Icelandic Met Office

47th Nordic Seismology Seminar

Reykjavík, Tuesday 11. - Thursday 13. October 2016

The 47th Nordic Seismology Seminar will be held in Reykjavík, Iceland, **11.-13. October 2016**. The meeting will commence on Tuesday 11. October in the early afternoon and will end in the evening of Thursday 13. October.

Traditionally, the seminar covers a wide range of topics related to seismological research done in the Nordic countries. These are:

- Detection seismology
- CTBT related studies
- Methodology in data analysis
- Hazard assessment and engineering seismology
- Structural studies of the crust and upper mantle
- Earthquakes, seismicity, volcanoes and tectonics
- Earthquake catalogues and operational aspects of monitoring

We look forward seeing you in Reykjavík!

On behalf of the Icelandic organizers,

Kristín Jónsdóttir, Martin Hensch and Ingibjörg E. Garðarsdóttir
Veðurstofa Íslands / Icelandic Meteorological Office

Fissure eruption in Holuhraun on 14. September 2014. Photo: Martin Hensch.

Icelandic Met Office

- ## Warning

  Storm (18-23 m/s) in expected in Iceland until noon.

  Valid to 21.10.2016 00:00

47th Nordic Seismology Seminar

Final program

Program

For detailed daily session program and abstracts please click on the respective day.

Poster presentations (during all three coffee breaks) (/norsem/norsem2016/program/poster)

Tuesday 11 October (http://en.vedur.is/media/vedurstofan/full/bustadavegur-7.jpg)

- **Arrival and check-in.** Most flights will arrive in the afternoon, so you should be at your hotel around 17:00/18:00.
- **19:00 Kickoff party at IMO (Bústaðavegur 7, 108 Reykjavík).** We will meet you at 18:30 outside Grand Hotel and walk together to IMO. Should anybody prefer to get a lift by car, please let us know. In case of bad weather, we will find a way to drive you all to IMO and back.

Wednesday 12 October (/norsem/norsem2016/program/wednesday)

- **08:30 - 17:10 Seminar at Grand Hotel Reykjavík.** Lunch / refreshments during coffee breaks.
- **17:30 - 19:30 EPOS meeting**
- 17:30 - 19:30 Those not attending EPOS can join us to **Laugardalslaug Geothermal swimming pool**, about 10 minutes walk from Grand Hotel. Entrance fee is around 500 ISK (depending on how many we are).
- **20:00 Conference dinner**

Thursday 13 October (/norsem/norsem2016/program/thursday)

- **08:30 - 12:10 Seminar at Grand Hotel Reykjavík**. Lunch / refreshments during coffee break.
- **13:45 - 19:00 Field trip to Reykjanes peninsula** ***(13:45 is the departure time!)***

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Session program Wednesday 12. October

Oral presentation are 20 minutes long, 15 minutes talk plus 5 minutes discussion.

08:30 – 10:00 Opening and oral session - Chair: Páll Einarsson

08:30 – 08:45 **Opening address**

Kristín S. Vogfjörð, Kristín Jónsdóttir, Martin Hensch

08:45 – 09:00 **Nordic collaboration and contribution**

to the European Plate Observing System - EPOS

Kristín Vogfjörð

09:00 – 09:20 (/media/norsem/norsem_gunnar.pdf) **Seismic activity in Iceland 2015-2016 and testing of**

near real time automatic relative locations

Gunnar B. Guðmundsson and the Natural Hazards monitoring team

09:20 – 09:40 **24/7 monitoring of natural hazards at the Icelandic Meteorological Office**

Kristín Jónsdóttir and the Natural Hazards monitoring team

09:40 – 10:00 (/media/norsem/norsem_giulia.pdf) **Infrasonic and Seismic Signatures of the 2014 Askja Landslide**

Giulia Barfucci, Maurizio Ripepe, Giorgio Lacanna, Emanuele Marchetti,

Kristín Jónsdóttir, Kristín S. Vogfjörð

10:00 – 10:30 Coffeebreak and poster session (http://en.vedur.is/norsem/norsem2016/program/poster/)

10:30 – 11:50 Oral session - Chair: Björn Lund

10:30 – 10:50 (/media/norsem/norsem_benni.pdf) **Calibration of a new ground motion model to earthquake strong-motion**

in South Iceland

Benedikt Halldórsson, Tim Sonnemann

10:50 – 11:10 (/media/norsem/norsem_sahar.pdf) **Soil structure impact on site effects and modeling spatial strong-motion**

variability across Icelandic strong-motion arrays

Sahar Rahpeyma, Benedikt Halldórsson

11:10 – 11:30 (/media/norsem/norsem_voss.pdf) **A review of the earthquake monitoring in the Kingdom of Danmark -**

challenges and future development

Peter H. Voss

11:30 – 11:50 (/media/norsem/norsem_harris.pdf) **The ISC data (and how to get it)**

James Harris, Dmitry Storchak

11:50 – 13:30 Lunch break

13:30 – 15:10 Oral session - Chair: Annakaisa Korja

13:30 – 13:50 (/media/norsem/norsem_lindholm.pdf) **Neotectonics in Nordland; NEONOR 2**

Conrad Lindholm et al.

13:50 – 14:10 (/media/norsem/norsem_michalek.pdf) **Seismicity of the Nordland area, Norway**
Jan Michalek, Lars Ottemoeller, Berit Marie Storheim, Marte Louise Strømme

14:10 – 14:30 (/media/norsem/norsem_janutyte.pdf) **Fault plane solutions of the earthquakes in Nordland, Norway**

Ilma Janutyte, Jan Michalek, Conrad Lindholm and Lars Ottemoller

14:30 – 14:50 (/media/norsem/norsem_lund.pdf) **The recent Bothnian Bay M4.1 earthquake: where, how and why?**

Björn Lund, M. Uski, H. Shomali, D. Buhcheva, S. Amini, J. Kortström

14:50 – 15:10 (/media/norsem/norsem_mantyniemi.pdf) **Macroseismology in Finland from the 1730s to the 2000s: From an obligation of the learned elite to citizen science**

Päivi Mäntyniemi

15:10 – 15:50 Coffeebreak and poster session (http://en.vedur.is/norsem/norsem2016/program/poster/)

15:50 – 17:10 Oral session - Chair: Kristín Jónsdóttir

15:50 – 16:10 **Monitoring hydrological changes in relation to earthquakes**

Helga Rakel Guðrúnardóttir

16:10 – 16:30 (/media/norsem/norsem_palli.pdf) **The Reykjanes Peninsula Oblique Rift, a zone of crustal extension and strike-slip faulting**

Páll Einarsson

16:30 – 16:50 (/media/norsem/norsem_atakan_ip.pdf) **European Plate Observing System Implementation Phase (EPOS-IP): Services for Solid Earth Science**

Kuvvet Atakan and the EPOS-consortium

16:50 – 17:10 (/media/norsem/norsem_atakan_norway.pdf) **European Plate Observing System - Norway (EPOS-N): Integrating the Norwegian Solid Earth Data**

Kuvvet Atakan and the EPOS-Norway consortium

17:30 - 19:30 EPOS meeting - Chair / Organisation: Kuvvet Atakan

alternative: Laugardalslaug Geothermal swimming pool for those not attending EPOS

20:00 Conference dinner at Grand Hotel Reykjavík

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Session program Thursday 13. October

Oral presentation are 20 minutes long, 15 minutes talk plus 5 minutes discussion.

08:30 – 10:10 Oral session - Chair: Martin Hensch

08:30 – 08:50 (/media/norsem/norsem_asdis.pdf) **Ambient noise tomography of Eyjafjallajökull**

Ásdís Benediktsdóttir, Ólafur Guðmundsson, Bryndís Brandsdóttir

08:50 – 09:10 (/media/norsem/norsem_bryndis.pdf) **Long-period earthquakes recorded on a dense seismic array during the 2014 Bárðarbunga rifting event**

Bryndís Brandsdóttir et al.

09:10 – 09:30 (/media/norsem/norsem_matthew.pdf) **Expanding hydrological monitoring capabilities using seismic tremor and infrasound**

Matthew J. Roberts et al.

09:30 – 09:50 **Tracking seismicity in Icelandic volcanoes**

Kristín Vogfjörð

09:50 – 10:10 (/media/norsem/norsem_ragnar.pdf) **From the Nordic SIL research project towards warnings on the long- and on the short-term before large earthquakes**

Ragnar Stefánsson

10:10 – 10:40 Coffeebreak and poster session (http://en.vedur.is/norsem/norsem2016/program/poster/)

10:40 – 12:10 Oral session - Chair: Peter H. Voss

10:40 – 11:00 (/media/norsem/norsem_dori.pdf) **High-rate GPS seismology in Iceland**

Halldór Geirsson et al.

11:00 – 11:20 (/media/norsem/norsem_slunga.pdf) **Rock stress boundaries deduced from rock stress measurements**

Ragnar Slunga

11:20 – 11:40 (/media/norsem/norsem_ingi.pdf) **In situ seismic velocity changes in Southern Iceland**

Ingi Þ. Bjarnason, W. Menke, E. Kjartansson, B.S. Þorbjarnardóttir, M. Hensch

11:40 – 12:00 (/media/norsem/norsem_martin.pdf) **Temporal stress changes associated with the 2008 May 29 Mw6 earthquake doublet in the western South Iceland Seismic Zone**

Martin Hensch, B. Lund, Th. Árnadóttir, B. Brandsdóttir

12:00 – 12:10 **Closing remarks**

Kristín S. Vogfjörð, Kristín Jónsdóttir, Martin Hensch

12:10 – 13:45 Lunch break

13:45 – 19:00 Fieldtrip to Reykjanes peninsula (http://en.vedur.is/norsem/norsem2016/field-trip/)

13:45 is the departure time outside Grand Hotel Reykjavík!

We need to start the trip on time to avoid ending in darkness.

We aim on being back to Reykjavík around 19:00, depending on weather conditions.

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Poster presentations

The preferred poster format is A0 portrait. However, we will be able to deal with landscape format as well, but it might exceed the poster board slightly.

A short (2 minutes) overview on each poster shall be given by the presenting authors in front of their poster during the first coffee break on Wednesday morning. We kindly ask all participants to attend the poster introduction and to use the remaining coffee breaks for detailed discussions of the posters.

Observations on Intraplate Seismicity in Central Fennoscandia (/media/norsem/norsem_korja.pdf)

Annakaisa Korja, Uski, M., Lund, B., Grigull, S., Nironen, M., E., Högdahl, K.

Relative earthquake location in Southern Iceland (/media/norsem/norsem_begga.pdf)

Bergþóra S. Þorbjarnardóttir and Ingi Þ. Bjarnason

This year's update on the Burträsk fault seismicity (/media/norsem/norsem_buhcheva.pdf)

Darina Buhcheva and Björn Lund

The SIL-system from an operational standpoint

Jón Söring

Communication between earthquake clusters seperated by tens of kilometers

Kristín Jónsdóttir, Kristján Jónasson, Magnús Tumi Guðmundsson, Martin Hensch and others

Macroseismic maps for two border crossing earthquakes in northern Europe (/media/norsem/norsem_mantyniemi_poster.pdf)

Päivi Mäntyniemi, Darina Buhcheva, Björn Lund and Mathilde Sørensen

Towards an automated event verifier (/media/norsem/norsem_schmidt.pdf)

Peter Schmidt, Reynir Bödvarsson, Z. Hossein Shomali and Björn Lund

Seismic analysis using the auditory sense – Playing the sounds of the Earth (/media/norsem/norsem_vuorinen.pdf)

Tommi Vuorinen

Monitoring Icelandic Volcanoes by modelling accelerated seismicity rates

Salóme Jórunn Bernharðsdóttir

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47th Nordic Seismology Seminar - Reykjanes peninsula

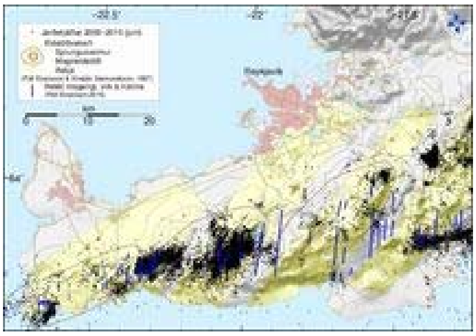
The trip will be guided by Páll Einarsson and Martin Hensch

We will depart at 13:45 from outside Grand Hotel Reykjavík and leave the capital area to the southwest. The drive will take us through the lava fields and mountains of Reykjanes peninsula. We will make several short and longer stops at various geologically interesting sites, such as hot springs and faults.

We will not take long hikes, however weather conditions and some short walks into the terrain require solid shoes and protective cloths. You should also bring something to drink and eat with you, but we will also stop at a gas station, where you can provide yourself with food etc. The whole trip will take around 5 hours.

Planned stops during the excursion:

- Lake Kleifarvatn and Seltún Geothermal Field
- Gunnuhver Steam Spring and fault systems in its surrounding
- Reykjanesviti at the tip of the peninsula, where the Mid-Atlantic Ridge comes onshore
- IDDP drilling site on Reykjanes



Ambient noise tomography of Eyjafjallajökull

Ásdís Benediktsdóttir[1,2], Ólafur Guðmundsson[3], Bryndís Brandsdóttir[4]

1 Nordic Volcanological Center, University of Iceland, Reykjavík Iceland
2 Department of Earth Sciences, University of Iceland
3 Department of Earth Sciences, Uppsala University, Uppsala Sweden
4 Institute of Earth Sciences, Science Institute, University of Iceland

We present the first tomographic model of Eyjafjallajökull volcano, south Iceland, using ambient noise tomography. The data were collected on a dense network of temporary and SIL seismometers prior to and during the 2010 eruption. Cross-correlations between stations enabled us to construct phase-velocity dispersion curves and create phase-velocity maps, for periods between 1.6-6.5 s. From the phase-velocity maps we constructed local dispersion curves and used them to invert for structure in depth. The resulting 3-D shear wave velocity model has a lateral resolution of 5 km and vertical resolution down to 10 km. The 3-D model shows two high-velocity zones, with a shear-wave velocity of 3.5 km/s, due east and west of the summit caldera of Eyjafjallajökull, at approximately 5-7 km depth. The high velocity zones are elongated in the east-west direction, in line with geological surface features and are separated by a zone of relatively lower velocity (3.0 km/s), where earthquakes prior to and during the 2010 summit eruption were located. The high velocity zones most likely correspond to intrusive bodies similar to those previously imaged beneath both Tertiary and Neovolcanic central volcanoes in Iceland. A low-velocity zone, with a shear-wave velocity of 2.0 km/s, centered 5 km southwest of the caldera reaches into the caldera at a 3-5 km depth. Our model resolution is not sufficient enough to resolve whether small pockets of melt reside within the low-velocity zone.

European Plate Observing System Implementation Phase (EPOS-IP): Services for Solid Earth Science

Kuvvet Atakan[1] and the EPOS-Consortium[2]

[1] *Department of Earth Science, University of Bergen, Norway, E-mail:* *Kuvvet.Atakan@uib.no*
[2] *EPOS* *www.epos-eu.org*

The *European Plate Observing System* (EPOS) aims to create a pan-European infrastructure for solid Earth science to support a safe and sustainable society. The main vision of the European Plate Observing System (EPOS) is to address the three basic challenges in Earth Sciences: (i) unravelling the Earth's deformational processes which are part of the Earth system evolution in time, (ii) understanding the geo-hazards and their implications to society, and (iii) contributing to the safe and sustainable use of geo-resources. The mission of EPOS is to monitor and understand the dynamic and complex Earth system by relying on new e-science opportunities and integrating diverse and advanced Research Infrastructures in Europe for solid Earth Science. Through integration of data, models and facilities EPOS will allow the Earth Science community to develop new concepts and tools for key answers to scientific and socio-economic questions concerning geo-hazards and geo-resources as well as Earth sciences applications to the environment and to human welfare.

One of the main challenges during the implementation phase (started in October 2015) is the integration of multidisciplinary data into a single e-infrastructure. Multidisciplinary data are organized and governed by the Thematic Core Services (TCS) and are driven by various scientific communities encompassing a wide spectrum of Earth science disciplines. These include Data, Data-products, Services and Software (DDSS), from seismology, near fault observatories, geodetic observations, volcano observations, satellite observations, geomagnetic observations, as well as data from various anthropogenic hazard episodes, geological information and modelling. In addition, transnational access to multi-scale laboratories and geo-energy test-beds for low-carbon energy will be provided. In total more than 450 DDSS elements will be integrated into Integrated Core Services (ICS), a platform that will ensure their interoperability and access to these services by the scientific community as well as other users within the society. This requires dedicated tasks for interactions with the various TCS-WPs, as well as the various distributed ICS (ICS-Ds), such as High Performance Computing (HPC) facilities, large scale data storage facilities, complex processing and visualization tools etc. Computational Earth Science (CES) services are identified as a transversal activity and is planned to be harmonized and provided within the ICS.

EPOS-IP project aims to develop the first implementation of the ICS by October 2017. In the first implementation priority will be given to those DDSS elements that are mature (i.e. existing or partially existing). The system will then be tested and validated before the relevant service contracts are prepared for the various service providers. TCS roadmaps are being prepared for further implementation of DDSS elements that are not yet mature.

European Plate Observing System - Norway (EPOS-N): Integrating the Norwegian Solid Earth Data

Kuvvet Atakan[1] and the EPOS-Norway Consortium[2]

[1] *Department of Earth Science, University of Bergen, Norway, E-mail: Kuvvet.Atakan@uib.no*
[2] *EPOS www.epos-no.org*

The *European Plate Observing System* (EPOS) aims to create a pan-European infrastructure for solid Earth science to support a safe and sustainable society. The main vision of the European Plate Observing System (EPOS) is to address the three basic challenges in Earth Sciences: (i) unravelling the Earth's deformational processes which are part of the Earth system evolution in time, (ii) understanding the geo-hazards and their implications to society, and (iii) contributing to the safe and sustainable use of geo-resources. The mission of EPOS-Norway is therefore in line with the European vision of EPOS.
EPOS-Norway project has started in January 2016 and will during the next five years focus on the implementation of the three main components. These are: (i) Developing a Norwegian e-Infrastructure to integrate the Norwegian Solid Earth data from the seismological and geodetic networks, as well as the data from the geological and geophysical data repositories, which is in line with European EPOS, (ii) Improving the monitoring capacity in the Arctic, including Northern Norway and the Arctic islands and (iii) Establishing a national Solid Earth Science Forum providing a constant feedback mechanism for improved integration of multidisciplinary data, as well as training of young scientists for future utilization of all available solid Earth observational data through a single e-infrastructure.

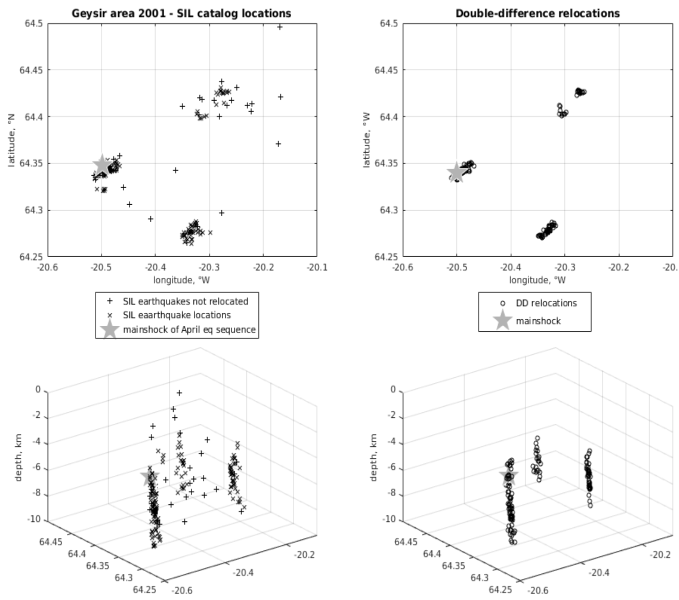
Currently, a list of data, data products, software and services (DDSS) is being prepared. These will be integrated in to the EPOS-N data/web-portal, which will allow users to browse, select and download relevant data for solid Earth science research. In addition, advanced visualization technologies are being implemented which will provide a platform for a possible future ICS-D (distributed components of the Integrated Core Services) for EPOS.

Planning and site selection process for the new instrument installations are well underway as well as the procurement of the required equipment. In total 17 new seismological and geodetic stations will be co-located in selected sites in Northern Norway, Jan Mayen and Svalbard. In addition, a seismic array with 9-nodes will be installed in Bear Island. The planned aeromagnetic survey along the Knipovich Ridge is being conducted this year and data will give new insights to the tectonic development of the ridge systems in the North Atlantic Ocean.

Relative earthquake location in Southern Iceland.

Bergþóra S. Þorbjarnardóttir and Ingi Þ. Bjarnason.

Science Institute, University of Iceland, Reykjavík, Iceland.



The project, 4D Seismic in the South Iceland Seismic Zone: A tool for strong earthquake forecasting, is supported by the Iceland Research Fund. The hypothesis whether in situ temporal changes exist before significant earthquakes in Southern Iceland is tested, and also whether these changes can be used for earthquake prediction purposes. Our intention is to constrain in situ changes in seismic velocity at ~0.5 % significance level and with a relatively high spatial resolution of ~10x10x3 km3, using the local earthquake data recorded by the Icelandic Meteorology Office (IMO).

The better constrained earthquakes in the SIL earthquake catalog of the IMO (~1/3 of total) tend to have location uncertainties of ~1.0 km, which is too high for the significance level required.. To improve location accuracy of the IMO catalog, the relative earthquake location algorithm of Waldhauser and Ellsworth (2000) (W&E) is being applied. The algorithm minimizes measured and calculated travel time differences for pairs of closely spaced earthquakes observed at a series of recording stations. Each earthquake is paired with several other earthquakes and the best fitting distances between them as a group are determined. Methods based on this kind of minimization are called double-difference (DD) earthquake location algorithms.

The observed travel time differences already mentioned can either be obtained from absolute times of measured (picked) phase arrivals (logged in earthquake catalogs) or as relative times between phases measured with cross-correlation (CC) of waveforms. CC between closely spaced earthquakes can give highly accurate relative time differences between phases, and can correct bad picks from seismic analysis. The time accuracy is usually an order of magnitude higher than the routinely measured phase arrival times, offering the possibility of measuring the relative distance between earthquakes with high accuracy. However, at the beginning we will use the picked phase arrivals from the SIL catalog, since W&E have shown that applying DD to good quality catalog data tend to improve earthquake locations significantly.

Our first step is to test the algorithm on a small subset of 215 earthquakes in year 2001, as reported in the SIL catalog, the earthquakes being located in and around the Geysir region in Southern Iceland. Three small areas were active during the year of 2001, although only one of them was recorded to be active as an earthquake sequence (western cluster; main shock mag. ~3.0 and aftershocks). The DD relocation gives tighter clustering of earthquakes in all three areas, and the strike of a fault segment, unclear in the catalog data, becomes clearly visible after relocation. Relocation shifts the centroids of the clusters by ~300 m from catalog locations, but relative distances between clusters do not change significantly. Our next step is to extend the analysis to other areas of South Iceland.

Calibration of a new ground motion model to earthquake strong-motion in South Iceland

Benedikt Halldorsson and Tim Sonnemann

Director of Research (BH and PhD student (TS), Earthquake Engineering Research Centre, and Research Professor (BH), Faculty of Civil and Environmental Engineering, School of Engineering and Natural Sciences, University of Iceland.
Email: BH: skykkur@hi.is, TS: tsonne@hi.is

The simulation of earthquake strong-motion for earthquake engineering applications is an important tool for the quantification of earthquake hazard and the management of seismic risk. The simulations should ideally be based on seismological models that have been calibrated on the basis of recorded data. While earthquake strong-motion records show considerable variability in key parameters such as peak ground acceleration and derived quantities such as spectral response, for a given earthquake magnitude and distance, this variability is generally not captured by ground motion prediction equations. However, this variability is especially important in various practical applications such as fragility analyses. A feasible way of incorporating such variability into simulations is to use a ground motion model that is centered on a simple, yet physically realistic model of the earthquake source. The specific barrier model provides the most complete, yet parsimonious, self-consistent description of the earthquake faulting process and applies both in the near-fault and far-field region. The seismic moment is distributed on the fault plane via subevents on the basis of moment and area constraints. Thus, the model allows for consistent ground motion simulations over a large range of frequencies and distances. For simulations in the far-field region the source acceleration spectrum exists in analytical form and accounts for a high degree of earthquake source complexity and source-site geometry. In the near-fault region, the near-fault velocity pulses, which are the most characteristic feature of near-fault strong-motion, scale with key parameters of the specific barrier model and may effectively be simulated using a phenomenological model. The key model parameter, the local stress drop, has been inferred from Icelandic strong-motion data. The variations in site conditions of the recording sites have been approximated with frequency dependent functions, which may contrast with recent results of site response on lava. The variation of the seismological model in terms of individual parameters is captured using Bayesian inference. Variations of the earthquake source spectra are introduced via theoretical models quantifying the effects of various subevent populations on the earthquake source and empirical models accounting for directivity effects. Finally we discuss the corresponding implications on the level of source complexity (subevent populations) of earthquakes of different magnitudes. That in turn has important implications for using the specific barrier model in modeling the earthquake as an extended source for near-fault simulations.

Long-period earthquakes recorded on a dense seismic array during the 2014 Bárðarbunga rifting event

Bryndís Brandsdóttir[1], Thorbjörg Ágústdóttir[2], Jennifer Woods[2], Robert S. White[2], Tim Greenfield[2],
Robert G. Green[2], Jonathan Smith[2], Clare Donaldson[2] and Corentin Caudron[2]

[1]Institute of Earth Sciences, Science Institute, Univ. of Iceland
[2]Department of Earth Sciences, University of Cambridge, UK

Crustal accretion along the divergent plate boundary in Iceland is governed by rifting episodes and dyking. Over a period of two weeks in August-September 2014, magma propagated laterally from the subglacial Bárðarbunga central volcano, Iceland, about 50 km along the divergent plate boundary to the NNE where it erupted continuously for six months. The dyke propagation was associated with more than 30,000 earthquakes at 5–7 km depth, advancing in short bursts at 0.3–4.7 km/h. Following each surge forward, the seismicity behind the dyke tip dropped, implying that the subsequent dyke opening was mostly aseismic. More detailed analyses of the seismic data recorded by a dense network around the Vatnajökull icecap have revealed small magnitude, long-period (LP or B-type) events which in some cases coincide with an increase in continuous tremor. Most of the LP events originate at shallow depths NNE of the edge of the icecap beneath a 1000 m wide and 5 km long graben, which formed and subsided up to 8 m during the initial phase of the Holuhraun eruption. Furthermore, shallow LP events are also observed in the subglacial part of the dyke trajectory, under three distinct cauldrons. The LP events lie within the 0.5-8 Hz band and are too small to be detected by the national network of the Icelandic Meteorological Office (i.e. less than ML=1-1.5). The LP events are most likely associated with surface ruptures caused by magma moving vertically from the laterally propagating dyke.

This year's update on the Burträsk fault seismicity

Darina Buhcheva, Björn Lund

Department of Earth Sciences, Uppsala University, Sweden

The melting of the ice sheet over Fennoscandia after the last ice age some 10,000 years ago triggered a number of earthquakes with magnitudes over 7. Today, the Burträsk fault, one of these reactivated faults, is located in the most seismically active region in Sweden, with an average earthquake occurrence of around 2 events/day with M>-1. In August 2015 we deployed six new stations close to the Burträsk fault to improve the data quality and azimuthal coverage of the temporary seismic network. Now, our Burträsk network consists of 12 temporary stations together with 10 complementary stations of the Swedish National Seismic Network (SNSN). We observe more than a 30% increase in the average number of catalogued earthquakes for the last six-month period of analysed seismicity after the new stations have been added. Here we present an analysis of the data gathered from December 2012 to February 2016. In this time frame we have recorded and manually inspected over 2700 earthquakes. We use our best located events to invert for a new 1D minimum velocity model for both P- and S-waves using VELEST. A depth region of a lower vpvs ratio down to 20 km depth is revealed. We perform relocation of the whole dataset using the new velocity model and the double-difference relocation technique. We look into details of the depth distribution of the events and how the relocation procedure affects the final hypocentral locations. We calculate focal mechanisms and analyze faulting style variations in the region. The current seismicity is then used to aid the analysis of the endglacial M7+ Burträsk earthquake.

High-rate GPS seismology in Iceland

Halldór Geirsson (1), Vala Hjörleifsdóttir (2), Kristín Jónsdóttir (3), Benedikt Ófeigsson (3), Félix Rodríguez Cardozo (2), Eyjólfur Magnússon (4)

1: Faculty of Earth Sciences, University of Iceland

2: Departamento de Sismología, Instituto de Geofísica, Universidad Nacional Autónoma de Mexico

3: Icelandic Meteorological Office

4: Institute of Earth Sciences, University of Iceland

High-precision GPS is traditionally used for accurate (mm-scale) measurements of Earth´s deformation due to a variety of processes such as plate motion, glacio-isostatic-rebound, earthquakes, volcanoes, and geothermal deformation. However, GPS data can also be processed in a kinematic mode to capture rapid deformation such as seismic waves or co-eruptive volcanic signals. This requires higher sampling rates than the traditional 15 or 30 seconds used for daily positioning, typically 1 Hz or greater, thus termed ´high-rate´. These measurements can be especially useful for near-field large-scale motion because the GPS does not saturate, and is thus useful for studying earthquake source processes and parameters. However, the sensitivity of motion is much lower than for seismometers and usually no deformation is seen for earthquakes smaller than magnitude 5, also depending on the depth of the earthquake. High-rate (1 to 20 Hz) GPS data are collected at most continuous GPS stations in Iceland. Here we showcase several examples of the use of high-rate GPS data for research of seismic and volcanic processes in Iceland. The 2014-2015 Holuhraun eruption was accompanied by over 70 5.7>M>5 earthquakes on the rim of the Bárðarbunga caldera. A GPS station was installed in the ice-filled caldera and captured both the slow subsidence of the caldera and displacement seismograms at 20 Hz of many of the larger collapse earthquakes. The GPS seismograms add constraints in the interpretation of the caldera collapse and the generation mechanism of the earthquakes.

Infrasonic and Seismic Signatures of the 2014 Askja Landslide

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Landslides commonly occur at active volcanoes and represent a major source of hazard for people and infrastructure. Due to the flank instability of volcanic edifices, landslides, or flank collapses, at active volcanoes can trigger major eruptions or produce tsunami waves when the material enters open or enclosed water bodies.

A large landslide occurred at Askja Volcano, Iceland, on July 21st, 2014. The landslide had a total volume between 30 and 50 million m3 and it originated from the southeast margin of the inner caldera, triggering a large tsunami into the lake. The tsunami wave inundated the shores all around the lake, reaching up to 40 m elevation above the lake level. The seismic waves produced by the landslide were recorded by most of the IMO's seismic stations in Iceland and allowed to establish the onset time around 23:24 UTC.
Events of this type may represent a serious risk if they occur in tourist spots such as the Askja region. We present observations of the July 21st, 2014 event as recorded by the national infrasonic arrays network installed in the country within the FUTUREVOLC European project. Infrasound released by the event was recorded at a distance of 210 km from Askja volcano.

We performed 2D FDTD modeling of the pressure wave propagation in the atmosphere in order to account for wind effects and atmospheric specification along the whole section from the source to the different arrays. Sound pressure level maps are evaluated for infrasound propagation towards the different arrays of the network.

We show how the comparison between seismic and infrasonic signals may be crucial in order to better define the timing and the dynamics of the event. An integrated analysis of the infrasonic and seismic signals effectively enhance our monitoring capabilities and hazard assessment related to geophysical phenomena occurring at the ground-atmosphere interface.

Seismic activity in Iceland 2015 – 2016 and testing of near-real time automatic relative locations

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At present, in September 2016 the SIL seismic monitoring network consists of around 70 seismic stations. The number of earthquakes located by the SIL system in 2015 was about 24000 and about 17000 in 2016, end of September. Following the seismicity from south to north, the northern most part of the Reykjanes ridge had large seismic swarms in June and July 2015. The largest earthquake in the swarms occurred on 1 July and had a magnitude $M_{lw}5.0$. Reykjanes peninsula had occasionally some small swarms, mainly at the tip of the peninsula, at Fagradalsfjall and at Kleifarvatn lake. The largest earthquakes occurred close to the Kleifarvatn lake during swarms in late May 2015 with an $M_{lw}4.0$ earthquake and at the beginning of Februar 2016 with an $M_{lw}3.9$ earthquake. There was a persistent seismic activity at Husmuli in the Hengill area. The area is close to a geothermal power plant where wastewater is injected into wells. A large seismic swarm occurred there in September 2016 and it had two earthquakes of magnitude $M_{lw}3.6$ and $M_{lw}3.4$. Very few seismic swarms occurred in other parts of the Hengill area but the largest earthquakes reached magnitude $M_{lw}3$. In the South Iceland seismic zone few earthquakes reached magnitude about $M_{lw}3$ and microseismicity prevailed at known faults. Seismic activity in the Katla volcano was relatively low in 2015. Two earthquakes $M_{lw}3.3$ and $M_{lw}3.2$ occurred respectively in the western part of the caldera in February and in the southern part of it in September. In 2016 the seismic activity within the caldera increased during the summer months. At the end of August two $M_{lw}4.5$ and $M_{lw}4.4$ occurred in the northeastern part of the caldera. Late in September an $M_{lw}3.9$ earthquake occurred in the southern part of the caldera and some days later it was followed by large swarm that lasted 2-3 days and had several $M_{lw}3$ earthquakes. A great number of the detected earthquakes during 2015 and 2016 originated in the northwestern part of Vatnajökull ice cap in connection with the Bárðarbunga volcano and the eruption in Holuhraun that started late August 2014. The last two M5 earthquakes in the Bárðarbunga caldera in a series of many before occurred in January 2015. The Bárðarbunga caldera was very seismically active and had many M4 earthquakes until the end of February when the eruption ceased. The dyke east of the Bárðarbunga caldera was still very seimically active until the autumn of 2015 but has since decreased very much. In the autumn of 2015 the seismic activity in the Bárðarbunga caldera increased and has since been steadily increasing with some M4 earthquakes. Seismicity north of the Vatnajökull ice cap, close to Herðubreið table mountain and the Askja volcano has been rather high during 2015 and 2016. In the Tjörnes Fracture Zone the most seismic activity has been on the Grímsey Oblique Rift Zone extending southeast from the Grímsey island into the Öxarfjörður bay. The largest event had a magnitude $M_{lw}3.8$ with origin east of Grimsey island during a swarm end of October 2015. A seismic swarm occurred in the western part of the Húsavík-Flatey-Fault early August 2016 and had an $M_{lw}3.7$ earthquake.

Since 2014 we have been testing in near-real time automatic relative locations (ARL) for the South Iceland Seismic Zone. It was implemented in connection with the European REAKT project and lead by Kristin Vogfjörð. We use cross-correlation and double difference methods from Ragnar Slunga. We correlate new single automatic located events with waveforms of events from a high-resolution library (catalog) of active mapped faults in the area and also from a library of well located single events. Some results from these testing will be shown.

The ISC data (and how to get it)

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The ISC data distribution has evolved over many years from print only, through CDs, the first simple flat file search on the web (1998), to the many and varied search tools currently available to search the 116 years of data at the ISC. There are three main datasets held at the ISC available to search: the ISC Bulletin, the EHB Bulletin and the IASPEI Ground Truth data. In addition there are the ISC Event Bibliography and Station Registry. These all have their own search tools on the ISC website (www.isc.ac.uk) with an FDSN web-service event search for the ISC Bulletin. With around 5000 searches a day, many through web-services, it is possible that many users are unaware of new tools, formats and options currently available.

This presentation aims to give an overview of the ISC data, products, services and details of how to use the various methods of retrieval.

In situ seismic velocity changes in Southern Iceland

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Detecting in situ velocity changes in the crust of the earth before significant earthquakes (preseismic changes), for the purpose of predicting earthquakes, has been described as the Holy Grail of seismology, i.e. highly desirable goal but with elusive results. Preseismic signals of the order of 10–20%, reported in the 1960ies and 1970ies, have not been convincingly reproduced. Lower level (0.5–3.5%) coseismic and postseismic in situ changes have, however, repeatedly been reported. Due to lack of seismicity prior to significant earthquakes, adequate data are often lacking to test the hypothesis of preseismic signals. Using earthquake data in order to detect such signals, errors in earthquake locations and velocity models may give a false-positive temporal signals. For the detection of a low level (~1.0%) preseismic change, good knowledge of seismic structure, high accuracy of earthquake locations, and a continuous high level of seismicity are important factors.

The local seismic network of the Icelandic Meteorology Office, the SIL network, is in many respects ideal for studying in situ preseismic changes before significant earthquakes. Since the beginning of its operation in 1991, four earthquakes of magnitude ~6.0 and greater have occurred in the region, which may have caused preseismic velocity changes in the crust. The original design of the network had a high clock accuracy (±1 ms). S-waves tend to be very clear, and successful 1D velocity model (SIL model) has been used to locate earthquakes in the area, suggesting relatively simple velocity structure in spite of active tectonic setting.

Earthquakes in Southern Iceland during the period 1991 to 2000 are being analyzed. The period includes two large earthquakes in year 2000, both of them of the magnitude 6.5. The analysis involves improving earthquake locations in order to determine if in situ changes do exist in the area (down to ~0.5% significance level), with the ultimate goal of locating them at relatively high spatial resolution (~10x10x3 km3). With such a high spatial resolution, identification of individual faults approaching failure can possibly be determined. However, with the current uncertainties of earthquake locations in Southern Iceland, in situ changes cannot be constrained at such a high spatial resolution. This requires improvement of earthquake location by approx. an order of magnitude from the current status of SIL catalog locations. We have started applying double-difference method of Waldhauser and Ellsworth (2000), to improve earthquake location accuracy in the area.

On spatial resolution scale on the order of the size of the Southern Iceland Lowland (~70 km), we have been able to measure velocity ratios at ~0.04–0.1% significance (1 σ) with the uncorrected SIL catalog data. Preliminary results can be interpreted to indicate a linear decrease in Vp/Vs ratio by 0.8%, starting in the years 1997–1998 and until 2000 (a yearly change of 0.2–0.3%). These results need to be verified with earthquake locations of improved accuracy, before we can conclude that preseismic in situ changes leading up to the two earthquakes of year 2000.

Fault plane solutions of the earthquakes in Nordland, Norway

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This study is a part of the ongoing NEONOR2 project which is carried out in Nordland, norther Norway. This work aims to define the fault plane solutions (FPS) of the earthquakes in the study area both onshore and offshore. The improved station coverage in Nordland with 26 temporary seismic stations in addition to the permanent deployments in Norway and Sweden enables to achieve this task with higher precision compared to the previous studies. To obtain the FPS we used three different programs: FOCMEC, HASH and FPFIT, which are implemented into the SEISAN program package. From the recorded data we obtained nearly 120 FPS of the earthquakes and assigned them with the quality factors. We grouped the earthquakes into several groups according to their geographical locations, and investigated the obtained results in each group separately. The overall results in the study area show the dominating normal type of faulting and the N-S to NW-SE direction of the compressional stresses. In the offshore area the obtained directions of the faults indicate the dominant NE-SW trend, i.e., along the coast of Nordland, which complies well with the maps of the major tectonic faults.

Observations on Intraplate Seismicity in Central Fennoscandia

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Fennoscandian Shield is situated in a seismically quiet intraplate setting in northern Europe. Intraplate seismicity has been attributed to ridge-push from the North Mid-Atlantic Ridge, post-glacial rebound stresses and to local gravitational potential energy differences associated with compositional differences and crustal thickness variations.

Based on a subset of the most recent earthquake data (2000-2012), most of the earthquakes (80%) occur in the upper crust down to 17 km in depth, a minority (19%) in the middle crust (17-31 km) and only a few in the lower crust 31-45 km (1%) [1]. The seismogenic layer is less than 30 km in depth. The layer seems to be rather uniform across Fennoscandia. We suggest that the middle to lower crustal boundary may add compositional and rheological constraints to the depth extent of the seismogenic zone in the study area.

The orientation of the overall maximum horizontal stress field in northern Europe is WNW–ESE to NW–SE. Pre-existing deformation zones that are optimally oriented in the present stress field can potentially be reactivated. The deformation zones were analysed for their length and azimuth and they were assigned a potential reactivation type (reverse, normal or strike slip) based solely on their azimuth. The earthquakes in the seismically most active area, close to Skellefteå, Sweden along the western coast of the Gulf of Bothnia and its north-easterly continuation, appear to cluster around the shoreline and along post-glacial faults, which are mostly oriented optimally for reverse or strike slip faulting. The seismically active Kuusamo area in Finland is transacted by wealth of deformation zones all trending in directions optimal for reactivation.

The seismically active areas are located in areas where the crust is less than 50 km thick. Where the crustal thickness gradient trends in a NE–SW direction, e.g. along the faulted western margin of the Bothnian Sea and along the Auho-Kandalaksha fault zone in the Kuusamo area, the gradient seems to be associated with a zone of increased seismicity. In these areas, the crustal thickness gradients are optimally oriented for reactivation. Because the spatial distribution of the registered earthquakes exhibits little to no correlation with the an existing ellipsoidal rebound model or Glacial Isostatic Adjustment (GIA) model [2], and the still active post-glacial faults do not occur parallel to the isolines of the rebound ellipsoid, it is concluded that there is no clear evidence that the rebound stress is the main source for triggering seismicity in Fennoscandia today. However, during late- and post-glacial times, glacially-induced isostatic rebound was probably much more important for the generation of earthquakes.

Reference:

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Neotectonics in Nordland; NEONOR 2

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M. Ask, J. Dehls, Y. Maystrenko, F. Riis, L. Rise and other project partners

The Nordland shore region is known to be seismically active with deep local sediment basins on the continental shelf that stretches some 200 km west of the coastline. The offshore areas west of Nordland have also been attractive for the petroleum companies with potentials for new resources. The multidisciplinary NEONOR 2 project is funded by the Norwegian Research Council in cooperation with ten petroleum companies and include seven research institutions led by the Norwegian Geological Survey (NGU). The activities started mid 2013 and is closing early 2017. The prime objective is to promote understanding of regional-scale stress and strain dynamics in the Nordland area through a detailed monitoring of seismicity and to link this to geodetic movements, in situ stress state, and in turn also to tectonics, exhumation and isostatic processes through modeling. Under these overarching goals the following activities have been conducted with significant achievements:

- A new seismicity map of the Nordland region has been obtained and linkage to mapped and hitherto non-mapped faults has been done.
- Inversion methods have been applied to estimate the regional stress field by integrating GPS, DInSAR, seismic data (focal mechanisms) and in situ stress.
- The contribution of Pleistocene sediment redistribution has been quantified using numerical modeling with basis in the present-day stress field.
- Pleistocene palaeo-stresses and palaeo-temperatures are estimated using numerical modeling.

The recent Bothnian Bay M4.1 earthquake: where, how and why?

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On 19 March 2016 a magnitude 4.1 earthquake occurred in the Bothnian Bay, between northern Sweden and Finland. The event was located approximately 59 km SE of Piteå and 80 km NE of Skellefteå in Sweden, while the distance to the nearest Finnish city, Raahe, was 100 km. The earthquake was widely felt in northern Sweden and Finland, the furthest reports come from some 250 km away, with intensities up to V. The main event was followed by 6 aftershocks within the first 8 hours, and two more events in the vicinity in the next two months. These aftershocks are interesting as aftershocks to M4+ events are not always observed in Sweden and Finland.

The Bothnian Bay is one of the most seismically active areas in continental Fennoscandia, but the cause of the seismicity is still not well known. Until recently, the offshore areas have been poorly monitored by the national seismic networks. The 2016 main shock, however, was well recorded on both shores (17 Swedish and 12 Finnish stations within 160km), and it provides a unique data set for joint seismological analysis.

We gather the available seismic data from Sweden and Finland and relocate the mainshock and aftershocks, comparing results with various velocity models and location software. The focal mechanism of the main event is estimated using a variety of methodologies, from a pure polarity solution via combined polarity and amplitude estimates to full waveform inversion in both time and frequency domains. The estimates show a strike-slip solution with nodal planes in approximate NW-SE and NE-SW. The events are located in an area of high microearthquake activity, forming a diffuse approximately north-south cloud off the Swedish coast. We combine seismic results with other geophysical data such as bathymetry, magnetics and deep seismic reflection (BABEL) data to speculate about the origin of the seismicity in general and the 2016 events in particular.

Macroseismology in Finland from the 1730s to the 2000s: From an obligation of the learned elite to citizen science

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The presentation is based on a snapshot of macroseismology in Finland from the 1730s to the 2000s that has recently been completed. It shares some highlights of the work. The focus is on the design and dissemination of macroseismic questionnaires and the authors, i.e. people who wrote down earthquake observations. Eight generations of Finnish macroseismic questionnaires since 1882 are discerned. The ownerships belonged to one geologist, the Geological Commission, the Geographical Society of Finland, the Seismological station of the University of Helsinki, the Sodankylä Geophysical Observatory of the Finnish Academy of Science and Letters, and the Department of Physics of the University of Oulu. The later generations belonged to the Institute of Seismology, University of Helsinki. At the turn of the 2000s the questionnaire was placed on the Internet.

The standard practice in Finland is to conduct macroseismic questionnaire surveys remotely. However, observations have occasionally been collected at interviews and questionnaires distributed during field trips, mainly in the 1900s. No networks of permanent correspondents have been arranged in Finland for the purpose of macroseismic surveys, so respondents have to be found in the affected area time and again. As an example of dissemination of questionnaires, the work of Henrik Renqvist between 1926 and 1946 is described.

The group of earthquake reporters that stands out throughout centuries is the clergy. Its leading position waned only in the 1900s. Finns became more literate, in particular in terms of writing skills, during the 1800s.

Macroseismic maps for two border crossing earthquakes in northern Europe

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We present macroseismic maps for two recent earthquakes that occurred in Sweden and were felt also in neighbouring countries. The first occurred in Sveg, Södra Härjedalen on 15 September 2014 and had magnitude M_L4.1. According to the available pre-instrumental seismicity record, the region has not experienced earthquakes of this magnitude. The earthquake was felt in much of central Sweden and Norway, and several persons reported sensations of earth shaking also in western Finland. These latter observations were not only made in higher floors of buildings.

The second earthquake occurred in the Gulf of Bothnia on 19 March 2016. The magnitude was assessed at M_L4.1. The earthquake was widely felt in northern Sweden and in Finland along the eastern shore of the Gulf of Bothnia. There are previous examples of earthquakes of this magnitude in the region in the pre-instrumental era, so the most recent event is usable for magnitude calibration. Here we present some estimates of the areas of perceptibility and compare them against those of historical earthquakes, and compare macroseismic magnitudes to the instrumental ones.

Temporal stress changes associated with the 2008 May 29 Mw6 earthquake doublet in the western South Iceland Seismic Zone

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On 2008 May 29, two magnitude MW ∼ 6 earthquakes occurred on two adjacent N-S faults in the western South Iceland Seismic Zone. The first main shock was followed approximately 3 s later by the rupture on a parallel fault, about 5 km to the west. An intense aftershock sequence was mostly confined to the western fault and an E-W aligned zone, extending west of the main shock region into the Reykjanes oblique rift. In this study, a total of 325 well-constrained focal mechanisms were obtained using data from the permanent Icelandic SIL seismic network and a temporary network promptly installed in the source region following the main shocks, which allowed a high-resolution stress inversion in short time intervals during the aftershock period. More than 800 additional focal mechanisms for the time period 2001–2009, obtained from the permanent SIL network, were analysed to study stress changes associated with the main shocks. Results reveal a coseismic counter-clockwise rotation of the maximum horizontal stress of 11 ± 10° (95 per cent confidence level) in the main rupture region. From previous fault models obtained by inversion of geodetic data, we estimate a stress drop of about half of the background shear stress on the western fault. With a stress drop of 8–10 MPa, the pre-event shear stress is estimated to 16–20 MPa. The apparent weakness of the western fault may be caused by fault properties, pore fluid pressure and the vicinity of the fault to the western rift zone, but may also be due to the dynamic stress increase on the western fault by the rupture on the eastern fault. Further, a coseismic change of the stress regime—from normal faulting to strike-slip faulting—was observed at the northern end of the western fault. This change could be caused by stress heterogeneities, but may also be due to a southward shift in the location of the aftershocks as compared to prior events.

Expanding Flood-Monitoring Capabilities using Seismic Tremor and Infrasound

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Weather- and glacier-related floods are common in Iceland. Floods of meteorological origin can result from intense rainfall or snow-melt, with various seasonal factors, such as frozen ground, compounding the severity of flooding. Glacial outburst floods (jökulhlaup) can occur anytime; sources include ice-dammed lakes and water reservoirs that develop at the base of ice-caps overlying volcanic or hydrothermal areas. Jökulhlaup due to volcanic unrest often occur with little warning and they usually cause damage to infrastructure and agricultural land.

River monitoring in Iceland is the responsibility of the Icelandic Meteorological Office (IMO). Floods are detected through a national network of over 20 gauging stations, which sends measurements to IMO in near-real-time. However, in relation to catchment sizes, the network covers only a small fraction of Iceland's major rivers. Compromises between station locations and accessibility result in flood warnings from the lower part of a catchment, which impacts on the effective response-time for mitigating hazards.

In this presentation, we highlight the possibility of expanding flood-monitoring capabilities using seismic tremor and infrasound. Over 70 permanent seismic (SIL) stations, also operated by IMO, are sited throughout the country for monitoring earthquake and volcanic hazards. Several stations are located near or on the Mýrdalsjökull and Vatnajökull ice-caps, where jökulhlaup occur frequently. At sites where SIL stations are in close proximity to gauging equipment, seismic amplitude measurements have been compared to water-level readings. The results show a remarkable positive correlation between water-level - a proxy for discharge - and tremor intensity. This relationship is especially apparent at fast-flowing, turbulent rivers. Similarly, an infrasound array to the north of the Vatnajökull ice-cap shows diurnal variations in acoustic signals that follow water-level changes in a nearby glacial river - Jökulsá á Fjöllum. The analysed seismic and infrasound measurements show how fluid movement can generate elastic waves that propagate through the ground and atmosphere. This underlines the potential for using tremor-amplitude and infrasonic measurements as an early warning for hazardous floods, particularly in regions where hydrological measurements are sparse.

Seismicity of the Nordland area, Norway

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The Nordland area (65-70N; 8-18E) is tectonically active part of Norway. Enhanced seismicity may reflect on off-shore subsidence combined with the uplift of landmasses usually attributed to glacial isostatic adjustment (related to Pleistocene unloading). Detailed monitoring of seismic activity in the Nordland area was done in August 2013 – June 2016 as a part of the NEONOR2 project and information obtained from analysis of earthquakes together with geodetic data should be the key inputs for modeling of deformation and uplift patterns and their mechanisms in the region. Local network of 26 broad-band stations was deployed and together with the permanent NNSN stations in that area it contained 33+ stations within span 350 x 200 km. About 1250 earthquakes of M>0.0 was recorded during the project period and new map of seismicity of that area was retrieved.

The main aim of the project is to reveal the stress field in that particular region and therefore determination of stable focal mechanisms is crucial. Despite the high number of stations, enough clear polarity readings (>=6) were obtained for only about 20 strongest events (M<3.2). Hence we developed methodology using automatic amplitude readings and the standard tools (FOCMEC, HASH) for focal mechanism determination which are implemented in SEISAN. The methodology is tested using the strongest events and conclusions for further application are suggested.

The Reykjanes Peninsula Oblique Rift, a zone of crustal extension and strike-slip faulting

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The structure of the plate boundaries in Iceland is relatively complex. Several of the plate boundary segments are oblique to the over-all plate velocity vector between the North America and Eurasia Plates. Oblique and immature plate boundaries are frequently characterized by complicated fault patterns, which makes their seismogenic potential and seismic hazard difficult to assess. The Reykjanes Peninsula oblique rift has an over-all trend of 70°, highly oblique with respect to the spreading direction, 101° in this region. It contains both volcanic systems and seismogenic strike-slip faults. Oblique spreading leads to extensive volcanism and large earthquakes, a combination that is otherwise uncommon in Iceland. The fissure swarms of individual volcanic systems contain normal faults and fissures, with a NE-trend, also quite oblique to the plate boundary. The fissure swarms fade out towards the NE and SW as they extend into the plates on either side. Overprinting this pattern of volcano-tectonic structures are sets of parallel, northerly striking transcurrent faults that generate the largest earthquakes in this zone, up to M 6.5. Their surface expressions are en echelon fracture arrays and push-up structures. The sense of displacement is right-lateral. The distance between them varies from 0.5 to 5 km, and together they form a bookshelf-type fault system taking up the left-lateral component of plate movements across the oblique rift zone.

It has been suggested that the plate spreading vector is partitioned into extension and transcurrent motion. The transcurrent motion then appears to be taken up by bookshelf faulting, i.e. by a series of parallel, strike-slip faults that are perpendicular to the plate boundary, and the extensional structures of the fissure swarms are activated primarily during magmatic events when dykes are intruded into the crust.

From the Nordic SIL research project towards warnings on the long- and on the short-term before large earthquakes

Ragnar Stefánsson

University of Akureyri

From it´s start in 1988 the SIL project was based on physical approach in earthquake prediction research. It was also stated from the start that the best information about crustal processes preceding earthquakes would come from multidisciplinary information carried with micro-earthquakes from seismogenic depths.

The old efforts in earthquake predictions were to a large extent based on "precursor statistics", mostly on shallow origin precursors, which were so large that they could be observed by the old seismic networks and by people. It was very difficult to invert these shallow precursors to what was happening at depth, until after the big earthquake. So the result was many "hindsight predictions" and very few successful "pre-earthquake predictions". These mistakes are gradually convincing more and more scientists that we cannot assume that pre-earthquake activity is the same before any two earthquakes, so statistics does not work at this level.

But these early precursor studies had the very significant outcome that something happens before most large earthquakes, although the observers did not understand what it was telling us. There the SIL project came in which aimed to revealing the physics of such pre-earthquake processes. One of the well known precursors was the so called seismic quiescence before large earthquakes, i.e. no earthquakes during days to years preceding them. But for how long time there was no information during the quiescence or in general about the pre-earthquake process. Going down to micro-earthquakes (magnitude zero) there is information all the time.

Multinational and multidisciplinary studies of the physics of pre-earthquake patterns in Iceland from SIL to PREPARED (1988-2005+) especially in the South Iceland Seismic Zone indicate that it is possible to observe and physically to model fault conditions and crustal process leading to a large earthquake during decades before it strikes.

The preparation process of earthquakes cannot be assumed to be the same. This and the long observable preparation period moves our efforts towards studying the ongoing pre-earthquake process at individual faults: "To create a constitutive relationship for the possibly pre-earthquake process, to extrapolate these conditions in space and time to predict activity, to constrain the model by the forthcoming activity, and thus gradually to refine the constitutive relationship towards the earthquake."

It is stated that by such an approach useful warnings/information about significant aspects of any large earthquake in Iceland may be issued during it´s preparation period, provided that relevant multidisciplinary geo-watching procedure is applied. Such a watching procedure, consisting of automatic and manual operations, should be capable of real time modeling explaining the continuous observations, from seismic observations of deep origin towards observations of forerunners with shallow origin.

Soil structure impact on site effects and modeling spatial strong-motion variability across Icelandic strong-motion arrays

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In earthquake engineering the estimation of the impact of subsoil characteristics on site effects, and modeling the distribution of ground motion amplitudes are known as key elements in accurate seismic hazard assessment programs. Recently, the deployment of Icelandic strong-motion arrays, ICEARRAY I in the SISZ and ICEARRAY II in the TFZ, has enhanced the Icelandic strong-motion database and made such detailed studies possible. That is of importance in particular because the site response in standard earthquake engineering practice in Iceland is generally assumed to be uniform across a small area. However, significant variability in relative earthquake ground motion amplitudes as well as prominent different site responses can be detected using recent strong-motion recordings across Icelandic arrays. In this study we quantify the localized site effects across ICEARRAY I and ICEARRAY II considering empirical methods (i.e. Horizontal to Vertical Spectral Ratio, HVSR, and Standard Spectral Ratio, SSR) using both strong-motion data and microseismic recordings. The results between different methods and data sets are consistent and show systematic variation between stations which are highly correlated to geological structures. In particular, we find that the standard modeling of vertically incident body waves is not practical for lava-rock stations characterized by velocity reversals due to recurring lava-sediment stratigraphy. Instead, we model the sub-soil structural as a multi-degree-of-freedom, MDOF, dynamic system to obtain the observed predominant frequencies of site amplification.

Moreover, we present a Bayesian Hierarchical Model, BHM, for spatial distribution of Peak Ground Acceleration, PGA, across both Icelandic arrays. Our proposed model considers a flexible probabilistic framework for multi-level modeling of PGA that accounts for the source and site effects as well as quantifying the uncertainties over multiple hierarchy levels. The main goal of the proposed BHM lies in combining different main factors which directly influence the ground-motion intensities. We find that the total uncertainty is a bit larger in comparison with the calibrated local ground motion prediction equations' standard deviation obtained for south Iceland. Moreover, the results indicate that inter-station variability can be considerable even over a very small area. In addition, the comparison of the obtained site term across ICEARRAY I and ICEARRAY II explicitly indicates that more complex subsoil structure causes more unreliable results with higher uncertainties. Our investigations notably emphasize on the importance of detailed micro-scale studies for seismic hazard assessment specifically for dense urban areas or spatially distributed infrastructures (e.g. pipeline systems, transportation networks, power systems). Therefore, developing our understanding of the main factors which affect the variation of the relative strong-motion amplitude can be critical for seismic hazard assessment or planning insurance rates for the areas under studying.

Towards an automated event verifier

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An important task at the Swedish National Seismic Network (SNSN) is the operation of an early warning system and production of a bulletin of globally significant earthquakes. For each event a simple hazard analysis is performed, classifying the event as unlikely, potential or likely to cause harm to society. The customers of this product are Swedish civil protection and crisis management authorities. The system is run in a highly automated manner with only limited human interaction. Input data to the system are event parameters from our in-house processing using Seiscomp3 and a virtual global network of stations, made available to us either directly from collaborating institutes or via IRIS and GFZ, as well as event parameters published by EMSC and USGS. After the initial alert, event parameters and classification are continuously updated as more data on the event becomes available. Being automated and targeted at early warnings, the system will occasionally have to deal with spurious events. At SNSN we are therefore investigating the feasibility to construct an event verifier. The basic idea is to emulate the decision made by a seismologist viewing a section of recorded traces, sorted by epicentral distance, and expecting to see direct P-phase arrivals on most traces out to the most distant phase pick. Here we will report on the current status of this project.

Rock stress boundaries deduced from rock stress measurements

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Jamison and Cook (1978) analyzed the state of stress in the crust based on a set of some 50 3-D stress measurements from all over the world. They found a linear relationship between the maximum shear stress and the sum of the maximum and minimum principal stresses. This indicates that the Coulomb failure criterion gives a good description of the crustal stresses. Tthe sizes of the shear stresses do not fit the shear strength of the rock but do fit the shear stresses limited by friction on shearing fractures. Extensive drillings have shown that the crustal rock contains large number of fractures (faults and joints of all sizes). All these fractures will slip if their Coulomb failure stress (CFS) exceeds zero. Thus the shear stresses are limited by frictional sliding on the numerous fractures.

Cook (1981) studied the behaviour of frictional sliding of granitic rock by use of stiff laboratory machines. The availability of stiff machines made it possible to study not only the sudden unstable slips (produced by less stiff machines) but also brittle stable slip. Cook studied the slip behaviour at different pressures and temperatures. He found that at shallow depths one expect in general brittle and stable slip (not unstable slip, earthquakes). This prevailed for the top 5 km of granitic crust. Between 5 and 20 km depth one got brittle unstable slip and when temperature and depth increased one got eventually ductile and stable deformations for the granite. This turned out to be in good agreement with the depth distributions of the Baltic shield seismicity, Slunga(1985).

The expected stable slip on shallow fractures means that the tectonic loading will increase the shear stresses until some fractures will slip stably. This stable slip preserve the shear slip close to zero. This explains the Jamison and Cook observation that the measured stresses were as large as the CFS allowed. Note that the stress observations are from the interiors of the small blocks while the CFS limitations just concern the block boundaries and joints within the blocks. These fracture (CFS) limitations thus strongly affects the interiors of the small blocks.

Brown an Hoek (1978) published a very often referenced picture showing observed crustal stresses by plotting the depth against the ratio between the mean horizontal stress and the vertikal stress. This ratio is often denoted k and thus k = (SH+Sh)/2/Sv. The main feature of the data set was the clear excess of horizontal stresses at very shallow depths, especially above some 300m. A large number of similar diagrams have been published by many authors and normally they also show hyperbolic curves fitted to embrace the observations, typically $0.5 + 1500/Z > k > 0.3 + 100/Z$ are used.

These curves have no direct physical meaning but are just chosen as they give good fitting boundaries on the k-values of the Brown and Hoek data set. Slunga (1988) showed the result by Jamison and Cook (stresses are as large as the friction allows) directly leads to boundaries on the k-values and that these curves not only has a simple physical meaning, they also show a significant difference from the numerical fitting. This encouraged me to later go on and use the same assumptions to put boundaries on the pore pressure within wet crust which then was the base for the QuakeLook complete stress tensor estimate from observed microearthquakes.

Geological Survey of Denmark and Greenland – GEUS

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GEUS

The goal for the seismic service at GEUS is simply; to monitor and register earthquakes and other seismic activity including possible nuclear explosions. For this purpose GEUS maintains an earthquake database covering registered seismic activity in the Kingdom of Denmark. Both the resources for and the quality of the database, have varied a lot since the establishment of the seismic service in 1928. Nevertheless, the seismic service has undergone several technological paradigm shifts since the establishment: WWSSN, digital recording and GLISN, all resulting in an increased detection level. The most recent challenge forced upon the seismic service is automatic processing of seismic data, from recording to bulletin. The outcome of this shift in operation is still unclear, but the preliminary results show that automatic detection especially of events in Greenland maybe is too great a challenge, mainly due to the low station coverage.

Recent activities at the seismic section at GEUS: We ended the microseismic monitoring in Northern Jutland by OKT 2015 where the 6 stations were recovered. A new broad band station was installed in Northern Jutland on OCT 8th, 2015, with the ISC code for this station is: OVD. Together with partners from Sweden and Finland we took part analyzing small finish earthquakes for NKS. North of Copenhagen we conducted a short noise study before the summer of 2016 and by the end of 2016 we will take part in the EU project INTAROS with colleagues from UiB. For the installation of a new broad band seismometer in Southern Jutland we are preparing a posthole installation. A noise survey has been conducted and a site is now selected, the ISC code for this new station is: SSRD. To meet the request from the ISC of providing seismic bulletins within a year, we are now providing reviewed monthly bulletins in Nordic format. The first reviewed monthly bulletin was that of April 2015.

Apart from the destructive earthquake in Italy and the nuclear explosion in the DPRK, the most significant seismic events recorded by the seismic service at GEUS in the recent period, are a sequence of earthquakes in the Disko Bay area in West Greenland. Since the beginning of the sequence on April 5th 2016, 95 earthquakes have been recorded. The two largest earthquakes measured 4.5 and 4.7 mb, respectively.

Seismic analysis using the auditory sense – Playing the sounds of the Earth

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Classifying a seismic event registered by a seismic network as a local earthquake, a local explosion or a more distant earthquake or explosion is an important part of the work of a seismic analyst. Normally preliminary event classification is done after the application of signal filter(s) by visually studying the seismograms and various computed spectrograms. In this work an alternative sense, the sense of hearing, is applied in seismic analysis.

The key issue is that seismic signal must be modified in order to make it audible. Frequencies used in seismic analysis typically range from tens of hertz down to few tenths of a hertz. This is considerably different from the normal hearing range of a person which ranges roughly from 20 Hz to 20 kHz. Several different methods of transferring the seismic signal to audible range and their applicability to auditory analysis are evaluated. High dynamic range of seismic data is also taken into account and different methods of signal amplification are discussed.

Usefulness of hearing in seismic analysis is assessed by studying whether listening to suitably modified seismic signal can provide information about the seismic source or quality of seismic data similar to visual inspection. This is done by utilizing subjective experiences of seismic analysts familiar with analysing seismic data using visual tools. Providing an easy-to-use tool to convert a seismic event/signal into audio is also a goal. Finally, some alternative applications for "auditory seismology" are also reviewed.