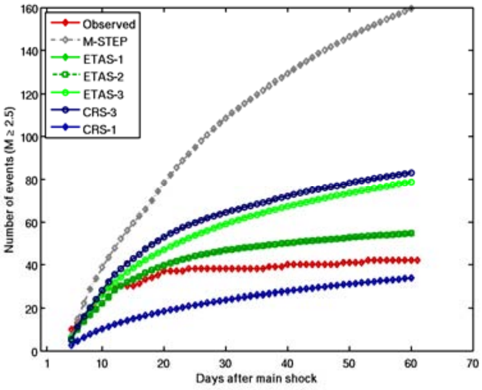

Figure 1: Cumulative observed number of events since the 2008 Selfoss earthquake (red), compared here with forecasts from six models.

As part of the EU FP6 Project SAFER (www.saferproject.net) we conducted an initial comparison of the forecasting skills of a range of physics-based and statistical models. We retrospectively analysed seismicity following the M_W=6.3 2008 Selfoss earthquake. The abundant seismicity in such sequences offers ideal conditions for studying earthquake interaction. We analyzed the performance of eight models from different classes: (1) two modified Short-Term Earthquake Probability models (M-STEP), (2) four Epidemic Type Aftershock Sequence (ETAS) models with and without time- and space-varying parameters and using various spatial triggering kernels, and (3) two models based on a combination of Coulomb stress change and rate and state theory (CRS).

The results of this case study (Figure 1) show that ETAS-type models perform quite well, followed by the CRS-3 model, which incorporates much more statistical variability than CRS-1. The fit of the M-STEP model is poor as it likely suffers from insufficient regionalization.

SOURCE MECHANISMS AND THEIR TIME AND SPACE VARIATIONS AS A TOOL FOR REVEALING A ROLE OF CRUSTAL FLUIDS IN THE BOHEMIA/VOGTLAND EARTHQUAKE SWARMS

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The West Bohemia (Czechia) and Vogtland (Saxony, Germany) is well known as an exceptional European region thanks to its geodynamic activity, particularly a periodic occurrence of intraplate earthquake swarms and a high flux of the mantle derived CO_2. The Nový Kostel (NK) focal zone, which dominates the recent seismicity in this region, shows a distinct planar character. Three earthquake swarms of 1997 (M_{Lmax}= 3.0), 2000 (M_{Lmax} = 3.4) and 2008 (M_{Lmax} = 3.8) and numerous micro-swarms took place there in the last fifteen years. The most of the earthquake foci are located on the main fault plane (MFP) at depths between 6 and 11 km. Hypocentres of the 2000 and 2008 swarms fall precisely on the same fault portion of the MFP, whereas the 1997 swarm was located about 1 km apart and formed a wedge-like cluster on the edge of the MFP (Fischer and Horálek, 2003; Horálek *et al.*, 2009a). To get an idea of faulting and driving forces acting in the West Bohemia/Vogtland earthquake swarms we analyzed source mechanisms (in the full moment tensor description) of the 1997 and 2000 swarms and their time and space variations; that of the 2008 swarm is in progress.

We found different patterns of source mechanisms in the 1997 and 2000 swarms, which implies their different development. In the 1997 swarm two different source mechanisms occurred: oblique normal faulting and a pure shear source in the 1st swarm phase and oblique thrust faulting and a combined source containing both shear and tensile components in the 2nd swarm phase (Horálek *et al.*, 2002; Vavryčuk, 2002). However, all the 2000-events were pure shears, with cognate source mechanisms signifying oblique normal faulting parallel to the main fault plane (dip and strike matching geometry of the MFP). The significant non-shear source mechanisms in the 1997 swarm suggest a relevant role of fluids in driving the swarm activity, whereas the 2000-swarm source mechanisms indicate a self-organization due to the stress redistribution (Fischer and Horálek, 2005). It, however, opens a question of relevance of crustal fluids in origination and driving earthquake swarms, if there is any.

To shed light on this issue we analyzed the swarm-like seismicity that was induced by the fluid injection in the Soultz-sous-Forets geothermal field (Alsace) in 2003. We estimated source mechanisms of a set of events covering the whole injection, of magnitudes similar to those of the 1997 and 2000 swarms, and investigated their time-space variations depending on the flow rate and wellhead pressure. We found that the injection activated two segments of the natural faults existing in the area that showed different source mechanism patterns. However, all the analyzed events were pure shears without any non-shear attributes (Horálek *et al.*, 2009b).

Thus we infer that in the case of the favourably oriented fault plane, pressurized fluids play a decisive role in decreasing the strength of interfaces of fractures, which is governed by the Coulomb friction criterion; this can be due to both the decrease of the effective normal stress or to the reduction of the friction coefficient. The running swarm activity is then mainly driven by the stress changes, which can be a case of the 2000 swarm, of the 1st phase of the 1997 swarm and also of the 2003-Soultz induced seismicity. Provided a less favourably oriented fault plane, additional tensile force is needful to bring the fault to rupture, as it happened probably in the 2nd phase of the 1997 swarm (Horálek and Fischer, 2008).

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GEODETIC OBSERVATIONS OF THE 29 MAY 2008 SOUTH ICELAND EARTHQUAKE

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Abstract

The South Iceland Seismic Zone (SISZ) is an ~80 km long E-W transform zone accommodating the relative spreading of the North American and Eurasian plates across southern Iceland. The accumulated stress due to the plate spreading is released by earthquakes in the zone. The SISZ does not rupture along its whole length, but on many parallel N-S right-lateral strike slip faults. The largest earthquakes are therefore limited to moderate magnitudes (M~6-7), and often occur in sequences of similar size events, at times propagating from East to West. After a quiet period of 88 years two Mw=6.5 events struck the eastern and central part of the SISZ in June 2000. The main shocks ruptured two parallel N-S faults, spaced about 17 km apart, occurring 3 1/2 days apart (Árnadóttir *et al.*, 2001; Pedersen *et al.*, 2001, 2003). The sequence continued on May 29, 2008 when two Mw6 events occurred in the western part of the SISZ, rupturing two parallel N-S faults located about 4 km from each other. The small time delay (~3 sec) between the two events suggests that the western one was dynamically triggered by the initial event (Hreinsdóttir *et al.*, 2009).

Here, we present a geodetic study of the May 2008 earthquakes based on continuous and annual GPS measurements and InSAR images. We propose a dislocation model for the fault geometry, location and the slip distribution over the fault planes that best fit the geodetic data. We also present the post-seismic displacements recorded by a temporary GPS network that we maintained during the first month following the events. A transient deformation signal was recorded during the first 10 days following the earthquakes. This transient motion does not appear to be caused by poro-elastic rebound due pressure changes in the ground water system, as was observed following the June 2000 (Jónsson *et al.*, 2003).

Acknowledgements

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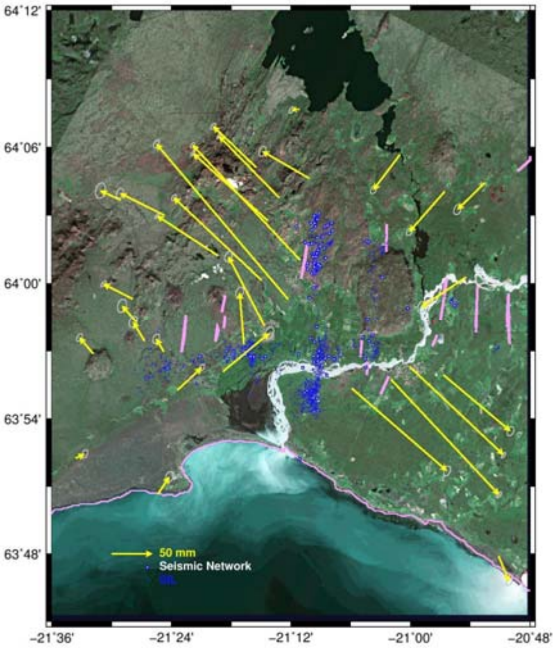

Figure 1: GPS measurement of the co-seismic displacements for the 29 of May 2008 earthquake in the Ölfus area. Blue dot highlight the aftershocks recorder by SIL network.

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HIGH-RATE GPS: APPLICATIONS TO EARTHQUAKES AND VOLCANOES

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Abstract

Today GPS networks installed around the world are used to quantify long-term plate rates and the temporal and spatial complexities of crustal deformation at plate boundaries. Daily position precisions of several mm and long-term position rates of 0.1 mm/yr are routinely reported. These kinds of precisions are the outcome of 20 years of sustained development of observable models, a global tracking network, and an accurate terrestrial reference frame. But many geophysical problems require positioning at intervals much smaller than these standard "one-day" GPS results. The focus of this talk will be sub-daily positioning applications, specifically using GPS to measure displacements during and after earthquakes and volcanic events. The methods I have used to analyze high-rate GPS data vary depending on the geophysical signal and the frequencies and amplitudes of the GPS error sources. For volcano applications, Kalman filtering can significantly reduce the errors due to multipath without suppressing the geophysical signal. I will discuss volcano results using the 2007 Father's Day eruption and intrusion dataset from Kilauea. Secondly I will discuss high-rate GPS as applied to seismology. Smoothing or averaging as shown for the previous cases is not a reasonable GPS analysis strategy for ground motions during an earthquake, and thus alternate multipath mitigation techniques must be used. Fortunately, the repetition of the GPS orbit can be used to develop empirical multipath corrections, significantly improving the precision of high-rate GPS solutions. I will focus on the Tokachi-Oki dataset, discussing both measurements of the seismic signal and early post-seismic deformation.

LP EVENTS AT GLACIER OVERLAIN KATLA VOLCANO, ICELAND

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Abstract

Repeating long-period (Lp) earthquakes (0.5-3 Hz) are commonly observed in volcanic regions worldwide. They are usually explained in terms of a volcanic source effect, commonly in terms of fluid motion and resonating magma pipes, or anomalous propagation through the complex volcanic structure. Recently, Lp events have also been associated with the motion of ice streams. Ekström *et al.* (2006) report seasonally modulated lp seismicity in massive ice streams in Greenland. O'Neel and Pfeffer (2007) report calving events with extraordinary long seismic codas with frequencies focused between 1-3 Hz and conclude that these features are a source effect. Roux *et al.* (2008) report lp events (1-4 Hz) generated by free falling ice blocks in an Alpine glacier (serac fall episodes).

Our joint analysis of climatic and new seismic data shows that small (M ~1-2.5) lp events (0.5-3 Hz) observed at Goðabunga, the western part of the Katla volcano, covered by the glacier Mýrdalsjökull in south Iceland, are likely to be related to ice movements in a steep outlet glacier and not, as previously thought, to volcanic intrusive activity (Jónsdóttir *et al.,* 2009*).* The over 13,000 lp events recorded since year 2000 are consistent in character and magnitude with seasonal changes of the glacier.

For decades persistent, seasonally modulated, long-period earthquake activity has been registered at Goðabunga. The events are emergent, of unusually long duration and the coda is complex. We investigate Lp events registered at Goðabunga from a new temporary deployment of 10 broad band stations (CMG-3ESP, 60 s), including a mini-array in the near vicinity of the seismic activity giving us better restrictions of the earthquake locations than before. A study of the source time function suggests that the low frequency extended coda can be attributed to the source. The events can be divided into groups of repeating waveforms suggesting a repeating source mechanism at the same location. Consistently all the events are located in a steep outlet glacier were blocks of up to 80 m thick ice fall of a 100 m high escarpment.

Joint interpretation of various climatic data, i.e. electrical conductivity and flow from glacial rivers, precipitation and temperature from nearby weather stations together with a detailed analysis of seismological data reveals a new explanation for the observed seismicity which is consistent with all available data.

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INTERPRETING SEISMIC SIGNALS FROM ICELANDIC VOLCANOES

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Abstract

The use of relatively located micro-earthquakes to map sub-surface faults in Iceland's transform- and volcanic zones has led to substantial advances in mapping details of fault structures. The similarity of waveforms from neighbouring earthquakes with similar mechanisms enables highly accurate relative time measurements through cross-correlation of the waveforms. In volcanic regions, the events do not necessarily occur on common faults, their source time functions can be long and complicated, and the local structure can be highly heterogeneous. However, relative locations of volcano-tectonic events allow magma movements to de delineated. Over the 19-year operation of the SIL seismic network, a wealth of signals emanating from Icelandic volcanoes have been captured by and analysed. These include Hekla, Eyjafjallajökull and Katla, as well as Bárðarbunga, Gjálp and Grímsvötn beneath the Vatnajökull ice cap.

Relative locations of the roughly one thousand earthquakes recorded in Eyjafjallajökull volcano reveal a pipe-like feeder channel just northeast of the crater rim, extending from the base of the crust, at around 22 km depth, up to the 6 km depth of sill intrusion emplacement. Two main intrusion episodes have been captured: 1994 and 1999. They started with rather intense activity in the feeder pipe, at 8-12 km depth, followed a few months later during the sill emplacement with southward migration of seismicity at around 6 km depth. Focal mechanisms of the upper crustal events vary, but mechanisms of events occurring in a swarm at the base of the crust in 1996, show predominantly E-W oriented, horizontal tension in agreement with the direction of spreading. A third intrusion episode appears to be in the making in 2009, with significant activity occurring in the feeder pipe at 8-12 km depth during the summer months.

At the neighbouring Katla volcano, the seismicity is about 15 times higher, with over 11 thousand events recorded on the volcano's western flank and over three thousand in the caldera. The flank activity exhibits seasonal variations; events are emergent and dominated by long periods, even though their magnitudes are in general no greater than M_L~2.5. The flank seismicity is extremely shallow (≤1 km), and much of the activity can be grouped into similar families of events, with some of the waveform complexities explainable by multiply reflected waves trapped in the near surface layers. Inside the caldera, on the other hand, the seismicity is generally of higher frequency, often with short impulsive waveforms and sometimes exhibits wave characteristics of regular tectonic events. This activity has been relatively located revealing nearly 80% of the caldera seismicity is also very shallow, or within 4 km of the surface. The distribution of this seismicity correlates well with locations of the main cauldrons on the ice surface, confirming its association with geothermal activity in the caldera. Additionally, significant activity is located in a small area near the caldera centre, where no cauldrons form. Temporal variations in the caldera seismicity correlate with changes in cauldron size over time, leading them by 1-2 years. In 2001, the activity in most cauldrons suddenly increased, peaked in 2002 and remained high until 2004. Two years prior to this activity, in July 1999, a small peak in seismicity occurred in the centre of the caldera, followed a week later by a sudden jökulhlaup from Sólheimajökull, which drained newly formed cauldron 7. The flood was accompanied by continuous frequency-banded tremor observable on stations around Katla. The peak activity at the centre location also occurred in 2002. The most seismically productive cauldron is at the northern caldera rim; similar to Eyjafjallajökull, this region was reactivated during summer 2009 and was accompanied by small floods in glacial rivers north of Katla.

Some scattered seismicity is located below 4 km depth in the Katla caldera, but with significant absolute and relative location errors. However a few events in a small cluster near the base of the crust, below the eastern caldera rim were well located in 2007 and 2008. Their locations suggest association with magma injection from the mantle into the crust, similar to the deep events at Eyjafjallajökull in 1996 and at Hjörleifshöfdi in 2007. The apparent regional increase in seismicity at the base of the crust could be real, but may also be affected by the improved detection threshold with time.

Seismicity associated with magma movements within Vatnajökull's main volcanoes: Grímsvötn, Gjálp and Bárðarbunga has also been recorded and relatively located. Additionally, continuous banded tremor is often observed from Vatnajökull, during eruptions and drainage of the two Skaftárkatlar cauldrons, as well as the Grímsvötn subglacial lake. The transient and continuous signals generated by these events will be discussed and compared to the events generated by Katla.

THE HYDRORIFT EXPERIMENT

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Abstract

Understanding the behaviour of fluids in the deep upper crust and at the brittle/ductile crust transition is of importance regarding both academic and industrial fields. Hydric fluids are thought to play a major role in the seismogenic cycle, mainly by decreasing friction along major faults. However, considering the complexity of the gouge at large seismogenic faults, fluids are evidently involved in other processes such as hydrofracturing before and during the fault slip and volume variations due to phase changes. This complexity is increased in supercritical conditions due to the compressibility and high enthalpy of supercritical fluids. Regarding the industrial point of view, the exploration and exploitation of deep hydric fluids is a recent challenge, partly motivated by the working out of conventional shallower reservoirs in geothermal areas but mainly due to their high energy potential. The HYDRORIFT experiment is part of the French project GEOFLUX that aims at understanding the behaviour of fluids in the deep upper crust using a range of different methods (e.g. in situ geophysical data, 3A-press rock mechanics experiments, physical, numerical and analogical modelling) The GEORG project (Geothermal research group) and HS ORKA support the project.

The HYDRORIFT experiment involves both ISOR (Iceland GeoSurvey) and a group of French GEOFLUX scientists in a geophysical experiment on the Reykjanes Peninsula in Iceland including both high-resolution TEM/MT studies and seismic tomography. This study follows a previous successful five-month seismic experiment in the same area (Geoffroy and Dorbath, 2008). The objective is to better stress the significance of the velocities anomalies discovered in the area following the 2005 experiment (notably beneath Kleifarvatn Lake) and to reach a more accurate physical knowledge of the geometry and time-evolution of the different fluid reservoirs within the active rift zone in Iceland. An array of 30 seismic stations, including three broadbands, was deployed in May 2009 for a six-month period. We present the details of the new seismic experiment as well as our first results mixed with those of the 2005 experiment.

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RECORDED MICROSEISMICITY DUE TO SEISMICALLY-INDUCED CRACKS AND COLLAPSES WITHIN A KARSTIFIED ROCK MASS

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Abstract

Seismometric arrays have been widely applied during the last decades to record controlled collapses in mines and caves due to explosions. Nevertheless, most hypogeous collapses are natural and spontaneous events and, as a consequence, they can occur unexpectedly and represent a high geological hazard. A research activity is carrying on in order to experience the use of accelerometric arrays for monitoring earthquakes as well as cracks and collapses within the strongly karstified rock mass, hosting the Peschiera Springs drainage plant of the Rome’s acqueduct (Italy). The Peschiera Springs slope, composed of Mesozoic limestones, is located about 80 km far from Rome. During the last seismic sequence of L’Aquila, started with the M6.3 mainshock on April 6, 2009, 665 records were recorded until July 31, 2009 including earthquakes, cracks and collapses occurred within the slope. The four accelerometric stations of the Peschiera Springs plant are equipped with triaxially arranged accelerometers (EPISENSOR Kinemetrics) connected to a digital data logger (K2 Kinemetrics); these devises were installed on September 4, 2008, within the drainage and the collecting tunnels of the plant, but only some tens of records were collected until the April 6, 2009. The recorded events were processed by use of a specifically implemented SAC-Fortran software capable to automatically distinguish the different kinds of records (i.e. earthquakes, cracks, collapses) as well as to compute energy, spectral (FFT) and kinematic (horizontal and vertical PGAs) parameters. The results obtained by analysing the whole dataset demonstrate that:

1) a seismically-induced sequence of rock mass hypogeous instabilities (i.e. cracks and collapses) was triggered by the seismic sequence of L’Aquila;
2) a trigger threshold for the seismically-induced rock mass instabilities was fixed at about 5E-4 g^2s by use of the cumulative Arias intensity computed for the recorded earthquakes;
3) the different values of the cumulative Arias intensity derived at the four accelerometric stations for the recorded rock instabilities show their possible location within the slope (i.e. closer to the GA station).

Moreover, the rate of the cumulative Arias intensity of the rock mass instabilities, recorded within the slope, shows different trends in the considered March-July time interval: an increasing rate-trend was observed during the first 5 days after the L’Aquila mainshock (until 10 April), a constant rate-trend was observed during the following three weeks (until 30 April), a decreasing rate-trend was observed in the following period (until the end of July). These different trends have been proposed as criteria to respectively adopt proceedings of awareness, alert and alarm by the manager office of the plant (ACEA-ATO2 agency) (Figure 1).

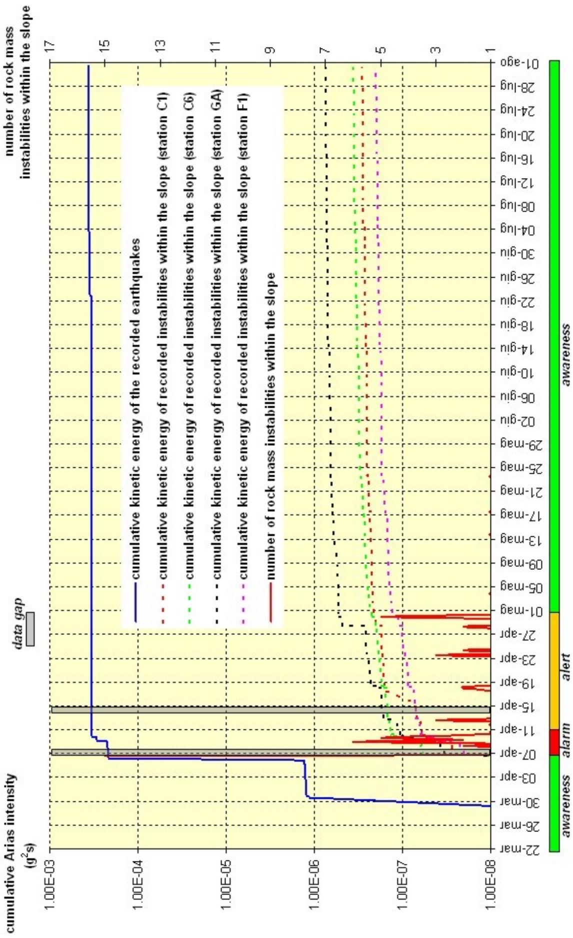

Figure 1: Cumulative Arias intensity computed for the recorded earthquakes and rock mass instabilities within the Peschiera Springs slope.

Acknowledgements

The Authors thank ACEA-ATO2 agency for providing data and technical supports to this research.

STRESS AND STRAIN ALONG AN OBLIQUE PLATE BOUNDARY, THE REYKJANES PENINSULA IN SW ICELAND

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Abstract

This study presents stress inversions of focal mechanisms from micro-earthquakes on the Reykjanes Peninsula, from the SIL seismic catalogue, and a comparison with geodetic strain rates.

During 1997–2006 most earthquakes on the Reykjanes Peninsula were located in two areas, Fagradalsfjall and Krísuvík on the central part of the peninsula. Pronounced swarm activity was observed in both areas, as well as moderate mainshocks in the Krísuvík area. A close spatial relationship between the area of high seismicity and the geothermal field in Krísuvík suggests that the geothermal activity has some influence on the seismicity in this area. No geothermal alteration is observed at the surface in the Fagradalsfjall area, and it is not known if there are particular triggering mechanisms behind the pronounced swarm activity in this area.

The state of stress estimated by inversion of micro-earthquake focal mechanisms from the SIL catalogue is mainly oblique strike-slip, with a tendency towards a normal stress state. Mapping the directions of the least compressive horizontal stress (S_{hmin}) shows an average direction of N(120±6)°E and a remarkable agreement with the directions of greatest extensional strain rate (ε_{Hmax}) derived from GPS velocities during 2000–2006. The agreement between the directions of stress at depth and strain rate observed at the surface indicates that the earthquakes are primarily driven by plate motion. Geothermal fluids may, however, act as a secondary triggering mechanism of the seismicity in the Krísuvík area.

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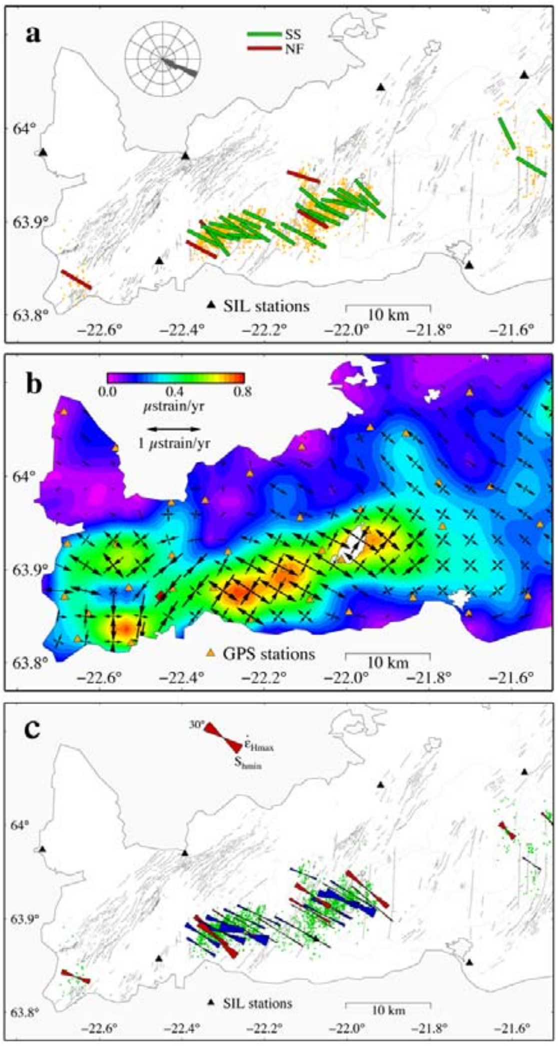

Figure 1: a) Directions of S_{hmin} from inversion of earthquake focal mechanisms, from July 2000–April 2006. The colours indicate the stress state: strike-slip (green) and normal (red). b) Greatest extensional and contractional horizontal strain rates (arrows), and magnitude of maximum horizontal shear strain rate (contours), based on GPS velocities from 2000–2006. c) Comparison of the S_{hmin} directions in panel a and the ε_{Hmax} directions in panel b. The bow-ties show the differences between the directions of S_{hmin} and ε_{Hmax}, with fill colours indicating whether S_{hmin} is oriented clockwise (red) or counter-clockwise (blue) to ε_{Hmax}. Modified after Keiding et al. (2009).

THIRTY YEARS OF BOREHOLE STRAINMETER MEASUREMENTS IN ICELAND

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Abstract

Over short intervals, borehole strainmeters can resolve strain changes as small as 0.0001 mm km^{-1} (i.e. 1×10^{-10}), making them ideal for measuring crustal deformation over periods ranging from minutes to months. Positioned at depths of ~200 m below the Earth's surface, borehole strainmeters are sheltered from environmental disturbances and are thus able to record minuscule levels of strain in the surrounding rock. As field-deployable sensors, the frequency response and dynamic range of borehole strainmeters is unsurpassed.

In 1979, in collaboration with the Icelandic Meteorological Office (IMO), the Department of Terrestrial Magnetism at the Carnegie Institution of Washington (CIW) installed eight Sacks-Evertson dilatometers in south-west Iceland (Table 1). Funding for the purchase and installation of these instruments was provided by CIW, with operational responsibility given to IMO. At each site, a volumetric strainmeter was grouted into place in a bedrock borehole at depths ranging 58–401 m (Table 1). To minimise the start-up cost of the network, disused boreholes were chosen to host the instruments; however, owing to varying borehole diameters, CIW had to make each strainmeter to individual specifications. Remarkably, the functionality of the network is good: six of the eight original sites are active today (Table 1).

Until September 1986, continuous readings from the network were saved as analogue tracings on paper drums at each station. Subsequently, measurements were telemetered via radio to IMO in Reykjavík, where the data were stored on magnetic reels. Since June 1991, data have been archived at IMO on hard-disk drives and compact discs. The conversion to digital telemetry afforded a continuous, 20-bit data-stream from the strainmeter network.

In the present configuration, analogue measurements from each strainmeter are over-sampled continuously at a rate of 109 Hz. Data from each strainmeter are transmitted via radio frequency at a baud-rate of 4,800 to a central repeater on a mountain range on the outskirts of Reykjavík; here, the digital signal is filtered at 50 Hz and then multiplexed into a single stream. From the repeater station, the data are beamed directly to IMO at a baud-rate of 19,200. The signal is then de-multiplexed and time synchronisation is provided by a GPS clock. The raw, 50 Hz data are held at IMO for 30 hours in a 1.1 GB ring-buffer, from which 1 Hz samples are archived from a single binary file. These data are stored in compressed ASCII format as hourly files in a directory for the current day. The same directory also contains auxiliary measurements of battery voltage at each location and, at some sites, precise measurements of borehole temperature. To date, over 45 GB of 1 Hz data have been collected.

The network was established to register crustal deformation before and during strong earthquakes in south-west Iceland, but it is also possible to observe strain changes during eruptions of Mount Hekla. Positioned ~15 km from the volcano's summit, BUR is the closest strainmeter to Hekla. Strain pulses registered at BUR tens of minutes before the 1991 and 2000 eruptions of Hekla enabled public warnings to be issued before each eruption began. Four Hekla eruptions have occurred since 1970 – each separated by a repose interval of ~10 years. With the increasing likelihood of another Hekla eruption, and the strainmeter network entering its thirtieth year of operation, the goal of this presentation is to document the present state of the network, and to outline how its measurement capabilities can be improved.

Station	*Latitude*	*Longitude*	*Depth*	*Active?*
BUR	*64.11 N*	*19.80 W*	*181 m*	*Yes*
GEL	*64.32 N*	*19.29 W*	*233 m*	*Yes*
HEL	*63.84 N*	*20.40 W*	*393 m*	*Yes*
JAD	*64.30 N*	*20.15 W*	*58 m*	*No*
RIF	*63.96 N*	*21.27 W*	*292 m*	*No*
SAU	*63.99 N*	*20.43 W*	*180 m*	*Yes*
SKA	*64.21 N*	*20.53 W*	*125 m*	*Yes*
STO	*63.75 N*	*20.21 W*	*401 m*	*Yes*

Table 1: Active strainmeters in the Icelandic network: September 2009. Although SAU and SKA are listed as active, both stations are considered unserviceable. Geographic co-ordinates are in decimal degrees relative to the WGS 84 ellipsoid. Depth measurements are referenced to the top of the borehole casing.

GEOTHERMAL SEISMIC NOISE AT ÖLKELDUHÁLS

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Abstract

Seismic noise is often observed around and associated with geothermal fields, e.g. in North America (e.g Oppenheimer and Iyer, 1980) and Iceland (Brandsdóttir *et al.,* 1994). The noise is found within a narrow frequency band centered close to 5 Hz. A possible mechanism for this harmonic tremor is hydrothermal boiling in groundwater flow channels (Leet, 1988).

Ten portable seismographs from the Loki instrument pool were deployed along a profile across Ölkelduháls geothermal area (near Hengill, SW Iceland) in summer 2008 in order to characterize harmonic tremor associated with the field. This was done by monitoring the distance decay of seismic noise away from the field. The instruments are Lennartz 3c, 5 s sensors and Rektek 130 recorders. They were first deployed along a line to the NE from Ölkelduháls with a spacing of about 300 m (Figure 1). Data were collected continuously at 100 Hz for two days. They were then moved to the SW of the geothermal field and deployed with a spacing of about 150 m, again for two days.

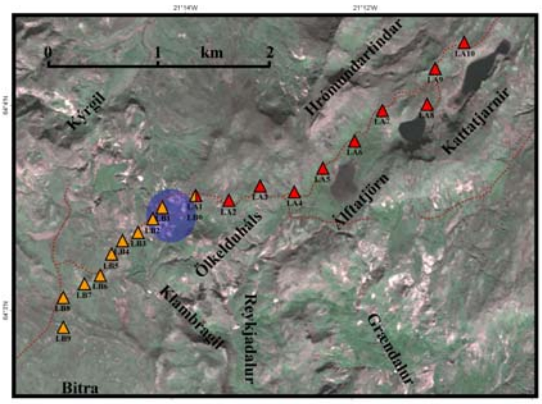

Figure 1. Layout of the experiment. 10 instruments were used, first deployed at 300 m spacing to the NE of the geothermal field (blue), then at 150 m spacing to the SW.

Amplitude spectra were computed for one-hour intervals in order to monitor temporal changes that could be associated with cultural or weather induced noise. The component of the spectra which was stable in time and clearly decayed away from the geothermal field was associated with the field.

The amplitude spectra are extremely stable in time in the frequency range between 4 and 6 Hz. The shape of the spectra in this range is reasonably consistent from one site to the next and their amplitude decays away from the geothermal field at Ölkelduháls (Figure 2). The decay of the spectra with distance away from Ölkelduháls clearly associates the noise with the geothermal field.

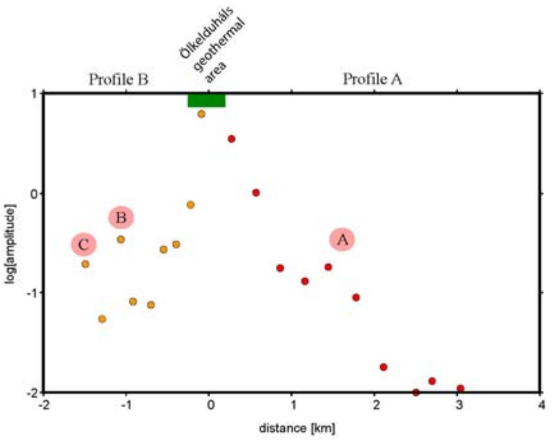

Figure 2. Spectral amplitude in the range 4-6 Hz as a function of distance away from the geothermal field at Ölkelduháls.

Irregularities in the amplitude decay with distance can be explained in part with other geothermal activity in the area, particularly to the NE. A local peak in the amplitude at 1.5 km (A, Fig.2) is about 500 m away from geothermal activity on the NW slopes of Hrómundartindar. Geothermal activity is also found just west of the SW end of the profile.

Array studies of geothermal noise at Norris Geysers, USA, indicate that the noise there is composed of surface waves with a shallow source (< 100 m) (Oppenheimer and Iyer, 1980). If this holds in general it will be difficult to use geothermal seismic noise as an exploration tool. However, we are able to detect the geothermal noise over many decades in amplitude with a cheap measurement. Weak signals from depth may therefore be detectable.

Assuming a surface wave origin of the geothermal noise the inferred elastic quality factor for the top 50 m of the crust is Q = 10.

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AMBIENT SEISMIC NOISE CORRELATION IN TWO DIMENSIONS

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Abstract

Ambient Seismic Noise Tomography (ASNT) has become a popular analysis method to study earth structure in recent years. The method is based on correlation analyses of ambient seismic noise measured at two seismographs (Shapiro *et al*., 2005). The correlation enhances from the stochastic noise those components which travel in line with the two stations. The correlogram can be used as a deterministic seismogram and measures of seismic velocity drawn from it.

The method was recently applied by Gudmundsson *et al.* (2007) to data from the HotSpot experiment to study crustal structure in Iceland. The results prove the methods potential as they show a strong correlation with surface geology. However, the full potential is not exploited since more data can be incorporated, e.g. from the SIL network. The results are presented below as group velocity maps at three periods sensitive to the upper and middle crust in Iceland.

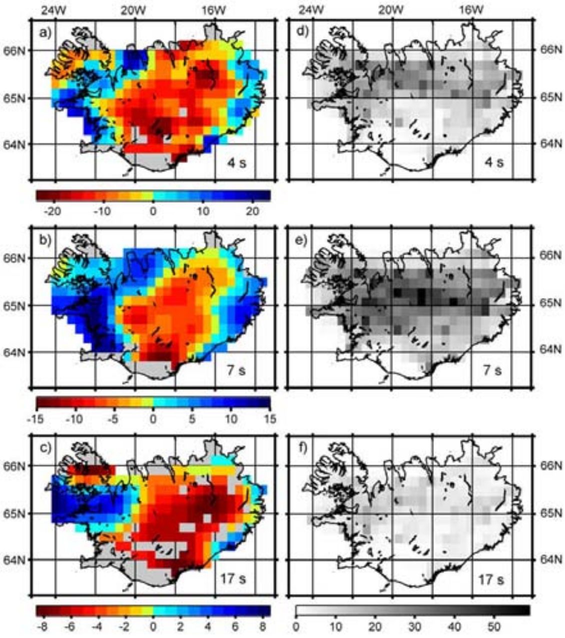

Figure 1. (a)–(c) Group velocity maps (percentile variation from reference velocity) and (d)–(f) maps of hitcounts for the three frequency bands used.

In ASNT it is usually assumed that the derivative of the cross-correlation function between simultaneous noise records at two stations provides an estimate of the Green's function between the stations. This result (Roux *et al.*, 2005) is based on a body-wave approximation and assumes a wavefield, which is fully diffuse, i.e. isotropic, in all three dimensions. However, seismic noise is usually dominated by surface waves that are two-dimensional phenomena and do not propagate equally in all three dimensions. The correlation of randomly orientated surface-waves does concentrate energy from the in-line direction between seismographs, producing a function which resembles the Green's function, but deviates significantly from it, even for a completely homogeneous Earth.

This function can be derived by considering an even distribution of impulsive surface-wave sources on a two-dimensional surface, or parts of it, randomly distributed in time. If the outer radius of the source region exceeds several times the intra-station distance the response rapidly approaches that for an even influx of surface waves from infinity. This response can be derived from simple energy flux arguments and is:

$$C(t) = \frac{\varepsilon v}{2\pi} \cdot \frac{1}{\sqrt{a^2 - v^2 t^2}}$$

where *C(t)* stands for the correlation, t for time, v for velocity and a for the intra-station distance. ε stands for the even energy flux.

The band-passed undifferentiated (or differentiated) correlation has a frequency dependent peak at a lag which systematically deviates from that of the corresponding Green's function, and thus introduces a bias to phase determination. This bias is proportional to period. The broadband noise correlogram is singular at the time corresponding to direct intra-station propagation and is therefore better suited for estimation of phase or group time than its derivative. This singularity renders the correlogram relatively insensitive to concentrations of sources that are not in line with the station pair being used. While the phase velocity estimated from the peak of the correlation function is always biased the estimated group velocity is not, in those idealised cases we have examined. This follows analytically from the fact that the phase bias is proportional to period.

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MAPPING OF HOLOCENE SURFACE RUPTURES IN THE SOUTH ICELAND SEISMIC ZONE

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Abstract

The South Iceland Seismic Zone is a transform zone marking the southern boundary of the Hreppar microplate. It is the source area of some of the most destructive earthquakes in Iceland's history. The surface formations of the zone are ground moraines, alluvial planes and Postglacial lava flows, and show widespread evidence of Holocene faulting. The fractured area is 15 km wide and 70 km long. A project to map by GPS-instruments all recognisable Holocene fault structures in this zone is described here. A large majority of all fractures strike NNE to NE and form left-stepping, en echelon fracture arrays with a northerly trend. They are associated with right-lateral faulting at depth. Right-stepping arrays also exist, apparently associated with faulting on conjugate faults with ENE strike, but they are an order of magnitude les frequent and mostly of secondary nature. Other fault trends also occur, but are rare. Push-up structures are prominent in association with the en echelon arrays, sometimes reaching heights of several meters. Fractures active during a few of the large, historical earthquakes in this region have been identified and traced, e.g. the 1630, 1784, 1896, and 1912 events. The fractures are found within narrow, N-S trending zones crossing the seismic zone. Thus the large scale, left- lateral transform motion across the plate boundary is accommodated by right-lateral slip on a series of transverse faults arranged side by side within the zone and by slight rotation of the blocks between them, a process sometimes called "bookshelf tectonism". Fractures formed during the earthquakes of June 17 and 21 (M_ω=6.5) in 2000 and May 29 in 2008 (M_ω=6.3) follow this pattern and confirm this general model of faulting along the transform zone. The size of push-up structures gives a clear indication of relative sizes of the earthquakes. The push-ups formed in 1630 and 1912 are an order of magnitude larger than the ones formed in the 2000 and 2008 earthquakes.

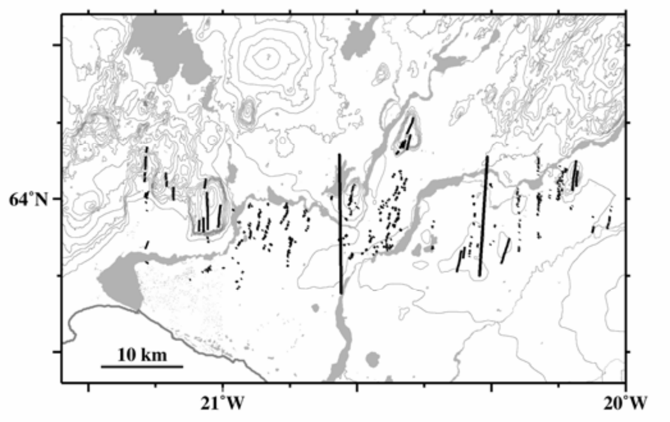

Figure 1. Surface fractures in the SISZ, active before 2000, shown with thin lines. Large thick lines show the source faults of the 2000 earthquakes.

Acknowledgements

Numerous persons have contributed to the mapping efforts reported here, to name a few: Jón Eiríksson, Kristinn Albertsson, Páll Imsland, Amy Clifton, Maryam Khodayar, Steingrímur Þorbjarnarson, Mathilde Böttger Sörensen, Ásta Rut Hjartardóttir, Benedikt Ófeigsson, Bergur Einarsson, Kristín Jónsdóttir, Vala Hjörleifsdóttir, Sigurjón Jónsson, Daði Þorbjörnsson.

RADON MONITORING IN THE SOUTH ICELAND SEISMIC ZONE

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Abstract

Studies of radon concentration in water from geothermal wells were initiated in the South Iceland Seismic Zone in 1977 (Hauksson and Goddard, 1981) spurred by strong indications that radon changes occurred prior to earthquakes. After 18 years of monitoring radon using a labour intensive method (Lucas cell) on discrete samples, a greatly improved method, using a liquid scintillation (LS) detector, was developed in 1999, where 200 ml water samples were sent twice a week to our laboratory for radon measurement in a simple automatic sample changer (Guðjónsson and Theodórsson, 2000). In order to get a continuous radon record and reduce working time a new system was developed for continuous measurement of radon in geothermal pumping stations. These projects have provided evidence for a relationship between earthquakes and radon excursions (Einarsson *et al.*, 2007).

The 1977-1993 time series revealed many earthquake-related radon anomalies, both positive and negative (Jónsson and Einarsson, 1996). They occurred mostly prior to the seismic events. Significant earthquakes were selected according to the criteria $M \geq 2.4 \log D - 0.43$ and $M \geq 2$ where M is the magnitude and D is the distance to a radon monitoring station. Thus 98 independent seismic events were selected. They were in the magnitude range 2 - 5.8. The main results were:

1. Radon anomalies were observed before 30 of the significant events.

2. 35% of all observed anomalies were related to seismicity.

3. 80% of the anomalies observed before earthquakes were positive.

4. If a positive anomaly is detected at one station, the probability of a significant earthquake occurring afterwards is 38%.

5. Some sampling sites were found to be more sensitive than others. The sensitivity appears to depend on local geological conditions.

6. A few radon anomalies appeared to be related to eruptive activity of the neighbouring Hekla volcano.

A new radon program was initiated in 1999 using a new instrument based on a novel liquid scintillation technique. Sampling from geothermal wells in the South Iceland Seismic Zone began a year before the two destructive earthquakes of June 2000 (M_{ω} 6.5) occurred. Water samples were taken about twice a week. The June 2000 earthquakes originated in the middle of the sampling network. Large variations in radon were observed that were correlated over the whole seismically active zone and were apparently related to the seismic events (Einarsson *et al.*, 2008). The following features can be verified:

1. Pre-seismic decrease of radon. Anomalously low values were measured in the period 101-167 days before the earthquakes.

2. Pre-seismic increase. Spikes appear in the time series 40-144 days prior to the earthquakes.

3. Co-seismic step. The radon values decreased at the time of the first earthquake. This is most likely related to the co-seismic change in ground water pressure observed over the whole area.

4. Post-seismic return to pre-seismic levels about 3 months after the earthquakes, probably also linked with the pressure change in the geothermal systems.

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IMPROVED RADON MONITORING NETWORK FOR EARTHQUAKE PRECURSOR STUDIES IN SEISMIC AREAS

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Abstract

Instruments for automatic detection and monitoring of radon have been under development for over a decade at the Science Institute, University of Iceland. The test area for the instruments has been the South Iceland Seismic Zone, where earlier radon programs had demonstrated radon anomalies in association with earthquakes (e.g. Hauksson, 1981, Jónsson and Einarsson, 1996). The new instruments are based on liquid scintillation counting by a photomultiplier tube (Theodórsson and Gudjonsson, 2003). In an early monitoring system 200 ml water samples from deep geothermal boreholes were sent to the lab twice a week for analysis. This program was run in 1999-2006 and demonstrated systematic variations in radon at six sites before, during and after the magnitude 6.5 earthquakes in June 2000 (Einarsson *et al.*, 2008). A new generation of automatic radon monitors has been designed and tested. Water from the boreholes is conducted through a silicon tube spiral at a rate of 30 ml/min. The spiral is located in a compartment where the radon atoms diffuse through the tube wall and are absorbed in a 15 ml scintillator in a vial. The vial is located above a vertical photomultiplier tube. A microprocessor electronic unit amplifies the pulses from the photomultiplier and sorts them in 4 counting windows according to size. The results are stored in an external USB memory or sent by a mobile phone every 24 hours to a central computer. Very high radon sensitivity is obtained by recording ^{214}Po separately, after pulse time series analysis. 99% of ^{214}Po alpha pulses (half-life 0.16 ms) come within 1.0 ms after the pulse of its mother nuclide, ^{214}Pb. This procedure reduces the background to about 1 pulse per hour. The new instruments will be set up at the six monitoring sites in the SISZ within the next year.

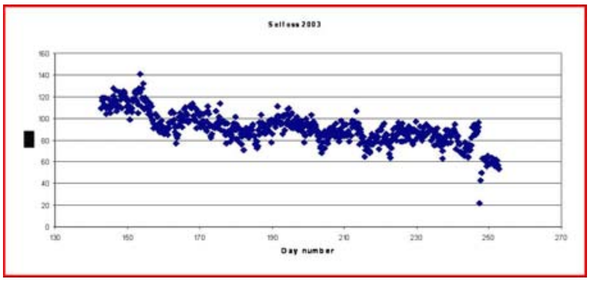

Figure 1: Time series of radon measured at a prototype station in Selfoss.

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MICROEARTHQUAKES, STRESSES, CRUSTAL STABILITY, AND EARTHQUAKE WARNINGS

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Abstract

A new seismic network in Iceland was presented in the Blue Book in 1986. One of the main aims was to create a seismic network allowing analysis of very small micro-earthquakes. The results of the micro-earthquake analysis at the FOA network in Sweden 1979-1982 had shown that each earthquake give the same amount of information independent of size, at least in the magnitude range -1 to 5. The number of micro-earthquakes (giving crustal information) increases with a factor of 8 if the magnitude threshold is reduced one unit.

Sigurdur Th. Rögnvaldsson, to which this seminar is dedicated, was early to realize the power of micro-earthquake analysis and his excellent work was much too early interrupted. From the beginning the automatic micro-earthquake analysis that was implemented into the SIL network included location, extraction of signal parameters, estimation of source parameters including seismic moment and fault radius, and fault plane solutions. It turned out that statistical methods including foreshock activity rate worked rather well as earthquake warnings before the larger Hengill earthquakes 1997 and 1998. However, the June 17 2000 EQ was not proceeded by high foreshock activity. This indicated that a more physical approach was motivated.

The early paper by McKenzie (1969) stated that micro-earthquake source mechanisms could only put weak constraints on the stress tensor causing the slip. That conclusion is true only if the volume around the EQ contains just one fracture.

All micro-earthquake analysis (both FPS and high accuracy locations) show that the crust is very fractured. If McKenzie's conclusion is wrong it is possible to rely on Coulombs criterion instead of the weaker Bott's criterion when estimating crustal stresses. By relating the water pressure to the stress tensor it turned out that the absolute in situ stress tensor causing a micro-earthquake could be estimated. The results of such stress estimates has been shown in a number of presentations here in Iceland and in different European scientific meetings. The results show that the place of the June 17 2000 EQ was seen in the stress mapping years before and the later studies (the SAFER project) show that there were clear indications during the last weeks and days before the EQ.

In conclusion the extremely promising results of the estimation of the absolute crustal stress tensor field by use of micro-earthquakes show how correct the early ideas of the Blue Book were, earthquake warnings require in situ information and micro-earthquake analysis is the key. It would have been nice to discuss these matters with Sigurdur.

FROM EARTHQUAKE PREDICTION RESEARCH TO USEFUL WARNINGS AHEAD OF EARTHQUAKES

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Abstract

Since 1988, the south Iceland seismic zone (SISZ) has been a significant multinational test area for earthquake prediction research. A scientific approach was taken to concentrate on studying the physics of processes leading to large earthquakes; this has yielded results showing that there is an observable crustal process on individual faults tens of years ahead of large earthquakes. Studying these ongoing processes makes it possible to establish, via real-time monitoring and ongoing modelling, a basis on which to extrapolate the processes into the future. This means that, in many cases, methods of prediction will be learnt from ongoing processes at each place, rather than identifying precursors common to all large earthquakes. This will help us to overcome the problem that no earthquake is the same, especially when considering micro-scale pre-earthquake processes. The processes that we have studied in the SISZ and the earthquake cycle that we have described illustrate that the approach to practical warnings has to be gradual; i.e. from finding places of preparatory activity, hopefully years before the earthquake occurs, and towards studying and modelling the dynamic processes using multidisciplinary observations.

The micro-earthquake technology that has been applied to the SISZ test area is the basis of this approach as well as the new multidisciplinary model, the 'F–S' model, which explains that near-lithostatic pore-fluid pressures can effectively migrate along lanes from below up into the seismogenic crust of the SISZ in response to strain to modify fracturing conditions there, on both long and a short time scales.

According to experience and theory all large earthquakes in Iceland can be expected to have an observable pre-process. By use of historical evidence, sensitive geophysical observations, evaluations of inter-seismic and likely pre-seismic processes, and real-time modelling, it is probable that all large earthquakes can be predicted to a significant degree. The request made 20 years earlier, in designing the SIL system, was to record and evaluate in real-time all earthquakes down to magnitude zero. Experience shows that, especially in the short-term, significantly more information is gained from even smaller earthquakes at seismogenic depths in a volume close to the target fault.

Recent progress in earthquake prediction research shows us that a scientifically well-organized watching system is required, which can cope with the gradual approach to prediction. The development of such a system, which analyses in real-time all relevant observations, has started to some extent but the work must be accelerated during the coming years. The build-up of such a system is a large undertaking, comparable to the development of the SIL system in Iceland. Such a system is a necessary condition for being able to make use of all the pre-earthquake processes already found for providing useful warnings ahead of earthquakes.

DEVELOPMENT HISTORY AND FUTURE POTENTIAL OF THE SIL SYSTEM

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Abstract

The European Council recommended in 1979 a concentrated effort on earthquake risk mitigation and earthquake prediction in five test areas in Europe. One of the suggested areas was the South Iceland Lowland (SIL). In the early eighties, Ragnar Stefánsson initiated discussions among Nordic seismologists regarding Nordic cooperation towards earthquake prediction in the form of a joint research project between the Nordic countries using the SIL test area. In April 1986, a three-day workshop was organized in Oslo where some specifications and the first draft of the network design was done (The Blue Book). In 1987, funds were made available to the project from the Nordic Minister Council, the Icelandic Government and the research councils of the Nordic countries and 1989, 20 years ago, the first SIL station was installed and two years later, the whole network of 8 stations was in operation in a fully automatic manner. Since then, the number of stations has increased to 55 and the number of earthquakes recorded and analysed are more than 300,000.

The request stated in the Blue Book was a design of a real-time seismological network with extremely high sensitivity that would record all seismic events down to magnitude zero within the network. The technical requirements were high dynamic range (> 130dB), high sampling frequency (>=100 s/s) and high timing accuracy (< 1 ms) with reasonable low investment and operational cost. This was not an easy task with the technology (digitizers, computers and data communication) available at that time.

In 1988 Sigurður Th. Rögnvaldsson started his PhD studies in Uppsala and most of his research was related to the seismological methods used in the SIL system which were to a large extent based on earlier work by Ragnar Slunga. The success of the SIL system is to large extent thanks to the work of Sigurður and the scientific descriptions of the methods are mainly found in his PhD theses and other scientific papers he has published. The unique features of the SIL system are the high detectability, ability to handle large amount of earthquakes in real-time, the automatic estimations of fault plane solutions using the spectral amplitude and first motion direction for all earthquakes and the relative location methods allowing for mapping of active sub-surface faults. Many of the innovative methods implemented in the SIL system in its early development stage were first recognized ten to fifteen years later by the international seismological community but are now to a larger extent also implemented in other seismological networks in the world. The SIL system technology is used in the Swedish National Seismic Network which consists of more than 60 stations.

Although the SIL system is performing very well at the present, there is a large potential for further development. The technical development during the last twenty years allows for further development of methods for extracting geophysical information from the crust (through small earthquakes) in real time. Some of these methods can make use of the new achievement in communication technology, which allows for real-time streams of time-stamped digital data from almost anywhere using cellular phones. Another, not less important technical achievement is the improvement of the computer capacity available. This opens for more massive analysis of data streams in real time and thus opens for the automatic event detection and location to perform better. Use of correlation techniques of the continuous data stream and continuous spatial mapping are two examples of methods that can implemented thanks to the technical developments.

This will decrease the amount of labour needed for the routine interactive analysis but increase the quality of the overall analysis. The seismologists can focus more on the geophysics reflected by the seismic activity in real time.

ANATOMY OF MELT INTRUSION AT 15–18 KM DEPTH BENEATH UPPTYPPINGAR, ICELAND

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Abstract

An extended sequence of micro-earthquakes at 14–22 km depth near Upptyppingar in the northern volcanic rift zone of Iceland has been attributed to the injection of melt into the crust (Jakobsdóttir *et al.*, 2008). The main sequence lasted more than 2 years, starting in February 2007 and extended over an area of ~50 km^2. A reduced level of activity continues to the present day. We use data from a detailed array of 26 seismometers deployed around Upptyppingar to investigate one of the most intense periods of seismic activity during July–August 2007.

Upptyppingar is located within the NW edge of the fissure swarm that occupies part of the Kverkfjoll volcanic system. The crustal thickness is ~30 km, (Darbyshire *et al.*, 2000), with the thick crust caused by the underlying Iceland mantle plume. The deep earthquakes occur in the normally ductile and aseismic region of the crust in response to locally high strain rates created by melt injection.

We deployed and operated a network of twenty broadband (0.03–50 Hz) Güralp 3-component CMG-6TD seismometers, supplemented by six Icelandic SIL network 3-component Lennartz LE5 seismometers (0.2–40 Hz). The Continuous Microseismic Mapping algorithm (Drew, 2009) was used to search in time and space using a signal onset function for event detection and initial location. A linear velocity-gradient crustal model was derived from seismic profiles within the Askja region and RRISP results (Angenheister *et al.*, 1980; B. Brandsdóttir, pers. comm.) supplemented by surface wave analysis of noise recorded across the seismometer array (Drew, 2009).

Over 2,000 events were detected between 6 July – 22 August 2007. The largest was a *M*L 2.2 earthquake on 21 July, at a depth of 15.5 km. The fault plane solution of the largest earthquake shows a thrust event on an east-west plane which is dipping southward at 55°. This is the same as the orientation of the dyke inferred from the hypocentres over a much longer period, and over a bigger depth range than our snapshot in July–August 2007. Numerous other fault plane solutions show the same thrust orientation on this southward dipping plane. We interpret these as due to melt injection into chilled lavas of the dyke. Swarms of such events typically occurred over a period of a few hours.

Abundant shallow seismicity in the top 7 km of the crust occurs where the crust is sufficiently cold to fail by brittle fracture under extension. It exhibits normal tectonic faulting caused by extension in the rift. T-axes of the fault plane solutions from the shallow seismicity align closely with the spreading direction of 106°. There is a distinct gap in the depth of seismicity between this upper brittle failure and the deep crustal events. Micro-seismicity in the lower crust which is normally ductile is attributed to locally high strain rates caused by melt injection.

Detailed micro-earthquake locations together with fault plane solutions constrained by both polarities and amplitudes show that the fracture is dominantly by double-couple mechanisms and is remarkably consistent between events. The melt injection occurred in dense swarms, and we were able to track the melt from individual injection events as it moved upwards and laterally through the dyke.

The deep seismicity in the Upptyppingar region coincides in time with similarly deep seismicity in the adjacent Askja rift system, for which a similar origin of melt injection into the normally ductile lower crust has been postulated (Soosalu *et al.*, 2009). It is possible that the enhanced seismic and melt movement activity in the two regions is related.

Acknowledgements

Seismometers from the NERC SEIS-UK facility were used for fieldwork. The rangers in the mountain huts of the Askja-Herðubreið nature reserve, and the Akureyri branch of the Icelandic Touring Association are thanked for their help in many practical matters.

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RELOCATED MICROEARTHQUAKES USED FOR MAPPING ACTIVE FAULTS AT DEPTH IN ICELAND

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Abstract

We have used seismological data, recorded by the SIL-network, to map fault patterns at depth in several different regions in Iceland. By using a double-difference relative relocation method (Slunga *et al.*, 2005) it is possible to reduce relative location error between events such that fault patterns may become resolvable. Slip direction on the fault planes can be estimated trough the joint interpretation of the event distribution and mechanisms (Rögnvaldsson and Slunga, 1993). It is also possible to estimate mechanisms of large earthquakes by slip distribution of aftershocks near the hypocentre. During the first years following the development of the software, the method was used to map faults in the Tjörnes fracture zone (TFZ) (Rögnvaldsson *et al.*, 1998), the Hengill area (Rögnvaldsson *et al.*, 1999) and in the South Iceland seismic zone (SISZ). After significant reconstruction of the software during 1999-2002, the first large mapping project was carried out on the seismic activity in the Hengill region during the uplift period between 1994 and 1998 which illuminated many fault planes in the area. The fault mapping was based on relocated events occurring between 1997 and 1998 (Vogfjörd *et al.*, 2005). The results show rather large N-S faults in the southern part, on Hellisheiði, which are cut through by more westerly trending faults, striking ~70°. In the northern part the faults tend to lign up along the surface fractures mapped in the area, although other strikes are also observed.

The next major project involved the seismicity following the two M_L~6.5 June 2000 earthquakes in the SISZ. The two large earthquakes induced over 16 thousand events in all Southwest Iceland during the next six following months. The mapping has not only revealed the details of the two large fault planes, but also many smaller fault segments in the SISZ, the western volcanic zone and on the Reykjanes Peninsula (Hjaltadottir *et al.*, 2005).

The aftershocks of the 2008 M_L6.3 earthquake in the Ölfus district (SISZ) were used to map the two fault planes of the earthquake, spaced 4 km apart. The mapping shows for example the left stepping en echelon structure of the larger fault plane, the Kross fault.

Further fault mapping based on several years of data has also been carried in selected areas on the Reykjanes peninsula (RP) and in the western volcanic zone (WVZ). Mapping of sub-surface faults near to Fagradalsfjall on the RP (Hjaltadóttir and Vogfjörð, 2006) has shown, similar to the SISZ, many N-S trending fault segments, but also faults trending SW-NE and SSW-ENE. Similar mapping in the vicinity of Prestahnúkur in the WVZ (Hjaltadóttir and Vogfjörð, 2009) shows that the event distribution forms a lineament which trends SW-NE, and that most of the faults segments strike SW-NE too.

The most recent fault mapping was carried out within a selected area on the Húsavík-Flatey fault in the TFZ where the whole SIL-catalogue was used. The comparison of relocated events with small relative location error and bathymetric data (Brandsdóttir *et al.*, 2005) shows clusters of events correlating with faults on the seafloor. Specifically, the seismicity shows clearly a N-S striking fault cutting through the largest lineament in the seafloor where it is offset by roughly half a kilometre.

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A DEEP-SEATED MAGMATIC INTRUSION AT UPPTYPPINGAR, ICELAND, DURING 2007 AND 2008

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Abstract

In February 2007 an episode of earthquake activity started in a previously seismically inactive area north of the Vatnajökull ice cap. The activity is known as the 'Upptyppingar – Álftadalsdyngja activity' after the land features where the activity is occurring. The intense seismic swarms and associated crustal deformation are remarkable in many ways. The earthquakes have deeper sources (14–22 km) than normally observed in Iceland, and the seismic activity has a distinct spatial pattern with time, moving between areas and progressing to shallower depths. More than 9,000 earthquakes were located in the area from February 2007 to April 2008. The swarms comprise brittle-type earthquakes less than 2 in magnitude. The largest earthquakes, of local magnitudes M_l 2.2–2.3, occurred in July 2007 and March 2008. The *b*-value varied with time, being highest ~2.4 in late July to early August 2007, but it remained high during the whole period (Jakobsdóttir *et al.*, 2008; Anaïs Boué and others, to be submitted*)*.

Three continuous GPS (CGPS) sites have been operating 20–25 km west and south of the area since 2005. In early summer 2007 a dramatic change in horizontal velocities equivalent to 30 mm/yr towards S or SSE was observed. In May 2008 the CGPS sites resumed their original velocities. These are the largest velocity changes observed in the CGPS network in Iceland since its initiation in 1999.

The seismic activity was most intense from April 2007 to April 2008. No effusive activity was observed during the unrest. Previous episodes of deep-seated earthquake activity in Iceland have been linked with magma unrest, for example at Mt. Eyjafjallajökull, Vestmannaeyjar islands, and Askja volcano. The seismicity and deformation near Upptyppingar - Álftadalsdyngja are interpreted to be the result of the intrusion of a ~0.05 km^3 sheet of magma into the lower parts of the crust at 22–12 km depth (Jakobsdóttir *et al.*, 2008).

After the 'Upptyppingar – Álftadalsdyngja activity' stopped, persistent seismic activity started north of Upptyppingar and south of Hlaupfell. This activity occurred at a depth ~5–8 km and is still ongoing. In July 2009 a swarm was recorded farther north, at depths less than 5 km. This swarm lasted for about two weeks. The *b*-value for these swarms is ~1. No land deformation has been detected by the GPS-network during with this activity.

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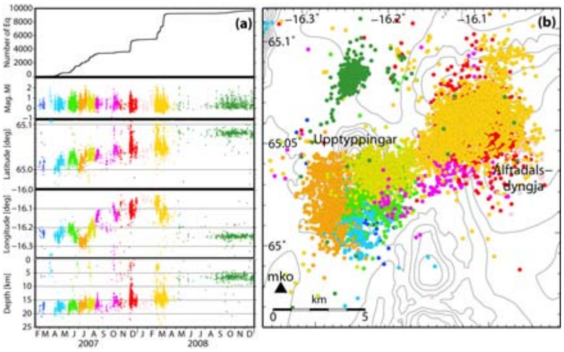

Figure 1: Spatial and temporal view of seismicity at Upptyppingar and Álftadalsdyngja using all available hypocenters from manual single-event locations. (a) Cumulative number of earthquakes, earthquake size (M_l) and temporal changes in latitude, longitude, and focal depth. (b) Map view of the earthquake distribution (colours represent the same events as shown in (a)). The seismic station mko is to the south-west of Upptyppingar.

TRIGGERING MECHANISMS OF THE WEST BOHEMIA / VOGTLAND EARTHQUAKE SWARMS

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The distribution of West-Bohemia/Vogtland seismicity is strongly clustered both in time and space. The time occurrence is manifested in a variety of forms including both swarms with fast and with slow energy release that last from hours to months and also solitary events. The lateral distribution of seismicity is limited to a small number of focal zones, which have been periodically reactivated during the past 19 years of instrumental observations. The most active is the zone of Nový Kostel, which dominates with 85% of energy release. The two largest recent swarms, the 2000 and 2008 swarms, took place in there (Fischer, 2003; Horálek *et al.*, 2009). The former lasted four months and consisted of more that 8000 M≤3.2 strike-slip micro-earthquakes, which were located along a steeply dipping fault plane at depths 6.5–10.5 km and showed a common rake angle of 30°. The latter swarm lasted less than two months and showed a faster energy release with thousands M≤3.8 events occurring on the same fault plane.

We analysed the statistics of the earthquake space-time distribution, both in the broader area and within individual swarms, at distances from hundreds meters up to tens kilometres and at intervals from fractions of second up to hours.

The analysis within the broader area (Horálek and Fischer, 2008) has revealed that the inter-event times of the seismic activity measured between earthquakes in separated focal zones show increased occurrence for time intervals below 8 hours. This fast switching of activity among focal zones with mutual distances above 10 km shows that the seismicity is correlated in a broader area and points to a common triggering force acting in the whole region of West-Bohemia/Vogtland. This force could be stress changes due to Earth tides, barometric pressure disturbances, or an abrupt change of the crustal fluid pore pressure. It would trigger the activity in the focal zones which are close to failure. Depending on the local stress and mechanical conditions in each zone, the activity could either cease or an earthquake swarm could be initiated. We also investigated the space-time relations between consecutive earthquakes of the 2000 swarm (Fischer and Horálek, 2005). It was found that the relative positions of consecutive event pairs showed maximum occurrence in the slip-parallel directions. Comparison with the complete Coulomb stress change upon the fault plane generated by a shear rupture showed that the observed elongation of the space-time distribution of the relative positions can be explained by a common effect of both static and dynamic stress changes, which act on different distance and timescale. The 2000 swarm included a number of multiple-events generated by multiple episodes of rupturing. Their analysis (Fischer, 2005) showed that the relative distance of the ruptured asperities reach 100 ms in time and 320 m in space; the later ruptures occur near the edge of the previous rupture. Their angular distribution indicates that many of them result from slip-parallel rupture growth, which could be considered an immediate effect of dynamic triggering.

The presence of fast interactions during the swarm is in accordance with the results of our model of the 2000 swarm (Hainzl, 2004), which took into account both the fluid diffusion and stress triggering. The model consisted of a planar brittle patch divided into a number of cells with variable strength. The individual cells rupture when the Coulomb failure criterion including both shear stress and pore pressure is fulfilled. The pore pressure of diffused fluids brings the cell into a critical state. Then the earthquake activity is governed by the stress changes due to the co-seismic and post-seismic slip, so that mutual triggering between ruptured cells occurs.

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GEODETIC CONSTRAINTS ON THE EARTHQUAKE CYCLE IN THE SOUTH ICELAND SEISMIC ZONE

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Abstract

The South Iceland Seismic Zone (SISZ) is an E-W transform zone that accommodates the relative plate spreading of the North American and Eurasian plates across southwest Iceland. The left-lateral E-W shear at depth (below ~15 km) is accommodated in the brittle crust by many parallel N-S structures that rupture in moderate size (M_S 6-7) earthquakes. An ongoing earthquake sequence in the SISZ started with two Mw=6.5 earthquakes in the eastern and central part of the zone on June 17 and 21, 2000. Fault models based on geodetic (GPS and satellite radar interferograms (InSAR)) observations indicate that the main shocks ruptured two 10-15 km long N-S right-lateral strike slip faults, spaced about 17 km apart, with most of the slip occurring above 10 km depth (Pedersen *et al.*, 2003). The geodetic fault models were used to calculate the co-seismic Coulomb Failure stress changes, which indicated positive stress changes likely to promote failure on faults in the western and eastern parts of the SISZ (Árnadóttir *et al.*, 2003). This was indeed the case when the June 2000 earthquake sequence continued with two Mw6 earthquakes on May 29, 2008 in the western part of the SISZ. Again, the two main shocks ruptured near parallel N-S vertical right-lateral strike slip faults. This time, however, the sequence was intense as the events occurred within 3 s of each other with a fault spacing of less than 5 km (Hreinsdóttir *et al.*, 2009).

Several GPS surveys have been conducted in SW Iceland since the initial measurements in 1986. Prior to the June 2000 earthquakes a sparse network was observed in 1992 and two more extensive surveys were conducted in 1995 and 1999. Annual campaigns have been conducted in SW Iceland since 2000. Since 1999 a network of continuous GPS stations has been rapidly growing, with several stations located in the SISZ. This geodetic dataset therefore provides the most complete set of observations of co- and post-seismic deformation in Iceland, as well as a glimpse of the plate-spreading signal (Árnadóttir *et al.*, 2008, and references therein). The measurements also capture deformation due to the intense seismic activity and uplift observed in the Hengill area in 1994-1998.

The GPS velocities have been used to construct a kinematic model of the plate boundary in southwest Iceland. The model indicates left-lateral deep slip rates varying from 18 mm/yr on the Reykjanes Peninsula to 20 mm/yr along the SISZ, with the locking depth increasing from ~5 km in the western part of the Reykjanes Peninsula to ~15 km in the eastern SISZ.

The geodetic observations following the June 2000 earthquakes indicate post-seismic transient deformation occurring on at least two different time scales. A rapid transient observed by InSAR in the epicentral area during the first two months after the June 2000 main shocks has been explained by poro-elastic rebound. A slower transient signal is observed by GPS indicating afterslip (most pronounced in the first year) below the co-seismic rupture and/or visco-elastic relaxation of the lower crust and upper mantle in response to the co-seismic stress changes. The optimal visco-elastic models have a lower crustal viscosity of 0.5-1 x 10^{19} Pa s and upper mantle viscosity of about 3 x 10^{18} Pa s. The visco-elastic model, indicating a strong lower crust and a weaker upper mantle, better explains the vertical deformation obtained from time series analysis of InSAR data spanning 2000-2005 than an afterslip model.

The geodetic models for the 2000 and 2008 earthquakes indicate that these events have only released about half of the geometric moment accumulated by plate spreading across the SISZ since the last major earthquake in 1912. Assuming that all the strain induced by plate spreading is released seismically we therefore need to enhance our monitoring of the RP and the SISZ in preparation of continued earthquake activity in the near future.

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