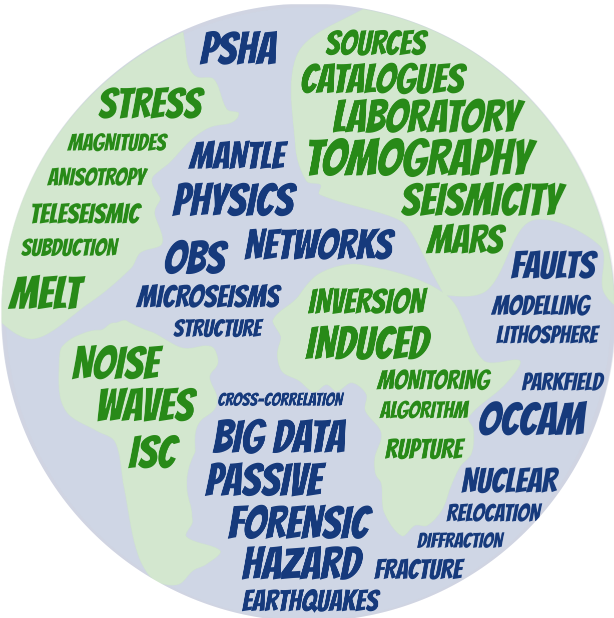
# BSM2017

## British Seismology Meeting
## 5th-7th April, Reading, UK




**Organised by the International Seismological Centre (ISC)**

# Timetable

| Day | Time | Session | Location |
|---|---|---|---|
| Wednesday 5th April | 13:00 – 14:00 | Registration | |
| | 14:00 – 14:15 | Welcome | Victoria Hall |
| | **14:15 – 16:00** | **1: The rise of induced seismicity** | Victoria Hall |
| | 16:00 – 16:30 | Coffee Break | Victoria Hall |
| | **16:30 – 18:00** | **2: Investigating unusual signals** | Victoria Hall |
| | 18:00 – 19:00 | Icebreaker | 3Bs |

| Day | Time | Session | Location |
|---|---|---|---|
| Thursday 6th April | **08.30 – 10:15** | **3: Passive sources and sensitive signals** | Victoria Hall |
| | 10:15 – 10:45 | Coffee Break & Posters | 3Bs |
| | **10:45 – 12:15** | **4: Understanding Earth's faults** | Victoria Hall |
| | 12:15 – 13:30 | Lunch and Posters | 3Bs |
| | **13:15 – 14:45** | **5: How hazardous?** | Victoria Hall |
| | 14:45 – 16:45 | Poster Session and Coffee | 3Bs |
| | **16:45 – 18:00** | **6: Catalogues: Power and completeness** | Victoria Hall |
| | 18:30 | Meet to walk to conference dinner | Outside Town Hall |
| | 19:00 – 00:00 | Conference Dinner | Crowne Plaza Reading |

| Day | Time | Session | Location |
|---|---|---|---|
| Friday 7th April | **08:45 – 10:30** | **7: Imaging the Earth at all scales** | Victoria Hall |
| | 10:30 – 11:00 | Coffee Break | Victoria Hall |
| | **11:00 – 12:45** | **8: Dealing with Big Data** | Victoria Hall |
| | 12:45 – 12:50 | Closing Remarks | Victoria Hall |

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# Welcome to BSM2017

In its 50+ year history, the International Seismological Centre (ISC) has never organized a scientific conference. Thanks to the energy of the ISC's new staff members, we are about to brush aside this unfortunate historical artefact. We have noticed that there has not been a wide-ranging, cross-disciplinary seismological meeting in the UK since 2009. The BSM2017 aims to re-start regular meetings of seismologists that work in and with the UK, both in the public and commercial sectors.

After all, Britain has so many talents to be proud of, to name a couple such as the Father of instrumental Seismology and the founder of the BAAS/ISS/ISC, Prof. John Milne, as well as Sir Harold Jeffreys, the Statistician, Astronomer, Geophysicist and one of the ISS Directors. This meeting aims to celebrate the current generation's geophysical expertise and, given recent events, should also help to strengthen collaborations between British and European scientists. I am also hopeful that one of the British institutions will pick up the baton from the ISC and organise the next BSM in two or three years from now.

I would like to thank *AWE*, the sponsor of our student conference grants, the *British Geophysical Association (BGA)* and *Güralp Systems Ltd*., all of whom have kindly supported this conference right from the beginning.

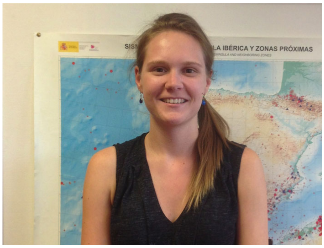
On behalf of the ISC, I welcome all BSM participants and look forward to an exciting scientific meeting with 45 oral presentations and 45 posters.

Dr Dmitry A. Storchak
Director
International Seismological Centre (ISC)
Thatcham, Berkshire, UK

# BSM2017 Organising Committee

The following members of ISC staff have been exceptionally busy organising and preparing for the British Seismology Meeting.


**Dr Elizabeth Entwistle**
ISC Seismologist




**Dr Jennifer Weston**
ISC Seismologist

**Dr Dmitry A. Storchak**
ISC Director

**Lynn Elms**
ISC Administrator

# International Seismological Centre (ISC)

The ISC is a non-governmental, non-profit international organization charged with maintaining the definitive global long-term record of earthquakes and other seismic events. We recently celebrated our 50th anniversary whilst our mission dates back to early 1900s.


We are supported by 67 institutions in 49 countries (including the Royal Society, BGS and AWE Blacknest in the UK) as well as 12 public and commercial sponsors (including Aon Benfield, Lloyds, Guy Carpenter, Catlin and Guralp in the UK).

The ISC is located in Thatcham, Berkshire, a 20-minute train ride away from the BSM venue and very close to AWE Blacknest and Guralp. The ISC has 19 members of staff from 10 countries. In collaboration with ~130 seismic networks worldwide, we provide the following datasets and services that are widely used in Geoscience research and several civil applications:

- ISC Bulletin (1900-2017)
- International Seismographic Station Registry
- IASPEI Reference Event List (GT)
- ISC-GEM Global Instrumental Earthquake Catalogue (1900-2013)
- ISC-EHB bulletin
- ISC-Event Bibliography
- CTBTO Link to the ISC database
- International Registry of Seismological Contacts

You will find both oral and poster presentations on the ISC products throughout BSM2017. More information on the ISC and our mission can be found at the ISC booth, located at the back of Victoria Hall. Alternatively, look out for the ISC staff members in red polo shirts.

# Media

To find out more about the ISC or BSM2017, please visit our websites or follow us on social media.

## ISC

| | |
|---|---|
| ISC Webpage | http://isc.ac.uk/ |
| Follow ISC on twitter **@ISCseism** | https://twitter.com/ISCseism |
| Follow ISC on Facebook | https://www.facebook.com/ISCseism |

## BSM2017

| | |
|---|---|
| BSM2017 Webpage | http://bsm2017.isc.ac.uk/ |
| Follow #BSM2017 on twitter | https://twitter.com/hashtag/bsm2017 |

# Sponsors and Exhibitors

BSM2017 would like to thank all of our generous sponsors and exhibitors, whose contributions have helped with the organisation and preparation of this meeting.

Thanks to AWE, 8 conference grants have been awarded to current Ph.D. and M.Sc. students. Their scientific contributions are highlighted in the talk and poster schedules by †.

# Conference Information

## About

The British Seismology Meeting 2017 aims to bring together seismologists from the UK and abroad to present and discuss a wide range of seismological research. We hope this will be an opportunity to strengthen and establish new links within and between seismological communities and industries. Moreover, with the help of UK Universities, we hope this will become a regular feature on the calendar of UK seismologists.

## Venue

The conference will be held in Reading Museum and Town Hall, a grade II listed building in the centre of Reading. Talks and exhibitions will take place in Victoria Hall on the first floor, which was originally part of the Georgian Assembly Rooms and is the oldest room in the Town Hall. The posters will be located in the 3Bs room on the ground floor. The Town Hall is only a 5-minute walk from the train station. Please note there are no car parking facilities at the venue.

**Registration:** *Wednesday 5th April, 13:00-14:-00*

The registration desk will be located at the top of the stairs on the first floor, just follow the signs for BSM2017.

**Icebreaker:** *Wednesday 5th April, 18:00-19:00, 3Bs*

On the first evening of the conference there will be an icebreaker in 3Bs (ground floor of Town Hall). Two free drinks (one alcoholic, one non-alocholic) for each participant, we hope to see you there!

**Conference Dinner:** *Thursday 6th April, 19:00-00:00, Crowne Plaza*

The conference dinner takes place at the Crowne Plaza, Reading, a 20 minute walk from the conference venue. It will be held in the Riversuite, overlooking the River Thames with welcome drinks on arrival, followed by a three course meal, and tea and coffee. A cash bar will also be available throughout the evening's festivities.

# Places to eat and drink

For when you are not at the conference and are hungry or thirsty, please find some suggestions below. We haven't been to all of them but most come highly recommended!

**The Oracle**

This is the shopping centre in the middle of Reading and it is only a 5-10 minute walk from the Town Hall. You'll find your easiest and quickest options for food here as there are many restaurants (mostly chains) within a 1-2 minute walk of each other. Just outside the Oracle, down by the river, there are several restaurants covering a range of cuisines; British, Portuguese, Japanese, Mexican.

**Workhouse Coffee** (King Street)

We highly recommend this place for all your coffee needs. It is independent and serves the best cup of coffee in town (in Jen Weston's opinion!). Plus, it has ridiculously tasty cakes and breakfast delights. For anyone staying at the George Hotel, this coffee shop is just next door.

**Picnic** (5 Market Place)

A lovely café a few minutes walk from the Town Hall, Picnic should satisfy all your coffee, tea, cake, smoothie and light lunch needs.

**Pepe Sale** (Queens Walk)

An excellent Italian restaurant. They make their pasta fresh every morning and have won awards for their food. It is slightly more expensive than your usual chain but we have been told it is worth it.

**Sushimania** (Queens Walk)

Very good fresh sushi….enough said!

**Coconut Bar & Kitchen** (63 St Mary's Butts)

A wide range of Japanese, Chinese, Korean and Thai delicacies, plus cocktails.

**Royal Tandoori** (4-8 Duke Street)
Excellent Indian food with an extensive menu.

**Zerodegrees** (9 Bridge Street)
For beer lovers who are hungry, this is a reasonably priced microbrewery and restaurant.

# Schedule

## WEDNESDAY 5th APRIL

**13:00 – 14:00**

REGISTRATION

**14:00 – 14:15**

Welcome: Dmitry Storchak, Elizabeth Entwistle and Jennifer Weston (ISC)

| **Session 1: The rise of induced seismicity**<br>Chaired by: Domenico Di Giacomo | | |
|---|---|---|
| **14:15** | **Torsten Dahm**, S. Hainzl & S. Cesca | Invited: The weal and woe of induced seismicity |
| **14:45** | † **Miles Wilson**, G. Foulger, R. Davies, J. Gluyas, et al. | Global review of induced and triggered earthquakes |
| **15:00** | **Antonio Villaseñor**, R.B. Herrmann, B. Gaite & A. Ugalde | Focal depths and mechanisms of induced earthquakes in the 2013 seismic sequence near the CASTOR Underground Gas, northeast coast of Spain |
| **15:15** | **Ian Main**, X. Li & A. Jupe | Induced seismicity at the UK 'Hot Dry Rock' test site for geothermal energy production: a new mechanism |
| **15:30** | **Anna Horleston** & D. Hawthorn | Anthropogenic noise on temporary seismic networks: implications for monitoring arrays in the UK |
| **15:45** | **Richard Luckett**, A. Butcher & B. Baptie | Local magnitudes at short distances |

**16:00 – 16:30 COFFEE**

| Session 2: Investigating unusual signals<br>Chaired by: David Bowers | | |
|---|---|---|
| **16:30** | **Steven Gibbons** | Invited: Accurate seismic event location: A question of context |
| **17:00** | **Kostas Lentas,** I. Bondár, E.Bergmann & E.R. Engdahl | Reference Event List (GT) for monitoring purposes |
| **17:15** | **Anton Ziolkowski** | Yields, source time functions and depths of North Korean announced nuclear tests |
| **17:30** | **Jennifer Stevanovic**, N. Teanby, J. Wookey, N. Selby, et al. | Bolide airbursts as a seismic source for the 2018 Mars InSight mission |

**18:00 – 19:00 ICEBREAKER**

**3Bs, Reading Town Hall**

## THURSDAY 6th APRIL

| Session 3: Passive sources and sensitive signals<br>Chaired by: Elizabeth Entwistle | | |
|---|---|---|
| **08:30** | **Eleonore Stutzmann**, M. Meschede, V. Farra, et al. | Invited: Frequency dependent microseism sources |
| **09:00** | **George Taylor**, S. Rost, G. Houseman & G. Hillers | Upper crustal structure of the North Anatolian Fault Zone from ambient seismic noise surface wave tomography |
| **09:15** | **Benjamin Schwarz**, A. Bauer & D. Gajewski | Using diffractions as passive source wavefields: A traveltime moveout perspective |
| **09:30** | **Anna Stork**, C. Allmark, A. Curtis, et al. | The feasibility of detecting CO2 leaks using passive seismic monitoring |
| **09:45** | **Jonathan Singh**, I. Main, A. Curtis, A. Cartwright-Taylor, et al. | Seismic Signals from Digital Rocks |
| **10:00** | **Alan Baird**, J.-M, Kendall & J. Budge | Discriminating between fractures and fabrics in a highly anisotropic shale using shear-wave splitting |

**10:15 – 10:45 COFFEE AND POSTERS (3Bs)**

| **Session 4: Understanding Earth's faults**<br>Chaired by: Jennifer Weston | | |
|---|---|---|
| **10:45** | **Tom Mitchell** | Invited: Earthquake fracture damage and healing in the seismic cycle |
| **11:15** | † **Christopher Harbord,** S. Nielsen, N. De Paola & R. Holdsworth | Frictional instability of rough faults |
| **11:30** | **Jessica Hawthorne**, A. M. Thomas & J-P. Ampuero | Estimating the rupture extent of low frequency earthquakes near Parkfield, CA |
| **11:45** | **Simone Mancini** & M. Segou | Physics-based modelling of the 2016 Amatrice (central Italy) earthquake sequence |
| **12:00** | **Ragnar Slunga** | Estimating the complete stress tensor field from microearthquake observations |

**12:15 – 13:15 LUNCH AND POSTERS (3Bs)**

| Session 5: How hazardous?<br>Chaired by: Dmitry A. Storchak | | |
|---|---|---|
| **13:15** | **Roland Roberts**, R. Bödvarsson, O. Gudmundsson, B. Lund, et al. | The Swedish National Seismological Network: Hazard assessment in a low-seismicity intraplate area |
| **13:30** | **Gloria Senfaute** | Probablistic seismic hazard assessment in low-to-moderate seismicity regions: outcomes from the SIGMA research program |
| **13:45** | **Lizhong Zhang**, M.J. Werner & K. Goda | A time-dependent seismicity model for south-western British Columbia, Canada |
| **14:00** | **Emmanuel Viallet**, N. Humbert & P. Mottier | Updating of a PSHA based on a Bayesian inference with historical macroseismic intensities |
| **14:15** | **Amy Gilligan**, N. Rawlinson, F. Tongkul & R. Stephenson | Developing a seismic hazard model for Sabah, East Malaysia, using seismic and geodetic data |
| **14:30** | **Domenico Di Giacomo,** E.R. Engdahl, D.A. Storchak & J. Harris | The ISC-GEM Global Instrumental Earthquake Catalogue (1900-2013) for hazard purposes |

**14:45 – 16:45**
**COFFEE & POSTER SESSION (3Bs)**

## Session 6: Catalogues: Power and completeness

Chaired by: Steven Gibbons

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|---|---|---|
| **16:45** | **Yuzo Ishikawa** | Difficulty of the determination of hypocenters in early 20 century |
| **17:00** | **Raul Castro**, J.M. Stock, E Hauksson & R.W. Clayton | Seismicity (M>3.0) in the period between 2002-2014 and active tectonics in the Gulf of California, Mexico |
| **17:15** | **Pierre Arroucau**, J. Grannell, S. Lebedev, C. Bean, et al. | New earthquake detections in Ireland from waveform template matching by cross-correlation |
| **17:30** | **Marleine Brax**, C. Beauval, P. Albini & R. Jomaa | An earthquake catalog for seismic hazard assessment in Lebanon |
| **17:45** | **Dmitry A. Storchak**, J. Harris & D. Di Giacomo | The ISC Datasets and Services |

**18:30 – Meet to walk over to conference dinner**

**19:00 – 00:00 CONFERENCE DINNER @ Crowne Plaza, Reading**
**Invited Talk by Roger Musson**

# FRIDAY 7th APRIL

| Session 7: Imaging the Earth at all scales<br>Chaired by: Karin Sigloch | | |
|---|---|---|
| **08:45** | **Maria Tsekhmistrenko**, K. Sigloch & K. Hosseini | Multifrequency measurements of P waves on ocean bottom seismometers in the Indian Ocean |
| **09:00** | **Keith Priestley** & A. Gilligan | Variations in lithospheric structure across the Indo-Eurasian collisional belt |
| **09:15** | **James Hammond** | Evidence for partial melt in the crust beneath Mt. Paektu/Changbaishan |
| **09:30** | **Andy Nowacki** & S. Rost | Invited: A low-velocity pipe-like structure at the base of the mantle beneath Hawaii inferred from focussing of seismic waves |
| **10:00** | **Paula Koelmeijer**, B. Schuberth, R. Davies & J. Ritsema | Constraints on the presence of post-perovskite in Earth’s lowermost mantle from tomographic-geodynamic model comparisons |
| **10:15** | **Kasra Hosseini** & K. Sigloch | Global seismic tomography using teleseismic and core-diffracted body waves |

**10:30 – 11:00 COFFEE**

| **Session 8: Dealing with big data**<br>Chaired by: Lonn Brown | | |
|---|---|---|
| **11:00** | **Tarje Nissen-Meyer**, K. Leng, M. van Driel, et al. | Invited: Appraising Occam: On the interaction of seismic waves with structure |
| **11:30** | † **Kuangdai Leng**, T. Nissen-Meyer, K. Hosseini, et al. | Global wavefield modeling in 3-D crustal structures |
| **11:45** | **Nicholas Rawlinson** | Seismic tomography: From damped least squares to transD |
| **12:00** | **Natalia Poiata** | Locating seismic sources with an automated multi-scale array-based detection and location scheme |
| **12:15** | **Karin Sigloch** & S.C. Stähler | Fully probabilistic seismic source inversion |
| **12:30** | **Jennifer Weston,** E.R. Engdahl, J. Harris, D.A. Storchak & D. Di Giacomo | ISC-EHB: Reconstructing the EHB earthquake database |

**12:45 – 12:50 Closing Remarks**

# Poster Schedule for Thursday 6th April

| Poster No | Authors | Title |
|---|---|---|
| **Session 1: The rise of induced seismicity** | | |
| 1 | **Antony Butcher**, J. Verdon, R. Luckett, et al. | Magnitude discrepancies and characterisation of mining events at New Ollerton, UK |
| **Session 2: Investigating unusual signals** | | |
| 2 | **Ross Heyburn** & D. Bowers | Seismic and Hydroacoustic Observations from Underwater Explosions off the East Coast of Florida |
| 3 | **Sheila Peacock** & J. Young | AWE Blacknest archive of seismic recordings of presumed underground explosions, 1964-1996 |
| 4 | **Sheila Peacock** | Maximum-likelihood magnitudes of announced underground nuclear tests by the Democratic People's Republic of Korea, 2006-2016 |
| 5 | **Irina Gabsatarova**, A.A. Malovichko & O. E. Starovoit | Seismic monitoring of the North Korea nuclear test site by Russian seismic stations |
| **Session 3: Passive sources and sensitive signals** | | |
| 6 | **Abderrahmane Haned,** E. Stutzmann, M. Schimmel, et al. | Global tomography using seismic hum |
| 7 | **Laura Ermert**, K. Nishida, K. Sager, et al. | Mapping primary microseism sources in and around the Sea of Japan |
| 8 | † **Emma Chambers**, N. Harmon, D. Keir, et al. | Using ambient noise to image melt in the Northern East African Rift System |

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|---|---|---|
| 9 | **Emily Crowder,** N. Rawlinson & D. Cornwell | Seismic imaging without a source: towards cost effective and low environmental impact hydrocarbon exploration |
| 10 | Emma Smith, **A.F. Baird**, J.M. Kendall, et al. | Ice fabric in an Antarctic ice stream interpreted from seismic anisotropy |
| **Session 4: Understanding Earth's faults** | | |
| 11 | **Stuart Nippress**, R. Heyburn & R. Walters | Relocating earthquake clusters across Iran |
| 12 | **Joshua Williams**, J. Hawthorne, S. Rost, et al. | Stress drops for the M ≥ 4.0 earthquake catalogue of the Blanco Oceanic Transform Fault |
| 13 | † **Roseanne Clement**, I. Main & A. Bell | Do large earthquakes nucleate as a result of repeating earthquake sequences? |
| 14 | † **Ghizlane Bouskri**, M. Elabbassi, A. Ammar, et al. | Seismological and seismic reflection imaging of active faults and their tectonic behavior in the Northern Moroccan margin |
| 15 | **Assia Dib,** M. Bezzeghoud, B. Caldeira, et al. | Seismicity along the seismogenic zone of Algarve region (southern Portugal). |
| 16 | **Kostas Lentas** & D.A. Storchak | Towards routine determinations of earthquake focal mechanisms obtained from P-wave first motion polarities |
| 17 | **Mohamed El Messaoud Derder,** P. Robion, S. Maouche, et al. | Neotectonic model of northern Algeria: Blocks tectonic rotations revealed by new paleomagnetic data |
| **Session 5: How hazardous?** | | |
| 18 | **Ilaria Mosca** | Integrating outcomes from probabilistic and deterministic seismic hazard assessment |
| 19 | **Farida Ousadou**, N. Benbelkacem & A. Ayadi | Empirical relation scaling $I_0$, $M_d$ and $M_w$ for Algeria towards a homogenization of the |

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|---|---|---|
| | | seismic catalogue |
| 20 | **Nato Jorjiashvili** | Local soil effects on the Ground Motion Prediction model for the Racha region in Georgia |
| 21 | Irmela Zentner, **G. Senfaute** & Ch. Durouchoux | Analysis of different statistical methods to estimate and represent Mmax in PSHA based on the truncated GR model |
| 22 | **Laouami Nasser** | Spectral Ground-motion Predictive Model for Algeria considering site effect based HVSR |
| 23 | **Gherboudj Faouzi** & L. Nasser | Site specific PSHA application with scalar and vector approach |
| 24 | **Nourredine Mezouar**, A. Messaoudi & M. Hadid | The use of real accelerograms as input to dynamic analysis |
| **Session 6: Catalogues: Power and completeness** | | |
| 25 | **Tanja Fromm** & A. Ecksteller | Permanent and temporary seismology at Neumayer III, Antarctica |
| 26 | **Tamara Jesenko** & M. Živčić | Modernisation of Slovenian seismic network: progress or just collection of data |
| 27 | **Roland Roberts**, R. Bödvarsson, O. Gudmundsson, et al. | Seismological research in Sweden: Current status and some highlights. |
| 28 | **Domenico Di Giacomo**, E. Ayres & D.A. Storchak | The ISC Event Bibliography: An update |
| 29 | **Lonn Brown**, J. Harris, K. Lieser, et al. | The rebuild of the ISC bulletin |
| 30 | **Edith Korger** & K. Lieser | Advancing the ISC Bulletin with the data from temporary seismic deployments |

| Session 7: Imaging the Earth at all scales | | |
|---|---|---|
| 31 | **Jennifer Jenkins,** R. Green, S. Cottaar, et al. | Constraints on Icelandic Crustal structure from Receiver function analysis |
| 32 | **Kherroubi Abdelaziz**, I. Koulakov, A. Yelles, et al. | The Boumerdes (Algeria) earthquake of May 21st, 2003 (Mw: 6.8): Tomographic inversion |
| 33 | † **Afsaneh Mohammadzaheri** & K. Sigloch | Multi-frequency Inversion of P-waves under America |
| 34 | † **Raffaele Bonadio**, P. Arroucau, S. Lebedev, et al. | Surface-wave tomography of Ireland, Britain and surroundings |
| 35 | **Mania Sabouri** & M.R. Gheitanchi | Attenuation of seismic waves in southeast Iran (Gheshm region) |
| 36 | **Harriet Godwin**, K. Leng, J. Gonzalez Santana, et al. | Seismological studies of the multi-scale core-mantle boundary landscape |
| 37 | **Eoghan Totten**, K. Sigloch, T. Nissen Meyer, et al. | Slab behaviour in the mantle transition zone |
| 38 | **Agnieszka Plonka** & A. Fichtner | Resolvability of regional density structure - a principal component approach to resolution analysis |
| 39 | **Elodie Kendall**, A Ferreira & C. lithgow-Bertelloni | Waveform modelling of 3-D seismic anisotropy in the Earth's mantle |
| 40 | **Sophie Lambotte** & C. Zaroli | Global tomography using normal-mode data: a synthetic-case investigation |
| 41 | Tak Ho, **K. Priestley** & E. Debayle | A new global upper mantle radial anisotropic model from multi-mode surface wave observations |

| Session 8: Dealing with big data | | |
|---|---|---|
| 42 | Arjun Datta, **K. Priestley**, C. Chapman, et al. | Surface wave mode conversion due to lateral heterogeneity and its impact on waveform inversions |
| 43 | **Christophe Zaroli** | Global seismic tomography using Backus-Gilbert inversion |

# Invited Speakers

**Professor Torsten Dahm**

GFZ German Research Centre for Geosciences, Germany

*torsten.dahm@gfz-potsdam.de*

**Wednesday 5th April, 14:15**

Head of the Seismology Group at the University of Hamburg from 2000-2012, and now head of Physics of Earthquakes and Volcanoes at the Helmholtz Centre Potsdam (GFZ), Torsten Dahm began his career in seismology whilst studying for his Ph.D. at the University of Karlsruhe, Germany, from 1990-1994. Torsten's broad research interests include earthquake physics and induced seismicity, the physics of fractures, theoretical and experimental seismology, and marine broadband seismology. Torsten is the German representative for both IASPEI and the EPOS Working Group on Induced Seismicity.

**The weal and woe of induced seismicity**

**Torsten Dahm**[1], S. Hainzl[1], S. Cesca[1]

[1] GFZ German Research Centre for Geosciences, Potsdam, Germany

Earthquakes are caused by stresses exceeding the strength of faults. Stresses may be of tectonic or natural origin, but may also be induced by human activity. Stable continental regions are often low seismicity areas, and any human related earthquake is percepted/received as „outstanding“, whether it may be small or not. But can we exclude large, significant intra-plate earthquakes? Can we discriminate tectonic-induced from human-induced earthquakes at all?

The study of induced microearthquakes is challenging and shows us the limits of our current monitoring and analysis approaches. How can we measure very shallow Ml 0.5 events, and how do we know that our magnitude scale is correct? How can we verify the completeness of catalogs of induced earthquakes, and is a statistical approach valid at all, if the human-induced stresses are quickly changing?

These questions and the ongoing discussions on anthropogenic earthquakes bear a high potential to advance our understanding of the earthquake generation processes. The presentation will focus on physics-based seismicity models to understand cases of induced seismicity, and how frequency magnitude distributions can be interpreted. Questions how to define and assess reliable catalogs of induced earthquakes and the complementary meta data parameters are discussed, together with the questions how the lesson's learned from induced seismicity possibly affect our understanding of tectonic main-shock aftershock sequences and the studies of stress shadows.

**Dr Steven Gibbons**

NORSAR, Norway

[steven@norsar.no](mailto:steven@norsar.no)

**Wednesday 5th April 16:30**

Steven Gibbons completed his Ph.D. in 1998 on the subject of numerical geodynamo modelling and has been employed at NORSAR since 2002. Steven is now a research geophysicist within the programme for Array Seismology and Test-Ban-Treaty Verification at NORSAR, where his primary research interests are array processing for seismic signals and full waveform methods for improving the detection capability in the seismic monitoring of nuclear explosions.

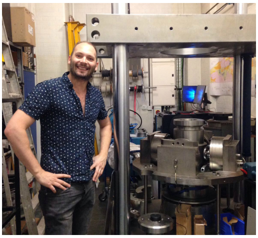
**Accurate Seismic Event Location: A Question of Context**

**Steven Gibbons**[1]

[1] NORSAR, PO Box 53, 2027 Kjeller, Norway

2017 marks the 50th anniversary of Alan Douglas' paper "Joint Epicenter Determination". He demonstrated that by considering multiple seismic events simultaneously, significant differences between the applied velocity model and true earth structure could be resolved and compensated for resulting in event location estimates with greatly reduced bias and uncertainty. Since then, there have been great advances in models of earth structure and the accuracy of both teleseismic and regional traveltime estimates has improved dramatically. However, a great amount of global seismicity still occurs in regions with very limited station coverage and significant error in estimates for seismic traveltimes can lead to significant event mislocation and a very blurred image of seismicity. We present two case studies in which larger events are constrained well teleseismically but many far smaller events are well-recorded only at regional distances on networks with limitations in geographical coverage. Current catalogs of aftershocks of the October 8, 2005, Kashmir earthquake describe a cloud of seismicity with a length-scale exceeding 100 km. A careful, step-wise, application of the Bayesloc program results in a far more structured image of the source region. This contextual location of all events, both large and small, generates implicit corrections for the large

regional traveltime deviations which - uncorrected - result in unacceptable event mislocations. The seismic network in the European Arctic has improved greatly over the past 15 years but the improvement in the seismic bulletins for ridge events has been very modest. Again, Bayesloc finds a likely distribution of event locations for which the traveltime residuals for given phases are spatially consistent, and solves for traveltime corrections. So-called precision seismology has vastly improved relative event location estimates over short distances for which waveform similarity is observed. For example, the declared nuclear tests in North Korea can be located relative to each other to within an accuracy of the order of 100-200 meters. However estimates made using only teleseismic phases have shown to be significantly different to those made using only regional phases. Users of seismic arrays are familiar with the observation of incoming wavefronts that differ significantly in direction and incidence angle from those predicted, due to near-receiver structure. The same is likely to apply in the source region to the outgoing wavefield but this is not accounted for in most double-difference type location calculations. By examining the delay times observed on regional phases in the context of those measured on steeply diving teleseismic phases we can solve for a set of corrections which make regional and teleseismic estimates consistent. Treating the different events as a source-array, we can image how the wavefield recorded at regional and global distances appears to leave the source region and better predict how the traveltime for different phases is likely to change with the precise event location. Precision seismology will improve greatly if it can encompass the progress made in the context-based multiple event location algorithms and account for deviations from the applied models resulting from features on smaller length scales than are currently amenable to modelling.



**Dr Tom Mitchell**

University College London, UK

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**Thursday 6th April 10:45**

Tom Mitchell obtained his Ph.D. degree from the University of Liverpool in 2007 and has since completed post-doctoral fellowships at Hiroshima University, Japan, Ruhr University, Germany, and INGV, Italy. As of September 2013, Tom has been based at University College London, UK, where he is now a reader in Earthquake Geology and Rock Physics. Tom's primary research aim is to relate laboratory work with nature, focussing on the interpretation of processes such as faulting, and the understanding of properties of strike-slip fault zones over a range of scales.

**Earthquake fracture damage and healing in the seismic cycle**

**Tom. M. Mitchell**[1]

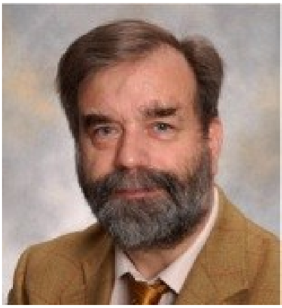
[1] Department of Earth Sciences, University College London, Gower Street, London, UK

The importance of the damage zone in the faulting and earthquake process is widely recognized, but our understanding of how damage zones are created, what their properties are, and how they feed back into the seismic cycle, is remarkably poorly known. Firstly, damaged rocks have reduced elastic moduli, cohesion and yield strength, which can cause attenuation and potentially non-linear wave propagation effects during ruptures. Secondly, damaged fault rocks are generally more permeable than intact rocks, and hence play a key role in the migration of fluids in and around fault zones over the seismic cycle. Finally, the dynamic generation of damage as the earthquake propagates can itself influence the dynamics of rupture propagation, by increasing the amount of energy dissipation, decreasing the rupture velocity, modifying the size of the earthquake, changing the efficiency of weakening mechanisms such as thermal pressurisation of pore fluids, and even generating seismic waves itself . All of these effects imply that a feedback exists between the damage imparted immediately after rupture propagation, at the early stages of fault slip, and the effects of that damage on subsequent ruptures

dynamics. As such, investigating the relative contributions of individual ruptures to cumulative off-fault damage is critical to fully understand the earthquake energy budget.

In recent years, much debate has been sparked by the identification of so-called ‘pulverized rocks’ described on various crustal-scale faults, a type of intensely damaged fault rock which has undergone minimal shear strain, and the occurrence of which has been linked to damage induced by transient high strain-rate stress perturbations during earthquake rupture. Damage induced by such transient stresses, whether compressional or tensional, likely constitute heterogeneous modulations of the remote stresses that will impart significant changes on the strength, elastic and fluid flow properties of a fault zone immediately after rupture propagation, at the early stage of fault slip. In this contribution, we will demonstrate laboratory and field examples of two dynamic mechanisms that have been proposed for the generation of pulverized rocks; (i) compressive loading by high-frequency stress pulses due to the radiation of seismic waves and (ii) explosive dilation in tension in rocks containing pressurized pore fluids. Our combined field, experimental and theoretical studies suggest that the passage of a rupture can lead to significant permanent variations in fault damage structure leading to changes in strength, stiffness and off-fault permeability, directly effecting fault weakening processes such as thermal pressurization, and hindering further rupture propagation.

From a seismologists point of of view, such off-fault coseismic fracture damage at depth can be inferred from reductions of crustal seismic velocity following large earthquakes. A growing body of geophysical evidence exists for ‘healing’ processes occurring in the crust following such earthquakes, inferred from time-dependent increases in seismic velocity lasting from days to years. This decrease in velocity has been attributed to coseismic fracturing, whereas the mechanisms that drive the recovery of velocities are poorly understood. If such velocity changes are due to fracture healing, little is known about the controls on co-seismic microfracture damage healing rates. We demonstrate that fractured granite samples placed in a hydrostatic permeameter and ‘cooked’ at 130 ◦C at 80 MPa effective pressure (shallow crustal conditions) for just 50 hours show significant decreases in P-wave velocity due to pervasive microfracture healing.



**Dr Roger Musson**

British Geological Survey, UK

*rogermusson@gmail.com*

**Thursday 6th April**
**Conference Dinner**

Roger Musson joined the Institute of Geological Sciences (subsequently British Geological Survey) in 1980 and in a 34-year career was responsible for the study of historical earthquakes, macroseismology, and the development of seismic hazard methodology. Since retirement, he retains an honorary position with the British Geological Survey, with the School of Geosciences, Edinburgh University, and also works as a private consultant. Particular achievements include the compilation of the historical earthquake catalogue for the UK, co-authorship of the European Macroseismic Scale, and the development and popularisation of the use of simulations as a method of undertaking probabilistic seismic hazard assessment.

**A history of macroseismology in the UK**

**Roger Musson**[1]

[1] British Geological Survey, Lyell Centre, Edinburgh, UK

Scholarly investigations of earthquake effects in Britain can be traced back as far as the second half of the 17th Century, and these continued through the 18th century under the auspices of the Royal Society. In the 19th century, it was the British Association for the Advancement of Science that took the leading role. These early investigations collected macroseismic data, but were purely descriptive; although forerunners of intensity scales appeared quite early in Italy, it was not until the 1880s that the concept of a numerical intensity scale became widely known. It was adopted and modified in Britain by Charles Davison, a Birmingham schoolmaster and amateur seismologist, who single-handedly undertook macroseismic investigations of most British earthquakes from 1889 to 1926. After this, his work was continued fitfully by various people, chiefly the geologist ATJ Dollar, of

Glasgow University and later, Birkbeck College London. Macroseismology was not put on any official standing in the UK until regular intensity surveys were developed by the Institute of Geological Sciences (subsequently British Geological Survey) in the early 1970s. Paper-based questionnaires were replaced by internet ones in 2006, and this system remains in use today.

**Dr Tarje Nissen-Meyer**

University of Oxford, UK

*tarjen@earth.ox.ac.uk*

**Friday 7th April 11:00**

Tarje Nissen-Meyer is both an associate professor of geophysics at the University of Oxford, UK, and an adjunct scientist at Lamont-Doherty Observatory, Colombia University, New York. After graduating with a Ph.D. degree from Princeton University, USA, in 2007, Tarje went on to post-doctoral positions at the California Institute of Technology, USA, and Princeton University, and was a senior research scientist at ETH Zurich, Switzerland. Tarje's main research focusses on deciphering the Earth's interior using seismic waves, with topics of interest including, but certainly not limited to, deep Earth structure, seismic tomography, noise interferometry, seismic hazard, and high-performance computing. Tarje developed the axisymmetric spectral-element method (AxiSEM) which is now used by many groups worldwide.

**Appraising Occam: On the interaction of seismic waves with structure**

**Tarje Nissen-Meyer**[1], K. Leng[1], M. van Driel[1], K. Hosseini[1], L. Krischer[1], S. Staehler[1], M. Pienkowska[1]

[1] Department of Earth Sciences, University of Oxford, Oxford, UK

Deciphering our planet's inner workings requires a deep understanding of how seismic observations encode information about their source and interaction with heterogeneous multi-scale structure. Inferring from those data, a snapshot of any given region of interest then relies upon choosing and processing informative data, accurate wave physics, and a reliable inversion (or alternative inference) procedure. Unfortunately, unresolved issues remain on all ends: Data are recorded in an extremely irregular fashion; scales of physical relevance extend over orders of magnitude in space-time; the computation of full-wave solutions is prohibitively expensive even on the largest supercomputers; and inversions are nonlinear, ill-posed, non-unique and unverifiable. Consequently, inevitable choices and approximations ought to be made to render this procedure at least somewhat feasible. To obtain robust images for geophysical interpretation, it is paramount to

choose from a sea of options wisely, and to consider uncertainties in the light of this subjective bias where possible. In this presentation, we will argue for honoring problem-specific sparsity in data, structure and modeling, which can be interpreted in the context of Occam's razor. We will focus on how to tackle the daunting computational cost while adhering to sufficiently accurate wave physics to address various geophysical problems between core and the crust. Examples include propagating global surface waves through complex 3D crustal structures, ambient noise generation in the oceans, large kinematic earthquakes, small-scale mantle scattering, lowermost mantle dynamics, inner-core anisotropy, wavefields on extraterrestrial bodies, and global tomography with diffracted waves. We will touch upon implications for two central questions: How do waves interact with, encode, and forget signals from complex structure? Can we possibly retrieve such complex structures from surface observations, or are our images fueled and fooled by Occam?

**Dr Andy Nowacki**

University of Leeds, UK

*a.nowacki@leeds.ac.uk*

**Friday 7th April 09:30**

Andy Nowacki is currently a Leverhulme Early Career Fellow at the University of Leeds, studying "The Secret History of the Earth's Mantle", which aims to investigate the lowermost mantle using observations and simulations of seismic waves emitted by earthquakes. Andy was awarded his Ph.D. degree from the University of Bristol, UK, in 2012, and continued to work at Bristol until 2015 as a post-doctoral research assistant. Some of Andy's research interests include D" structure and anisotropy, mantle flow, and microseismicity beneath volcanoes and in reservoirs.

**A low-velocity pipe-like structure at the base of the mantle beneath Hawaii inferred from focussing of seismic waves**

**Andy Nowacki**[1], S. Rost[1]

[1] School of Earth and Environment, University of Leeds, LS2 9JT, UK

Most of the Earth's lower mantle appears to be remarkably uniform in seismic velocity, with variations typically within one percent of the radial average as imaged tomographically. However, this is not true in the few hundred kilometres above the core–mantle boundary (CMB), known as D″. Here, much stronger variations in velocity hint at the presence of complex structures. On the large scale, two Large Low-Shear Velocity Provinces (LLSVPs) have S-wave velocity reductions of ~3% and dominate D″. Placed antipodally beneath Africa and the Pacific, they are the subject of debate regarding their origin. Variously, it has been proposed that they are large thermal upwellings, piles of chemically distinct, dense material, or clusters of smaller thermal plumes. These cases cannot currently be distinguished by tomography, because its resolution is too limited by sparse sampling and necessary smoothing. Hence we look to other ways to investigate D″ structure. We examine P and Pdiff waves from Pacific rim earthquakes for evidence of strong deviations in their propagation. This is a clear sign that strong lateral changes in velocity have occurred somewhere along their travel path. Events in this region give us good coverage of D″ at the edge of the Pacific LLSVP. We use the medium aperture, short-period, vertical component Yellowknife array in northern Canada to measure deviations in backazimuth and slowness from their theoretical values in a 1D Earth model, using the F-statistic to obtain high precision data. We also examine S and Sdiff waves using the Polaris network, also in Canada. We find that in some cases, P/Pdiff arrives up to 15° away from the expected great-circle direction. Backazimuthal deviations vary consistently and systematically with the location of the diffraction path or turning point of the wave. Non-diffracted P waves turn at most 300 km above the CMB, and there is no clear variation of backazimuthal deviation with turning depth, suggesting that the structure which causes the observations rises at least this far above the CMB, and that its shape or size does not change very much radially. Numerical forward modelling shows that the observations can be recreated by the presence of a cylinder of low P-wave velocity with diameter ~200 km, located just northwest of Hawaii, rising to at least 300 km above the CMB. A P-wave velocity reduction of ~10% is required to fit the pattern and amplitude of backazimuthal deviations. Unfortunately, no constraint on density is possible using body waves in this way, so the structure could be less dense, denser or have the same density as the surrounding mantle. Our results demonstrate that the lowermost mantle is more heterogeneous and complex than even previously shown, and that we are able to resolve small-scale structures which are invisible tomographically. Moreover, we speculate that, because the feature we see is so close to the Hawaiian hot-spot, there may be a connection between it and present-day intraplate volcanism there, supporting the idea that it is due to a deep-seated mantle plume arising at the CMB.

**Dr Eleonore Stutzmann**

Institut de Physique du Globe de Paris (IPGP), France

*stutz@ipgp.fr*

**Thursday 6th April, 08:30**

Eleonore Stutzmann is currently the director of the seismology group at IPGP, France, and was previously the director of the GEOSCOPE observatory, whose data are used by both the French and the international scientific communities. Eleonore completed her Ph.D. at IPGP and went on to a post-doctoral position at the University of Utrecht, Netherlands, between 1993-1994. On returning to IPGP, Eleonore has been involved in the RHUM-RUM project, investigating the La Réunion mantle plume from crust to core using ocean bottom seismometers, and she is now the principal coordinator on the MIMOSA project looking at the modelling and application of seismic noise recorded on broadband seismometers.

**Frequency dependent microseismic sources**

**Eleonore Stutzmann**[1], M. Meschede[1], V. Farra[1], M. Schimmel[2], F. Ardhuin[3]
[1] Institut de Physique du Globe de Paris (IPGP), CNRS, France
[2] CSIC-IICTJA, Barcelona
[3] IFREMER, CNRS, Brest

The Earth’s seismic wave field is mostly generated in the oceans as a result of ocean wave interactions. We analyze secondary microseisms, that is seismic signals in the period band 3-10 s, that is generated by ocean wave-wave interactions. We analyze microseisms recorded by several networks using a beamforming approach. In order to enhance the detection of phase coherent signals, we stack the beams using the phase weighted stack method in the frequency domain. Over one year, we observe microseism P-waves at all periods between 3 and 10 s but for a given time slot, they often can be detected only in narrow frequency bands. We investigate the source locations by back projecting the beam maxima. We construct a catalog of microseism source and investigate their properties. Microseism body waves are modeled considering sources as pressure fluctuations close to the ocean surface. These sources generate acoustic P-waves that propagate in water down to the ocean bottom where they are partly reflected, and partly transmitted into the crust to continue their propagation through the Earth. We show that the body wave amplitude variation with frequency is the result of both source frequency content and frequency dependent site effect. The quantitative comparison between modeled and observed beams shows that this approach provides independent constraints on the ocean wave model and in particular can be used to determine the amount of sources generated by coastal reflection either at the coast or along icebergs.

# Abstracts

## The Boumerdes (Algeria) earthquake of May 21st, 2003 (Mw: 6.8): Tomographic inversion

**Kherroubi Abdelaziz**[1], I. Koulakov[1], A. Yelles[1], A. Haned[1]

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On May 21st, 2003, a strong earthquake (Mw=6.8) struck the Boumerdes-Algiers area (central part of coastal Algeria). This destructive event is the largest one that occurred in northern Algeria since the El Asnam earthquake (10/10/1980, Ms 7.3). The Boumerdes earthquake is associated with a NE-SW trending and south dipping reverse fault. In the epicentral area, the deployment of a portable seismic network of 18 digital seismological portable stations, allowed to record the aftershock activity which followed the mainshock for about 1 year. In this study, we present the tomographic inversion from local and regional events using the Code LOTOS-11 We present also a global synthesis of this event.

## New earthquake detections in Ireland from waveform template matching by cross-correlation

**Pierre Arroucau**[1], J. Grannell[1], S. Lebedev[1], C.J. Bean[1], M. Mollhoff[1], C. Horan[1], T. Blake[1]

[1] Dublin Institute for Advanced Studies, Dublin, Ireland; ***parroucau@cp.dias.ie***

According to existing catalogs, the seismicity of Ireland is characterized by low magnitude, infrequent earthquakes. Such low seismicity levels are expected, considering the location of Ireland several hundred kilometers away from the closest plate boundaries. Yet, it still appears surprisingly low compared to neighboring domains, including Great Britain and more generally the rest of the west European margin. One explanation might be that the events reported in those catalogs do not reflect the actual seismic activity of Ireland due to the small number of permanent seismological stations on the Irish territory, so that most of the earthquakes occurring in that region might have been missed because of their low magnitude. This works is aimed at identifying new earthquakes in Ireland and its surrounding offshore basins by cross-correlating waveform templates of previously detected earthquakes with the available continuous waveform data recorded at permanent (INSN, BGS) stations and dense temporary seismic arrays deployed in the past 5 years by the Dublin Institute for Advanced Studies (DIAS) and the University College Dublin (UCD). For the period 2010 to 2016, we found more than 200 new, small magnitude earthquakes. These new events, after precise relocation with relative location techniques and source characteristics determination, will provide important information for seismotectonics and seismic hazard studies in the region.

## Discriminating between fractures and fabrics in a highly anisotropic shale using shear-wave splitting

**Alan Baird**[1], J.-M. Kendall[1], J. Budge[2]

[1] University of Bristol, Bristol, UK; ***alan.baird@bristol.ac.uk***
[2] Nexen

Organic-rich shales represent an increasingly important energy resource, however due to their fine-grain clay-rich composition they often have very low natural permeabilities and require fractures to enhance gas flow in order to be produced economically. The alignment of clays and other phyllosilicate minerals and the alignment of fractures and cracks are both effective means to produce seismic anisotropy. Thus the detection and characterisation of this anisotropy can be used to infer details about lithology, rock fabric and aligned crack properties within reservoirs, although care must be taken to distinguish their relative effects. We present a study characterising anisotropy using shear-wave splitting from microseismic sources in a highly anisotropic shale gas reservoir. We observe very strong anisotropy (up to 30% splitting in some cases) with a predominantly VTI symmetry (vertical transverse isotropy), but with some evidence of an HTI (horizontal transverse isotropy) overprint due to a NE striking vertical fracture set parallel to the maximum compressive stress. We observe clear evidence of a shear-wave triplication due to anisotropy, which to our knowledge one of only a very few observations of such triplications in field-scale data. We use modal proportions of minerals derived from X-ray fluorescence data combined with realistic textures to estimate the contribution of intrinsic anisotropy. Although much of the VTI anisotropy can be explained by the preferred orientation of clay minerals we find that an additional contribution from horizontal microcracks is required to produce the observed patterns of splitting. This has important implications for fracture treatments, as the reactivation and interaction of these horizontal cracks with induced hydraulic fractures may be an important mechanism to facilitate gas flow.

## Surface-wave tomography of Ireland, Britain and surroundings

**Raffaele Bonadio**[1], P. Arroucau[1], S. Lebedev[1], T. Meier[1], A. Schaeffer[1], A. Licciardi[1], N. Piana Agostinetti[1]

[1] Dublin Institute for Advanced Studies, Dublin, Ireland;
*raffaelebonadio@gmail.com*

***AWE Grant Awardee***

The lithospheric and asthenospheric structure of Ireland, Britain and surroundings is reasonably well known, thanks to a large number of academic and industry studies. However, many questions remain unanswered, in particular regarding the structure and evolution of the deep crust and upper mantle beneath Ireland, the geometry and extent at depth of the suture zones and their continuity across the Irish Sea, the thickness and bulk properties of the sedimentary cover at the regional scale, the deformation and flow of the deep crust, the thermal properties and thickness of the lithosphere today, and the thermal structure and dynamics of the asthenosphere beneath the area; detailed models of seismic-velocity structure and anisotropy can help us address these questions. In this project we obtain seismic models within the crust and upper mantle beneath Ireland, Britain and surroundings with very high resolution taking advantage of abundant, newly available broadband data from temporary array deployments and permanent seismic networks. The models of seismic velocity structure and anisotropy are obtained using a suite of different seismic methods, designed to extract the maximum of information from the data. A large set of phase-velocity measurements for pairs of stations is obtained using three independent approaches: a powerful recent implementation of the inter-station cross-correlation method, inter-station phase velocity measurement by waveform inversion, ambient noise cross-correlation. While the inter-station and the ambient noise methods produce most of the short-period measurements, often successful even when waveforms appear to be very complex, full waveform fitting contributes more to long-period measurements (in fact long-period surface waves can interfere with body waves, precluding accurate cross-correlation measurements). The measurements from these three methods complement each other and result in a very broad band. In order to extract structural information from all available data, automatic processing and measurement procedures are developed and applied. We obtain a very large number of dispersion curves for Rayleigh and Love waves, which are inverted in a tomographic procedure for surface-wave phase velocity maps. The maps constrain the 3D seismic-velocity structure of the crust and upper mantle underlying Ireland, Britain and neighboring offshore areas. The resulting seismic models are interpreted in the context of the geological evolution and enhance our understanding of the structure and dynamics beneath the area.

**Seismological and seismic reflection imaging of active faults and their tectonic behavior in the Northern Moroccan margin**

**Ghizlane Bouskri**[1], M. Elabbassi[1], A. Ammar[1], D. El Ouai[1], M. Harnafi[1]

[1] Mohamed V University, Morocco; ***ghizlane.bouskri@gmail.com***

***AWE Grant Awardee***

Seismological and seismic reflexion study, carried out along the Northern Moroccan margin, allowed browsing new details about the regional geological structures and their functioning. For this aim, we processed seismic signals of 4 years recording, combined to 1000km grid of industrial seismic reflexion profiles . Indeed, many projects were carried out (e.g. topo-Iberia project by ICTJA CSIC (Spain) and Picasso project by IRIS – Oregon University, USA). Hence, 59 broadband stations were deployed in total. PICASSO stations were equipped with Guralp CMG 3T sensors and Quanterra 330 digitizers, however Topo-Iberia stations have Nanometrics Trilium 120P sensors and Taurus digitizers, with records with a sample rate of 100 sample/sec. hence, we elaborated a high-resolution depth model and a global tectonic sketch for the South Alboran Basin, with localization of seismic zones. The influence of recent tectonic activity is manifested by normal and strike-slip faults, trending mainly N070° and N125°. In this segment, the well-known transforming Nekor strike-slip fault is probably connected to a secondary major fault system that changes direction from N30° to N70°, and changing behavior to left-lateral strike-slip fault with normal component. Analysis of local seismic activity recorded from 1990 to 2014 with moderate magnitudes activity shows alignments in clear superposition with the detected active faults in seismic reflection lines.

## An earthquake catalog for seismic hazard assessment in Lebanon

**Marleine Brax**[1], C. Beauval[2], P. Albini[3], R. Jomaa[1]

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[2] ISTerre, Université Grenoble Alpes, France.

[3] Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy.

Lebanon is a ~ 200 km x 50 km country situated on the Levant fault, the border between the Arabian and the African plates. The 20th century reveals low seismicity level while historical earthquakes have caused significant damage and left thousands of casualties behind. With the scope of defining the seismic sources and assessing the seismic hazard of Lebanon, a homogeneous and unified catalog was established reporting all known historical and instrumental earthquakes, in the region limited by 30°-37° N latitude and 32°-39° E longitude, as back in historical times as possible. An instrumental database was constructed based on the local bulletins and currently existing international catalogs. This catalog corresponds to the most exhaustive and complete earthquake dataset developed for the region of Lebanon. For each earthquake, the best epicenter location and magnitude among available solutions was selected. A comparable work was done for the historical earthquakes preceded by a meticulous revision and analysis of the published literature for the region. Magnitudes have been homogenized to moment magnitude Mw. Probabilistic seismic hazard assessment is now underway to estimate hazard over the Lebanese territory.

## Rebuild of the ISC Bulletin

**Lonn Brown**[1], J. Harris[1], K. Lieser[1], B. Shumba[1], R. Verney[1], E. Delahaye[1], D.A. Storchak[1], D. Di Giacomo[1]

[1] International Seismological Centre, Thatcham, UK; ***lonn@isc.ac.uk***

At present, the current published ISC locations represent a mixture of algorithms (Reviser, ISCloc) velocity models (Jeffreys-Bullen, ak135) and phases, (P-wave only, P&S, and finally all available phases starting in 2009). Thus, the primary goal of the Rebuild Project is to modernize the ISC bulletin, to homogenize our methods, procedures, and quality standards across more than four decades (1964-2010) of prior relocations at the ISC. We are also able to incorporate many new historical datasets which were not available to us in the past, from both temporary and permanent networks. Using the newest version of the ISC locator (ISCloc, Bondar & Storchak, 2011), all events in the bulletin are relocated using the ak135 global velocity model and all available phases. Event magnitudes are also handled in a more robust way – no longer will magnitudes be calculated using only one or two station readings. Using an internally developed and tested set of event quality criteria, our team of analysts review a subset of events which are flagged as requiring review. Afterwards, an updated set of quality checks are run and any flagged issues are then resolved. At present, we have finished work on thirteen years of historical data, and we show some of our preliminary results here. Our current predictions indicate that more than 150,000 flagged events will be reviewed by our analysts over the forty-six data-year period of the project. In this manner, the ISC intends to provide the most complete and most modern database of global seismicity publicly available anywhere in the world.

## Magnitude Discrepancies and Characterisation of Mining Events at New Ollerton, UK

**Antony Butcher**[1], J. Verdon[1], R. Luckett[2], J-M. Kendall[1]

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[2] British Geological Survey, Lyell Centre, Edinburgh, UK.

Subsurface extraction activities have often been related to seismic activity, and are becoming increasingly monitored by locally installed seismic networks. Two datasets recorded at Preese Hall and New Ollerton, which relate to hydraulic fracturing and coal mining respectively, are used to consider the impact proximity has on magnitude estimates. We then consider in more detail the nature and distribution of seismic events observed at New Ollerton. We demonstrate that significant discrepancies in magnitude estimates (up to a unit higher) occur between nearby stations (<5km) compared to those at greater distance (>50km). Both Preese Hall and New Ollerton (NOL) datasets contain events that occurred within comparable sedimentary layers, and we show that at near-event stations the ray path is predominantly within these layers. As sedimentary layers are generally lower in velocity and more attenuating than the underlying crystalline basement rocks, the UK ML scale is inappropriate for these types of events. As the UK scale is empirical and derived from earthquakes at distance, this is not unexpected, and we use the NOL data to derive an appropriate NOL ML scale for these near-event stations. After event magnitudes have been recalibrated using the NOL scale, we consider the frequency-magnitude distribution (FMD) of the observed events, and observe a significant break in slope at ML ~ 1.2. With the majority of the events below ML ~ 1.2, clearly this roll off cannot be attributed to magnitude completeness but instead a significant reduction in the number of larger magnitude events. Observations are modelled with a truncated power law distribution, which provides a reasonable fit to the observed FMD if rupture lengths are truncated at a length of approximately 50m. This suggests that the fracture length is limited in some way by the mining zone, resulting in the observed roll off seen on the FMD.

**Seismicity (M>3.0) in the period 2002-2014 and active tectonics in the Gulf of California, Mexico**

**Raul R. Castro**[1], J.M. Stock[2], E. Hauksson[2], R.W.Clayton[2]

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We formed a catalog of accurate epicenter coordinates of earthquakes located in the Gulf of California (GoC) in the period 2002-2014 to analyze the seismotectonics of this region. For the period April 2002 to December 2014 we use body-wave arrival times from regional stations of the Broadband Seismological Network of the GoC (RESBAN) operated by CICESE to improve hypocenter locations reported by global catalogs. For the northern region of the GoC ($30^0$N – $32^0$N) we added relocated events from the 2011-Hauksson-Yang-Shearer, Waveform Relocated Earthquake Catalog for Southern California (Hauksson *et al*., 2012; Lin *et al*., 2007). For October 2005 to October 2006 we incorporated hypcenters located by Sumy *et al*. (2013) in the southern GoC combining an array of ocean-bottom seismographs, of the SCOOBA experiment, with onshore stations of the NARS-Baja array. This well constrained catalog of seismicity highlights zones of active tectonics and seismic deformation within the North America-Pacific plate boundary. We estimate that the minimum magnitude of completeness of this catalog is $Mc$=3.3 and the $b$ = 0.92 value of the Gutenberg-Richter relation. We find that most earthquakes in the southern GoC are generated by transform faults and this region is more active than the central GoC region. However, the northern region, where most deformation is generated by oblique faults is as active as the southern region. We used the ISC catalog to evaluate the size distribution of seismicity of these regions, and the $b$ value of the Gutenberg-Richter relation and found that $b$ is slightly lower in the central GoC ($b$=0.86) compared to the northern ($b$=1.14) and the southern ($b$=1.11) regions.

## Using Ambient Noise to image melt in the Northern East African Rift System

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***AWE Grant Awardee***

Ambient seismic noise has long been regarded as a problem when processing coherent signals. However, this is changing with array based processing techniques and theory indicating a coherent signal can be found within the noise. Ambient seismic noise as a resource is now rapidly developing and can be used to detect velocity changes in a range of environments. These changes in velocity are used to provide images of the Earth's interior on global and local scales. Of particular note is the use of ambient noise tomography to image the internal structure and shallow magma chambers of volcanoes. Changes in the seismic velocity are used an indicator for deformation and the presence of fluids. Deformation data can be obtained from surface measurements and is complemented by seismic data from receiver function analysis and P-wave tomography using teleseismic earthquakes. This provides broad overviews of the internal structure but often has poor back azimuthal coverage for the earthquake sources and interpretation is difficult with the presence of partial melt. The resolution is also limited, with discernable features generally only obtainable in the range of 10's – 100's of kilometres. Ambient noise fills in some of these gaps by generating shear wave velocity models from cross correlation of seismic stations Rayleigh wave pairs.

Here I present initial results of the cross correlations and stacks of ambient seismic noise for seismic deployments in the Northern East African Rift System from 1999-present using asynchronous cross correlations. These are then inverted to generate a Rayleigh wave velocity model to detect changes in velocity within the subsurface, which relate to temporal perturbations in areas such as the crust. This in turn is interpreted as changes in the internal structure of volcanoes, in particular the presence of fluids, on a local and regional scale.

The results from Ambient Noise Tomography will be combined with results from a previous teleseismic Rayleigh wave study which used the same network to image the lower crust and mantle down to 250 km depth (Gallacher et al., 2016). By integrating these two studies we will provide a detailed model of seismic velocities from ~5 – 250 km with periods of 7-125s, and provide further insight into the rifting processes in the East African Rift. This will provide a better understanding of the stresses involved prior to an eruption and may lead to improved monitoring of volcanically active areas.

## Do large earthquakes nucleate as a result of repeating earthquake sequences?

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***AWE Grant Awardee***

Earthquakes are a natural phenomenon that can cause catastrophic consequences around the world. While most large earthquakes come out of the blue, some are apparently preceded by patterns of smaller events that may be related to the nucleation process, at least when examined at in retrospect. These include conventional foreshocks and localised sequences of small 'repeating' earthquakes, which may be associated with either an accelerated nucleation process, or with stable repeated slip. What happens before an earthquake with these characteristics is still poorly understood, as is the potential significance for earthquake forecasting based on these signals. Here we examine the potential of current methods of identifying candidate foreshocks due to nucleation, with a view to suggesting ways of probabilistically detecting such events in real time. We describe an analysis of synthetic seismograms which include repeating events in order to create an algorithm which will find the repeaters automatically, benchmarked on known sequences where repeaters have been identified. We are currently optimising this algorithm so it can detect repeaters in cases where they are not known a priori, in order to find out how many significant earthquake sequences have had (or have not had) precursory repeating events, as well as how many times a repeating sequence does not lead to a subsequent event. The algorithm involves cross-correlation and short/long-term averaging (STA/LTA) triggering methods for automated event detection. The success rate of the algorithm is evaluated by comparing the known event time-stamps to the times which the algorithm has triggered (i.e. where the algorithm says there is an event). Repeating events are generally very small so the algorithm will need to be effective for noisy data. We are optimising the methods by testing the algorithm on synthetic data with different levels of realistic background seismic noise in the appropriate frequency range, as a pre-requisite to obtaining a better outcome when we then apply it to real data. We assess the success of our algorithm by not only how many repeating events are picked up (hits), but also by the number of false alarms, missed events (repeating events which haven't been triggered) and correct rejections (no triggering with no event). This way of quantifying the success of a particular method should be used, as no prediction scheme should be evaluated until these four outcomes are accounted for, in order to avoid retrospective selection bias. In the case of synthetic data these proportions are known a priori, so the overall performance of the method for different ratios of signal to noise can be tested objectively. From this, we can evaluate how well the algorithm has worked on synthetics seismograms and expand it onto real earthquake sequences. This will allow us to deepen our understanding of what happens prior to an earthquake, especially in those which have had nucleating foreshocks in the form of repeating events.

**Seismic imaging without a source: towards cost effective and low environmental impact hydrocarbon exploration**

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Long term recordings of ambient seismic noise can be cross-correlated to produce empirical Green's functions between all station pairs in an array/network. The application of dispersion analysis to these waveforms allows period-dependent surface wave group and phase velocities to be extracted and combined to create tomographic images of the crust and upper mantle. Recently, it has been demonstrated that seismic structure at the exploration scale can be revealed using this method, but much more work is required before it could be used as a routine tool in the commercial sector. In this project, I will develop a data-processing workflow that enhances ambient noise signal with a particular emphasis on high frequency energy. Methods will focus on pushing the boundaries of what is currently possible in terms of spatial resolution of near surface structure. This will include exploiting the ellipticity of Rayleigh wave particle motion, which has the potential to greatly improve the recovery of structure in sedimentary basins and implementation of advanced Bayesian tomography methods. The new techniques will be applied to datasets collected in Australia and elsewhere. For instance, large volumes of ambient noise data have been recorded by stations located in Tasmania and SE mainland Australia as part of the WOMBAT transportable array experiment. This is an ideal location for ambient noise tomography as Bass Strait and the Southern Ocean provide a strong source of diffuse seismic energy. Furthermore, the ability of ambient seismic noise methods to delineate the structure of sedimentary basins beneath Bass Strait can be tested against a vast repository of seismic reflection data collected by industry.

## Surface wave mode conversion due to lateral heterogeneity and its impact on waveform inversions

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Surface wave tomography based on great circle ray theory has certain limitations which become increasingly significant with increasing frequency. One such limitation is the assumption of different surface wave modes propagating independently from source to receiver, valid only in case of smoothly varying media. In the real Earth, strong lateral gradients can cause significant interconversion among modes, thus potentially wreaking havoc with ray theory based tomographic inversions that make use of multimode information. The issue of mode coupling (with either normal modes or surface wave modes) for accurate modelling and inversion of body wave data has received significant attention in the seismological literature, but its impact on inversion of surface waveforms themselves remains much less understood. We present an empirical study with synthetic data, to investigate this problem with a two-fold approach. In the first part, 2D forward modelling using a new finite difference method that allows modelling a single mode at a time, is used to build a general picture of energy transfer among modes as a function of geometry and strength of lateral heterogeneities. In the second part, we use the example of a multimode waveform inversion technique based on the Cara and Leveque (1987) approach of secondary observables, to invert our synthetic data and assess how mode conversion can affect the process of imaging the Earth. We pay special attention to ensuring that any biases or artefacts in the resulting inversions can be unambiguously attributed to mode conversion effects. This study helps pave the way towards the next generation of (non-numerical) surface wave tomography techniques geared to exploit higher frequencies and mode numbers than are typically used today.

## Neotectonic model of northern Algeria: Blocks tectonic rotations revealed by new paleomagnetic data

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The seismic activity of the Western Mediterranean area is partly concentrated in northern Africa, particularly in northern Algeria, as it was shown by the strong earthquakes of Zemmouri 21 May 2003 Mw=6.9 and the El Asnam 10 October 1980 Ms= 7.3. This seismicity is due to the convergence between Africa and Eurasia plates since the Oligocene. This convergence involves a tectonic transpression with N-S to NNW-SSE shortening direction, which is expressed by active deformation along the plate boundary. Along the Tellian Atlas (Northern Algeria), active structures define NE-SW trending folds and NE-SW sinistral transpressive faults affecting the intermountain and coastal Neogene to Quaternary sedimentary basins (e.g. Cheliff and Mitidja Plio-quaternary intra-montaneous basins, …). The NE-SW reverse active faults are coupled with NW-SE to E-W trending strike-slip deep faults. The active deformation in northern Algeria can be explained by a kinematics model of blocks rotation: the transpressive tectonics with NNW-SSE direction of convergence defines NE-SW oriented blocks, which have been subjected to clockwise rotation. In north Algeria, paleomagnetic studies were carried out in the central area, on Neogene sedimentary and magmatic formations (Derder et al, 2009, 2011; 2013). They pointed out tectonic rotation of large blocks, in agreement with the kinematic model. Narrow zones represent important shear zone with strong rotation of smaller blocks (Derder et al., 2013). A new paleomagnetic study was conducted on the recent magmatic rocks outcropping in the Northwestern Algeria, in order to validate this model on a regional scale. The results point out presence of systematic clockwise blocks rotation. These results confirm that the Africa-Europe convergence is partly accommodated in northern Africa by blocks rotations. They also highlight that rotations are not homogeneous

in north Algeria and thus the importance of future works in this area.

# Seismicity along the seismogenic zone of Algarve region (southern Portugal)

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The seismicity of the Portuguese teritory and its adjacent Atlantic region located on the western part of the Iberian Peninsula is very heterogeneous. It is characterized by different regions with various seismicity. The seismicity of the Portuguese territory is more concentrated in the south and the Atlantic margin part than in the rest of the country. In southern Portugal, there are several tectonic structures, which are most likely, responsible of the large historical earthquakes in the Algarve region close to the boundary between the African and Eurasian plates.

The present seismological study focuses on Algarve region, in the framework of a cooperation project between the Universities of: Évora (Portugal), Lisbon (Portugal), Strasbourg (France) and the IPMA (Lisbon, Portugal). One and a half year seismological survey will enable us to locate seismic events and obtain the local velocity structure of the Algarve region. P and S arrival times at 30 stations will be used (Geostar stations, Telemetred network, U. Lisbon and IPMA stations). Our data have been recorded during the campaign operated from January 2006 to July 2007.

This work aim to produce a more detailed knowledge of the crust structure over the region of Algarve and identify seismogenic zones with seismic sources able to generate significant events.

## The ISC-GEM Global Instrumental Earthquake Catalogue

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The first version of the ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009) (www.isc.ac.uk/iscgem/index.php) was released in January 2013 (Storchak et., 2013) after a 27-month project co-funded by the GEM Foundation. The catalogue was required to reassess the homogeneity (to the largest extent possible over time) of the earthquake parameters (especially location and magnitude) and list them along with formal uncertainties to facilitate seismic hazard and Earth's seismicity studies.

The first release included earthquakes selected according to the following time-variable cut-off magnitudes: Ms=7.5 before 1918; Ms=6.25 during 1918-1963; and Ms=5.5 from 1964 onwards. Because of the importance of having a reliable seismic input for seismic hazard studies, funding from USGS, NSF, GEM and a few commercial companies in the US, UK and Japan allowed us to start working on the extension of the ISC-GEM catalogue both for earthquakes that occurred after 2009 and historical earthquakes listed in the International Seismological Summary (ISS), which fell below the original ISC-GEM cut-off magnitude of 6.25 before 1964. This is a four-year project that aims to add as many earthquakes as possible that occurred between 1904 and 1959. In this contribution we present the updated ISC-GEM catalogue at the end of the third year extension program (Version 4.0), which includes over 2,000 more earthquakes during 2010-2013 and thousands more between 1920 and 1963 as compared to the first version. We also discuss the current work to include as many earthquakes as possible during 1904-1919. The extension of the ISC-GEM catalogue will be useful to regional seismic hazard studies because the ISC-GEM catalogue can serve as basis for cross-checking location and magnitude of those earthquakes listed both in the ISC-GEM global and regional catalogues.

# The ISC Event Bibliography: An update

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Researchers studying specific earthquakes and/or seismic events in general are often required to do time consuming searches in order to retrieve the literature concerning the events of their interest. To facilitate this task, in 2012 the International Seismological Centre (ISC) launched a new service, the ISC Event Bibliography (Di Giacomo et al., 2014), that allows users to do interactive searches (www.isc.ac.uk/event_bibliography/bibsearch.php) of scientific articles based on event parameters and, optionally, publication metrics (e.g., journal, author, year of publication etc.). The journals included in our database are not limited to seismology but bring together a variety of geoscience fields (e.g., engineering seismology, geodesy and remote sensing, tectonophysics, monitoring research, tsunami, geology, geochemistry, hydrogeology, atmospheric sciences, etc.) making this service useful also in multidisciplinary studies. Usually papers dealing with large data set are not included (e.g., papers describing a seismic catalogue). Some of the most notable earthquakes are the subject of several hundreds of articles published over a period of few years. Currently the ISC Event Bibliography includes over 18,000 individual publications from about 500 titles related to over 15,000 events that occurred in last 100+ years. The bibliographic records in the Event Bibliography start beginning of last century, and it is updated as new publications become available, and with this contribution we intend to show the usefulness of the ISC Event Bibliography considering recent large events.

## Mapping primary microseism sources in and around the Sea of Japan

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The distribution and relative amplitude of microseism sources have important implications for seismological applications such as waveform-based noise tomography, and for the understanding of microseismic noise generation. In particular, quantitative models of primary microseism generation (microseism at periods of more than ~ 10 seconds) have emerged in recent years and additional observational constraints on source location and power are needed. While body wave sources of secondary microseisms have been imaged in great detail, spanning short and long observation periods thanks to sophisticated beamforming and backprojection techniques, body waves are not readily observed in the primary microseism range. Surface wave sources of primary microseisms also remain somewhat elusive due to the nature of surface wave propagation, which lacks the 3-D incidence angle that constrains body wave source locations better. In the present study, we propose to image sources of the primary microseism in and close to the Sea of Japan using ambient noise cross-correlations of data from F-Net and NecessArray. The Sea of Japan is a nearly closed, deep back-arc ocean basin with laterally varying bathymetry where large significant wave heights are observed both during winter, and during the passage of typhoons and severe tropical storms in summer. Thus, it is expected to produce episodes of strong microseismic signals. During the deployment of North East China Extended Seismic Array (NecessArray), recordings from Japan and China can be used to encircle microseismic sources within the Sea of Japan. This makes the Sea of Japan a prime candidate to study the interaction of ocean wave heights and bathymetry in microseism generation. In the first part of our study, we identified day- to weeklong periods during the years 2010 and 2011 (NecessArray was deployed from fall 2009 - fall 2011) when microseisms recorded in Japan show dominant incidence angles from the Sea of Japan. We removed earthquakes and other impulsive signals from the instrument-corrected data using several carefully calibrated threshold criteria, and subsequently applied data processing that retains the cross-correlation amplitude. In order to image the geographical distribution of source amplitudes, we measure the cross-correlation energy in different arrival

time windows, determining simplified sensitivity kernels of these measurements to source location. This allows us to perform a 1-step update of the noise source distribution.

## Site specific PSHA application with scalar and vector approach

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In recent years, Vector probabilistic seismic hazard analysis has developed and it became possible with the emergence of several correlation relationships, this study shows an application of this approach in real site located in the north of Algeria, the modified PSHA software is adopted to conduct the vector-PSHA for a rock site in function of different parameters such as PGA, PGV, energy and significant duration of strong motion. Site effect is analyzed by a fully probabilistic method by using convolution between hazard curves obtained at rock site and soil amplification function distribution as was described by bazzuro et al (2004). The use of vector approach improves the prediction of amplification for spectral acceleration at frequencies small than the fundamental frequency of our soil profile. Finally, a comparison between scenario selection based on rock and surface deaggregation approach is presented.

**Permanent and temporary seismology at Neumayer III, Antarctica**

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The Alfred-Wegener Institute operates a small seismological network and conducts temporary experiments around the research station Neumayer III in Dronning Maud Land, East Antarctica. Here, we present details about the network and temporary projects. The permanent network contributes to the global GEOFON Virtual Network (GEVN): three broadband stations transmit real time data, one of them is a small aperture array of 15 short period seismometers. Four offline stations complete the network. This network provides data to detect small regional earthquakes and cryogenic events. In addition to the permanent stations, temporary mobile stations have been developed and can be placed in specific areas to focus on different research questions. For example, a local circular magnetic anomaly close to Neumayer III has been investigated from 2013 to 2015. Currently four mobile stations are placed near the grounding lines of the shelf ice to investigate the distribution of ice quakes. In the future we plan to spread the stations across Dronning Maud Land and map large-scale tectonic features.

# Seismic Monitoring of the North Korea Nuclear Test Site by Russian Seismic Stations

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North Korea announced about five nuclear tests: 9 October 2006, May 25, 2009, February 12, 2013, January 6, 2016 and September 9, 2016. All tests were detected by National Russian network. Results of the epicenters locations in Alert Service GS RAS, regional centers of GS RAS, operating in the tsunami warning system (Kamchatka and Sakhalin), are presented in this report. The obtained parameters are compared to the data from other centers IDC CTBTO, NEIC and CSEM. Characteristic properties of the wave form at the regional distances are described. The discrimination using the Pg/Lg spectral ratio was conducted. Network average spectral ratio lg(Pg/Lg) by 3C stations «Vladivostok», «Mys Shultsa», «Gornotajezhnoje» and «Ussuryisk» were agreed with the value lg(Pg / Lg) of the South Korean seismic network [L.-F. Zhao, et al., 2012] and Chinese station MDJ [P.G. Richards, W.-Y.Kim, 2008]. Analysis of the deviation observing Pn arrivals at Russian station from the Travel Time Curve AK135 were conducted. We used velocity reduction VPn = 8 km/c for building of the reduced travel time curves TTC AK135 and Tarakanov for three Far Eastern regions: the western, southern and Kuril-Japan zone. Russian stations deviations showed that the location of the station at a distance less than 400 km correction do not exceed -1 c, at a distance of 800 km - it is equal to approximately -2 c, at 1200 km - -4 c correction must be applied to TTT AK135.

## Developing a seismic hazard model for Sabah, East Malaysia, using seismic and geodetic data

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Earthquakes may result in death, injuries, disruption to infrastructure, and significant economic loss. It is therefore crucial to assess the seismic hazards present in earthquake-prone regions to help mitigate against the risks posed. Most of Malaysia has low levels of seismicity, however the state of Sabah, in north east Borneo, has moderate levels of seismic activity. In June 2015 a magnitude 6.0 earthquake occurred near the town of Ranau, causing large landslides. 18 people were killed on Mt Kinabalu, and there was damage to buildings in nearby towns and villages. The region around Ranau is one of the main centres of seismicity in Sabah, the other being in the east of the state, around the town of Lahad Datu, where a magnitude 6.2 earthquake occurred in 1976. Despite rapid population expansion over the last 40 years, seismic hazard in Sabah remains poorly understood. Using seismic and geodetic data we hope to better quantify the hazards posed by earthquakes in this region, and thus help to minimize risk. The Malaysian Metrological Department (MetMalaysia) has had a network of seismic stations located throughout Sabah since 2005. This part of the the Malaysian National Seismic Network currently consists of nine broadband instruments and six accelerometers. We calculate P receiver functions from data recorded at these stations and use these, together with surface wave data (Tang et al., 2013), to construct a new crustal model for Sabah. We (re)locate earthquakes that have occurred in Sabah since 2005 using this new crustal model and arrival times picked from data recorded at the MetMalaysia seismic stations. We use a probabilistic nonlinear earthquake location program, NonLinLoc (Lomax, 2001) to locate the earthquakes and then refine their relative locations using HypoDD (Waldhauser, 2001). The recorded waveforms are further used to obtain moment tensor solutions for these earthquakes. Earthquake locations and moment tenor solutions are then compared with the locations of faults throughout Sabah. Faults are identified from high-resolution IFSAR images, with a particular focus on the Lahad Datau and Ranau areas. Used together, these seismic and geodetic data can help us to better

assess the seismic hazard in Sabah, to aid in the delivery of outreach activities regarding seismic hazard within local communities, and to understand the seismo-tectonic processes taking place in Sabah.

**Seismological studies of the multi-scale core-mantle boundary landscape**

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At nearly 3000 km depth, the core-mantle boundary (CMB) marks the largest physical change within the Earth, separating the liquid iron outer core and the solid silicate mantle. On the mantle side, large-scale convection provides the driving forces for plate tectonics whereas the rapid convection in the outer core sustains Earth's magnetic field. The interplay of these dynamic processes at the CMB produces a range of structural imprints at scales from tens to thousands of kilometres. Seismological studies of these multi-scale structures shall offer critical insights into core and mantle dynamics, leading ultimately to better constraints on the history and evolution of our planet. On the data selection side, both normal modes (standing waves) and body waves (travelling waves) can be employed to study Earth's deep interior. On the one hand, normal modes provide an invaluable tool for probing the long wavelength, large-scale structure since they are global in character and they are affected by density structure in addition to velocity variations. On the other hand, body waves allows us to look at localised, regional and possibly sharp features in more detail. Various approaches exist to infer from these data to constrain their structural origin, most prominently tomography and waveform modeling. Tomography typically delivers a broad, smooth large-scale picture of the Earth's interior, whereas waveform modeling is geared towards assessing waveform effects of localised structures, possibly stemming from sharp interfaces and small-scale heterogeneities. We strive to combine these diverse data and inference approaches to further our understanding of the multi-scale dynamics of this intriguing but inaccessible region. Here, we report on our approaches for data selection and modeling to illuminate complex multiscale structures in the lowermost mantle. Modeling seismic waveforms for 3D multiscale structures at the global scale is a formidable, if infeasible task. We have developed a new method for seismic wave propagation (AxiSEM3D) that allows for a drastic computational shortcut and thus enables us to compute high-frequency seismic waveforms in the presence of 3D multiscale structures for the lowermost mantle. We will present simulations at 2s for ULVZ structures embedded within a realistic 3D tomography model, which for the first time accommodates effects of 3D

scattering due to these structures. Such kind of modeling delivers constraints on structural geometries with potentially sharp boundaries and predicts those data that are most sensitive to these kinds of structures. We then compare global constraints on the velocity and density structure from normal modes with the results of detailed body-wave analyses in regional settings, particularly focusing on areas beneath Africa and Central America to further refine our picture of these intricate and crucial regions subject to multiscale structures and dynamics. An overarching goal of this effort is to constrain tomographic models with sharp features, and to amend localised structures with their long-wavelength counterpart.

## Evidence for partial melt in the crust beneath Mt. Paektu/Changbaishan

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Mt. Paektu (also known as Changbaishan) is an enigmatic volcano on the border between the Democratic People's Republic of Korea (DPRK) and China. Despite being responsible for one of the largest eruptions in history, comparatively little is known about its magmatic evolution, geochronology, or underlying structure. In a recent paper (Kyong-Song et al., 2016) we presented receiver function results from a seismic deployment in the DPRK. These are the first estimates of the crustal structure on the DPRK side of the volcano and, indeed, for anywhere beneath the DPRK. The crust 60 km from the volcano has a thickness of 35 km and a bulk VP/VS of 1.76, similar to that of the Sino-Korean craton. The VP/VS ratio increases ~20 km from the volcano, rising to >1.87 directly beneath the volcano. Recently we have extended this work to also show estimates of bulk crustal structure beneath the Chinese side of the volcano. These show a similar pattern of high Vp/Vs directly beneath the volcano, but show that crustal thickening is more significant towards the southeastern side of the volcano, suggesting while molten rock is currently present directly beneath the volcano, historic volcanism may extend preferentially towards the southeast. Through future collaborations we hope to combine the datasets together to provide a single combined view of the crustal structure on all sides of the volcano.

## Global tomography using seismic hum

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The seismic noise is much used for regional tomographic models but it is not used on a global scale. In this thesis, we validated a new noise data processing approach and obtained a global tomographic model of the upper mantle from broadband seismic ( 30 to 250s). The application of phase correlation combined with the phase weighted stack has enabled us to build Green functions between pairs of stations, from which the group velocities of the fundamental mode of Rayleigh waves were measure. The group velocities were calculated by a resampling approach. We have shown that it is necessary to use 2 years of continuous data to obtain robust measures of group velocity. The hight signal-to-noise ratio of the Green's functions obtained allows us to identify not only Rayleigh waves but also body waves. Group velocities are regionalized and then inverted versus depth using a simulated annealing method in which the number and shape of splines that describe the model are variable. The obtained tomographic model allows the study of big structures such as cratons and ridges. It is in good agreement with the tomographic models essentially obtained from seismic data where we quantified differences. We then used the group velocities to obtain anisotropic tomographic model and we compared the anisotropy directions with models derived from earthquakes. We have demonstrated that the proposed methodology, from 2 years of data allows to get a robust global tomographic model. The resulting dataset can be used in addition to seismic data to improve coverage of global tomographic models.

## Frictional instability of rough faults

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Fault roughness is an important control factor in the mechanical behaviour of fault zones, in particular the frictional slip stability and subsequent earthquake nucleation. However, there is little experimental quantification as to the effects of varying roughness upon rate- and state-dependent friction (RSF). Utilising a triaxial deformation apparatus and a direct shear methodology, to simulate initially bare faults in Westerly Granite, we performed a series of velocity step friction experiments. We varied initial root mean square roughness (Zrms) in the range 3.7-28.2 microns, normal stress in the range of 30−200MPa and slip velocities between 0.1−10 micron per second. In general smooth faults (Zrms < 6 micron) are unstable, and rough faults (Zrms > 6 micron) are stable. Transitions in stability from stable sliding to marginally stable and unstable slip and vice versa, were observed, as a function of both the normal stress and Zrms. Of particular surprise is that instability observed at 100-150MPa on the smoothest fault (Zrms=3.7 micron) disappears at high normal stress. Additionally, instability can develop when $a - b > 0$, suggesting that bare surfaces may not strictly obey the RSF stability condition. We instead suggest that bare fault surfaces may require a different stability criterion to gouges, based on the competition between weak patch scaling Lambda c, and the slip weakening nucleation length, Lc. We use these observations to suggest that this process may be an additional mechanism to rheological changes to suppress seismicity at depth in brittle faults.

**Estimating the rupture extent of low frequency earthquakes near Parkfield, CA**

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Non-volcanic tremor observed in association with slow slip events is dominated by relatively low frequencies, usually around 2 to 10 Hz. Recent analyses have suggested that the large low frequency energy arises because the low frequency earthquakes (LFEs) that constitute tremor have durations much longer than "normal" earthquakes with similar magnitudes. M 1-2 earthquakes in Parkfield, CA appear to last around 0.2 seconds. If the LFEs propagate at typical earthquake rupture speeds during those 0.2 seconds, they should have rupture extents larger than 1 km. So here we attempt to assess whether such a standard rupture model and rupture speed is appropriate for low frequency earthquakes by more directly determining the rupture extents of low frequency earthquakes near Parkfield, CA. We estimate the spatial extent of two families of low frequency earthquakes with an approach similar to directivity analysis: by examining how LFE seismograms vary among the recording stations. In this approach, we first cross-correlate records of two LFEs at each station to eliminate the Green's functions' phases. This leaves us with the relative phases of the apparent source time functions. At a given frequency, the apparent source time functions are expected to vary among stations only if the spatial extent of the LFE is large compared with the seismic wavelength of interest, so we can estimate the spatial extent of LFEs by examining inter-station coherence. Individual LFE records have low signal to noise ratios, so we implement this analysis in two ways. First, we create two stacks of several thousand LFEs coming from a single location and compare the stacked records. We find that the stacks are coherent at up to at least 10 Hz, a wavelength of 300 m, suggesting a rupture extent of at most a few hundred meters, which is much smaller than would be expected for standard rupture models and speeds. However, it may be that stacking LFEs emphasizes the coherent signals, so we are currently continuing with an alternative approach: comparing each LFE with the entire stack. For each LFE and frequency, we estimate the energy that is coherent with the stacked template, the energy that is incoherent with the template, and the energy due to noise. This set of energy estimates should allow us to estimate the average fraction of coherent energy in the LFEs at each frequency, and thus to constrain the LFEs' rupture extents.

## Seismic and Hydroacoustic Observations from Underwater Explosions off the East Coast of Florida

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The United States Navy is required to test the ability of new classes of ship to withstand explosions. During these shock trials, three identical underwater 10000lb chemical explosions are detonated close to the hull of the vessel undergoing testing. In terms of monitoring compliance with the Comprehensive Nuclear-Test-Ban Treaty, as some ground-truth information exists, these explosions provide an opportunity to assess the capability of the International Monitoring System (IMS) to detect, locate and characterise small yield underwater explosions (body-wave magnitudes between 3.2 and 3.6). In this study, seismic and hydroacoustic signals from a series of test explosions in 2001, 2008 and 2016 near Florida are analysed. As the locations of the 2008 explosions are known, the arrival times of both seismic and hydroacoustic signals can be used to relocate the explosions relative to each other and obtain high accuracy estimates of their absolute locations. This allows us to assess the reliability of source locations estimated using a global network of stations such as the IMS. The seismic and hydroacoustic signals are also used to estimate the yield of the explosions and characterise the explosion sources. Bubble pulses characteristic of underwater explosions are identified at seismic stations in the United States and the estimated explosion depths are shown to be consistent with published ground-truth information. The absence of bubble pulse observations at IMS hydrophone stations demonstrates the importance of combining seismic and hydroacoustic observations to characterise the sources. The explosions have also provided an opportunity to assess the capability of T-phase stations adjacent to IMS hydrophone stations to detect underwater explosions.

## A new global upper mantle radial anisotropic model from multi-mode surface wave observations

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We present a new radial anisotropic (xi) tomographic model HPD2017xi for the upper mantle and discuss the significance of the observed lateral variations in the radial anisotropy. HPD2017xi is based on large (4.0 million paths) Vsv and (0.5 million paths) Vsh data sets. This model confirms large-scale upper mantle features seen in previously published xi(z) models, but a number of these features are better resolved because of the increased data density of the fundamental and higher modes. The average xi(z) is similar to PREM in the upper 100 km but shows a stronger value of xi deeper than 100 km. At shallower upper mantle depths (<200 km) there is a strong correlation between continental areas of fast wavespeed, the cratonic roots, with xi, much more so than in most of the regional and global xi models. At 150 km depth all of the cratons show xi < 1. This switches to xi > 1 in the 200-250 km depth range. In the Pacific the depth of maximum xi increases with seafloor age to about 75 m.y. then remains at a near constant depth beneath the older part of the Pacific. The depth of maximum xi tracks the upper part of the LVZ. Below about 275 km xi is close to 1, however there is a small positive increase in xi at transition zone depths. The pattern of radial anisotropic we observe, when compared with the pattern of azimuthal anisotropy determined from Rayleigh waves, suggests that the shearing at the bottom of the plates is only sufficiently strong to preferentially align the crystals when the plate motion exceeds some critical value which Debayle and Richard (2013) suggests is about 4 cm/yr.

### Anthropogenic noise on temporary seismic networks: implications for monitoring arrays in the UK

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In recent years, many temporary seismic networks have been deployed for baseline seismicity studies in areas of potential hydraulic fracturing. These networks are designed to record the natural seismicity levels in the regions, prior to the start of, and potentially during, any industrial activity. They aim to record local earthquakes in the area of interest, down to a magnitude 0 ML or less, so that any seismicity observed during hydraulic fracturing activities can be categorised as natural or induced. Currently, in the UK, any seismic activity at this level needs to be monitored in line with the UK Traffic Light System. The BGS has deployed two such networks in Lancashire and the Vale of Pickering under the DBEIS-funded Baseline Monitoring consortium project with the Universities of Bristol and Liverpool. Site locations for dense temporary networks are primarily controlled by logistical practicalities. There is only a small area of land that fits the optimum network spacing and within that area land-owner permission must be obtained. As such, sites are often located in the best available geographical locations and the burial material (clays, sands, bedrock etc.), by necessity, may become a secondary consideration. Furthermore, sites may be nearer to anthropogenic noise sources than would be ideal. To study the effects of site location and burial material we have performed noise analyses on all the BGS stations in these two regions and across the UKarray as a whole. We will present a comparison of the noise observed at different sites, with particular reference to the burial material; the depth of burial (surface versus shallow borehole (20-30m)); the sensor type (broadband versus short period); and any local anthropogenic noise sources (traffic, light industry, trees, farming etc.). This will include the site noise within the expected frequency spectrum and amplitude of small, local earthquakes. Better understanding of the dominant factors affecting the noise spectra may suggest ways in which these dense networks can be optimised, and provide valuable insights for the design of potential future networks.

## Global seismic tomography using teleseismic and core-diffracted body waves

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Significant recent advances in seismic data acquisition and computing power have drastically increased the resolution of tomography models in all scales. Broadband seismic waveforms can now be simulated up to the highest naturally occurring frequencies and consequently, measurement techniques can exploit seismic waves in their entire usable spectrum and in multiple frequencies. We developed a method that routinely measures finite-frequency traveltimes of arbitrary seismic waves by cross-correlating observed waveforms with synthetic seismograms across the broad-band frequency range. We scaled and automated this technique to process the voluminous waveform data of ~2000 earthquakes in our archive. We have assembled a Pdiff traveltime data set of an unprecedented size with a total of 479,559 traveltimes in frequency passbands ranging from 30.0 s dominant period to the highest frequencies that produce satisfactory fits (~3 s). Pdiff waves extensively sample the lower third of the mantle and the core-mantle boundary. Hence their inclusion in a technically rigorous manner vastly improves spatial resolution of the deepest mantle. The few examples of prior tomographies that incorporated Pdiff phases included only a few hundred measurements and not in a broadband, multifrequency framework, such as here. An inversion framework with adaptive parameterization and locally-adjusted regularization is developed to accurately map the information of this data set onto the desired model parameters. This broad-band waveform inversion seamlessly incorporates the Pdiff measurements alongside a very large data set of conventional teleseismic P and PP measurements. In addition to the multifrequency measurements, a subset of short period arrival times from EHB (Engdahl et al., 1998), a catalog of routinely picked and processed arrival times, was selected. The inclusion of picked arrival times greatly enhanced the coverage in locations where the information content of the multifrequency measurements was poor. We present a new global seismic tomography model of isotropic P-wave velocity anomalies at all mantle depths. The mapped features confirm several previously imaged structures. At the same time, sharper outlines for several subduction systems and uprising mantle plumes appear in our model. We trace some of these features throughout the mantle to

investigate their morphological characteristics in a large (whole-mantle) context. Moreover, we present and discuss obtained first-order features of the lower-mantle structures: geometries of fast velocity anomalies representing the oldest subducted slabs still visible, and the subdivisions of Large Low Shear Velocity Provinces.

## Difficulty of the determination of hypocenters in early 20 century

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The instrumental observation started in late 19 century in the world. But hypocenters of most of earthquake were not determined by instrumental data at that time. ISC and GEM released the ISC-GEM Global Instrumental Earthquake Catalogue for 1900 to 2012. This catalogue included earthquakes of which minimum M is 7.5 before 1918, 6.3 after 1918, and 5.5 after 1935. In eastern Asia, seismometers were more densely distributed in early 20 century. Japan Meteorological Agency determined hypocenters using seismic networks in Japan, Taiwan and Korea and published the JMA earthquake catalogue. It included M6 and bigger earthquakes before 1922 and M4 and bigger earthquakes after 1923. It is a good local earthquake catalogue, but some events were mislocated by the cause of the bad station arrangement or poor reading data set. I show some mislocated events here. First one is the 1936 Mj5.3 Mw5.1 event in Korea peninsular named the Ssanggyesa earthquake. In this case, the data of P and S waves arrival times are lot, but the arrangement of the seismic stations were very bad. Pyongyang, Incheon, Seoul, Taegu, and Bosan in Korea peninsular showed linear distribution. Additionally, Izuhara and some stations in Kyushu in Japan located on the prolongation. In such case, estimated positions for the hypocenter are located at the line symmetry. Unfortunately, JMA estimated the virtual image point as the hypocenter. I checked the directions of the P wave first motion and the intensity distribution. Then, I got the real point as the hypocenter. So, the information of intensity and the direction of P wave are important for such case. The other case was the 1923 M6.0 event in Kanto, Japan. It was one of the aftershock of the 1923 M7.9 great Kanto earthquake. The data of P and S waves arrival times were not many. JMA estimated the minimum error point as the hypocenter at the surface of the southwest part of Ibaraki prefecture. But there are no hypocenters in the recent seismicity map. In this place, all events are located at 40 to 60km at depth. I checked the data and obtain the more realistic location as the hypocenter near Kasumigaura lake. So, in this case, recent information of the hypocenter distribution is the important. Some other cases will be reported.

**Constraints on Icelandic Crustal structure from Receiver function analysis**

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Iceland sits astride the mid-Atlantic ridge, and is thought to be underlain by a hot mantle plume. Crustal thicknesses across Iceland are estimated to vary from 15km at the edge up to 43km in the centre beneath Vatnajökull glacier. The extreme thickness in central Iceland compared to average oceanic crust leads to the first order interpretation of elevated temperatures in addition to decompression melting, and thus to the hypothesised location of the plume core in the uppermost mantle. Crustal thickness maps are generally created from inversion of long wavelength surface wave or gravity data constrained by relatively few point depth estimates from receiver functions and reflected phases from active refraction surveys. Here we present receiver function measurements of P to s converted crustal phases measured by seismic stations from the previously used temporary arrays HOTPOT and ICEMELT, in conjunction with over 100 additional stations from the Icelandic meteorological office (IMO) and the University of Cambridge Icelandic seismic networks. Data is analysed using a variety of different methods including joint inversion with surface wave data, multi-phase common conversion point stacking and H-K stacking to provide hundreds of new point constraints of the seismic structure of the Icelandic crust. With this vast increase in data it will be possible to further improve our understanding of Icelandic crustal structure at shorter wavelengths, and to determine which areas are well constrained in current country wide models.

## Modernisation of slovenian seismic network: progress or just collection of data

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After the 12 April 1998 earthquake in the Upper Soča Valley (MLV = 5.6) in NW Slovenia that caused damage in the epicenral area, the process of the modernisation of the national seismic network started. In 2001 some old stations were equiped with new instruments and from 2002 till 2008 new stations were built and added in network. Currently, there are 28 digital seismic stations incorporated in seismic network with real-time continuous data transmission to the data centre in Ljubljana. During period of 15 years (2001-2015) slovenian network recorded more than 52.000 local events, among them more than 36.000 earthquakes. The rest were anthropogenic origin (including rockbursts and mine explosions). In the last 15 years there were no earthquakes (in Slovenia or near its border) with local magnitude equal or greater than 5,0, 5 had local magnitude between 4,0 and 4,9 and forty between 3,0 and 3,9. The aim of this work is to study what the modernisation of the network brought us, to present the differences in completness of our catalogue with or without modernization and to compare differences during years when more and more new stations started to operate (for the whole Slovenia and also for separated regions, particular those where earthquakes are frequent). Very important is also data exchange with neighbouring countries (Austria, Croatia, Italy and Hungary). Modeling with those data (included, excluded) were also made. This study allows us to identify if we are where we wanted or is still work to be done in the future.

## Local soil effects on the Ground Motion Prediction model for the Racha region in Georgia

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The Caucasus is a region of numerous natural hazards and ensuing disasters. Analysis of the losses due to past disasters indicates those most catastrophic in the region have historically been due to strong earthquakes. Estimation of expected ground motion is a fundamental earthquake hazard assessment. The most commonly used parameter for attenuation relation is the peak ground acceleration because this parameter gives useful information for Seismic Hazard Assessment that was selected for the analysis. One of the most important topics that have a significant influence on earthquake records is the site ground conditions that are the main issue of the study because the same earthquake recorded at the same distance may cause different damage according to ground conditions. In the study earthquake records were selected for the Racha region in Georgia which has the highest seismic activity in the region. Next, new GMP models are obtained based on new digital data recorded in the same area. After removing the site effect the earthquake records on the rock site were obtained. Thus, two GMP models were obtained: one for the ground surface and the other for the rock site. At the end, comparison was done for the both models in order to analyze the influence of the local soil conditions on the GMP model.

**Waveform modelling of 3-D seismic anisotropy in the Earth's mantle**

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Combining observations of seismic anisotropy, the directional dependency on wave speed, with mineral physics and geodynamical modelling provides crucial information to understand the temperature, composition and physical processes occurring within our dynamic planet. The mapping of anisotropy in various parts of the Earth's interior including the uppermost mantle and the mantle transition zone begun in the 1960's; however, today, decades later, global 3-D anisotropic models are far from consistent. Radially anisotropic models can be substantially sharpened with the use of state-of-the-art simulations of seismic wave propagation which, in turn, is one of the key ways to constrain the geometry of mantle flow in the Earth's mantle. This forward waveform modelling of surface waves allows the study of upper mantle anisotropy, including the lithosphere-asthenosphere region. We present surface waveform comparisons using the spectral element method (Komatitsch and Tromp, 1999), specifically the SPECFEM3D_GLOBE package for S-velocity models SGLOBE-rani (Chang et al., 2015) and S40RTS (Ritsema et al., 2011). We study the effects of 3-D isotropic and anisotropic Earth structure on surface waves in a wide frequency range for paths across the Pacific. Ultimately, we will link newly constrained anisotropic structure with mantle geodynamical modelling.

## Constraints on the presence of post-perovskite in Earth's lowermost mantle from tomographic-geodynamic model comparisons

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Lower mantle tomography models consistently find an increase in the ratio of shear-wave velocity (VS) to compressional wave-velocity (VP) variations, accompanied by a significant negative correlation between shear-wave and bulk-sound velocity (VC) variations. These seismic characteristics, first observed in the tomographic model of Su and Dziewonski (1997), which was constructed using ISC travel times and waveforms, are also observed in the recent SP12RTS model. Traditionally, these features have been interpreted as indicative of large-scale chemical variations, though more recently the lower mantle post-perovskite (pPv) phase has also been invoked as a possible explanation. Constraining the origin of these features is important as geodynamical calculations of thermal plumes and thermochemical piles predict a fundamentally different style of mantle convection, interface topographies and core heat flow. Here, we investigate whether the presence of pPv can explain the observed high VS-VP ratios and negative VS-VC correlation and whether these global seismic characteristics can be used to distinguish between isochemical and thermochemical models. We address these questions by comparing the velocity structures of SP12RTS to synthetic tomography images derived from 3D mantle convection models. We include geodynamic models with and without pPv and/or chemical variations, which are converted to seismic velocities using mineral physics data, reparameterised to the same parameterisation as SP12RTS and convolved with the tomographic resolution operator. In contrast to previous studies, where only the VS structures have been compared, we use both the VS and VP resolution operator of SP12RTS to allow direct comparisons of the resulting velocity ratios and correlations. We demonstrate that, even though the tomographic filtering significantly affects the synthetic tomography images, the patterns observed in the ratios and correlations of seismic velocities are robust features. Our study suggests that the seismic characteristics of SP12RTS require the presence of post-perovskite, both outside

and inside the LLSVPs. However, these characteristics cannot be used to discriminate between isochemical and thermochemical models of mantle convection.

## Advancing the ISC Bulletin with the data from temporary seismic deployments

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The ISC mission is to maintain the definitive long-term record of global instrumentally recorded seismicity. We make seismic wave arrival times, amplitudes and periods, seismic event hypocentres, magnitudes and source parameters available to researchers all over the globe. To fulfil this mission, the ISC regularly collects bulletin data from ~130 agencies/networks around the world, making use of more than 6,500 permanent seismic stations in recent years. Re-computed and verified bulletin data can be requested in different formats through the ISC web and ftp sites. The ISC operations are possible thanks to the non-governmental and non-profit status of the ISC, widespread international data exchange and financial support of 67 institutions in 49 countries.

Due to the positioning of landmasses, political borders and thus generally uneven distribution of permanent seismic stations, there are areas around the globe showing seismic activity that is poorly covered by seismic networks. Temporary seismic deployments provide a great opportunity to add regional or local seismic data to events with teleseismic recordings, improve the station azimuthal coverage and thus better constrain the main source parameters, especially the event depth.

With permission and help from principal investigators of many temporary seismic deployments, we obtained a large volume of manual absolute picks, hypocentres and moment tensors gathered all over the world. In this poster, we present examples of the positive effect of including these unique data into the ISC Bulletin.

### Global tomography using normal-mode data: a synthetic-case investigation

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Normal mode data are crucial to constrain the low degree structures of the Earth's interior, as they are sensitive to variations in density, Vp and Vs velocities, and boundary topographies. New measurements of normal mode structure coefficients from recent studies (Deuss et al. 2011, Koelemeijer et al. 2013) have renewed the interest in these long period data for seismic tomography. Through the use of 'synthetic' normal-mode data, we aim at better understanding some of the limitations to bear in mind before interpreting global tomographic models. In particular, we are interested in quantifying how crustal correction errors may propagate into tomographic models. Considering four different crustal models (crust 1.0, 2.0, 5.0, and 3SMAC), we shall show that crustal errors can significantly propagate into the deep mantle, depending on the selected modes. We shall also investigate the sensitivity of normal-mode data to different Vp/Vs and Vp/density scaling factors, as well as to various topography patterns of the core-mantle boundary.

## Global wavefield modeling in 3-D crustal structures

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The 3-D velocity structure of the Earth's interior is largely inferred from global seismic tomography based on various datasets. The Earth's crust can significantly influence the seismic data used in tomography, especially surface waves. Three-dimensional wavefield modeling is the essential approach to accommodate and understand wave scattering in the crust, which is fundamental to a variety of applications such as crustal corrections for travel times and waveforms, sensitivity kernels for surface waves, dispersion measurements, phase velocities, seismic imaging at exploration scale, nuclear monitoring, simulating waves emanating from realistic finite earthquakes, and estimating correct amplitudes for hazard assessment. However, implementing a realistic 3-D crust at a global scale is computationally challenging. So far, no numerical method has been well validated for this purpose. One of the major difficulties arises from crustal thickness which varies drastically between oceanic (~8km depth) and continental regions (~60km), leading to sharp undulations on the Moho discontinuity, especially near the ocean-continent boundaries. To honor the Moho perfectly, the structured global mesh has to be stretched, rendering the simulations much less efficient or unstable. In this study, we present a novel implementation of 3-D crust based on the theory of particle relabelling transformation, according to which the undulations of a radial discontinuity such as the Moho can be equivalently interpreted as material (elasticity and density) perturbations of the contiguous media. Our implementation is based on AxiSEM3D, a new efficient method for global wave propagation in 3-D Earth models. AxiSEM3D is a hybrid of spectral element method and pseudo-spectral method, where the azimuthal dimension of the wave equation is reduced by means of a global Fourier series parameterization, the number of terms of which can be locally adapted to the inherent azimuthal smoothness of 3-D wavefields. It has proved two orders-of-magnitude faster than 3-D discrete methods for spherically-shaped Earth models with 3-D material heterogeneities. We adopt the state-of-the-art crustal model, Crust 1.0, considering topography, bathymetry, and crustal thickness variations. Oceans are simulated as hydrodynamic loads. For a

reference solution, we employ an independent 3-D spectral element method, SPECFEM3D_GLOBE, which implements the crust by mesh stretching. By comparing the synthetic seismograms to high-quality seismic data, we show that SPECFEM3D_GLOBE and AxiSEM3D both well predict body waves but AxiSEM3D better replicates observed surface waves compared to SPECFEM3D_GLOBE, while also being much faster.

## Towards routine determinations of earthquake focal mechanisms obtained from P-wave first motion polarities

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We investigate the possibility to calculate earthquake focal mechanisms in a routine and systematic way based on P-wave first motion polarities. We use any available parametric data in the ISC database. We also use ISC auto-picked polarities from waveform data up to teleseismic epicentral distances (up to 90°) for stations in the international registry that are not reported to the ISC. We use the HASH algorithm for the determination of the earthquake mechanisms as it provides an elegant way to take into account uncertainties in earthquake location and Earth's structure. We modified the algorithm to be compatible with a wide range of epicentral distances and to take into account the ellipsoids defined by the ISC location errors. We first carry out benchmark tests for a set of ISC reviewed earthquakes (mb > 4.5). We use the HASH classification to define the mechanism quality and we find that the mechanisms of quality A, B, and C with an azimuthal gap up to 90° are well compared to our benchmark mechanisms. Nevertheless, the majority of our mechanisms fall into class D as a result of limited polarity data from stations in local/regional epicentral distances. Specifically, we compute the minimum rotation angle between our mechanisms and the benchmarks and we find 24% of D cases with a rotation angle up to 35° and azimuthal gap up to 120°. We finally specify selection criteria with respect to the stations' distribution, misfit and nodal plane uncertainties in order to separate the trusted mechanisms from the rest.

## Reference Event List (GT) for monitoring purposes

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The IASPEI Ground Truth (GT) reference events list is a database of earthquakes and explosions, for which hypocentral information is known with high confidence, with an error typically up to 10 km that is defined by the 95% confidence level. Specifically, the events are defined as GT*X*, meaning that an event is known within *X* km, to a 95% confidence level. The GT database currently contains ~8700 events from 1959 to 2015, with mb/MS < 6.0. The GT events are associated with over 1 million seismic phases recorded from local/regional to teleseismic distances, and therefore, are ideal for location calibration purposes. The database is maintained by the International Seismological Centre which routinely searches for candidate events, relocates and validates them accordingly, based on selection criteria with respect to phase arrivals in local distances, azimuthal gap and secondary azimuthal gap metrics. Typically, events with a 95% confidence level within the 0-5 km range are chemical explosions, rock bursts, mine-induced events, as well as a few earthquakes, whereas GT5 events are typically earthquakes with crustal depths.

## Local magnitudes at short distances

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The local magnitude scale, as used by the British Geological Survey and many other agencies, has been found to be inappropriate when calculated from amplitudes measured less than a few kilometres from the source. Station magnitudes very close to an earthquake are not consistent with those for distant stations. This is not unexpected, as the scale is entirely empirical and was derived using measurements at distances greater than 60 km. This has become particularly topical as networks required to monitor seismicity induced by fracking will need to be within a few kilometres of the source volume in order to record events of very small magnitude. Here, efforts are made to quantify the effect on local magnitude of recording very close to the source. The BGS database has been searched for instances in the past where a station has been within a few kilometres of the epicentre – mostly mining events with a few shallow aftershocks. In addition, data from a dense network of stations installed after the Amatrice earthquake in Italy will be investigated as thousands of the aftershocks recorded were less than 5 km from the nearest station. Methodology includes comparison of magnitudes at different distances and between moment magnitude and local magnitude at nearby stations.

**Induced seismicity at the UK 'Hot Dry Rock' test site for geothermal energy production: a new mechanism**

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In enhanced geothermal projects, fluid is deliberately injected at high pressure to stimulate fracturing and fluid flow through otherwise relatively impermeable underlying hot rocks to generate power and/or heat. The stimulation often induces a series of detectable micro-earthquakes centred around the injection site, which can be used to infer the response of the host reservoir, including its effective permeability, the architecture of its flow channels, and to assess the risk of even larger felt or damaging events. Induced seismicity is routinely monitored at geothermal sites for these reasons, but the precise triggering mechanism involved, and the relationship of induced micro-earthquakes to new and pre-existing fracture networks is still the subject of some debate. Here we investigate the triggering mechanism for induced micro-earthquakes at the UK 'hot dry rock' experimental geothermal site at Rosemanowes in Cornwall. We re-analyse a pre-existing data set to quantify the evolution of several metrics now commonly used to characterise induced seismicity, including the seismic strain partition factor and the 'seismogenic index', both strong controls on the event rate and maximum magnitude. The results show a low strain partition coefficient of 0.01 %, indicating that aseismic processes dominate. This is consistent with the net volume injected being a large fraction of the total, implying a high degree of storage in compliant tensile fractures that do not radiate seismic energy. The strain partition factor decreases with ongoing injection, indicating a decelerating rather than an accelerating (more critical) response to the stress perturbation. We also analyse the spatio-temporal distribution of hypocentres, using simple models for the evolution of hydraulic diffusivity by (a) isotropic pore-pressure relaxation and (b) hydraulic tensile fracturing, noting the likely architecture of the fracture network in the present-day stress field. The results are inconsistent with (a) but consistent both with (b) and with anisotropic pore pressure relaxation acting simultaneously. The principal axes of the diffusivity or permeability tensor inferred from the spatial distribution of earthquake foci are aligned parallel to the present-day stress field, although the maximum permeability is vertical, whereas the maximum principal stress is horizontal. This implies a pre-existing permeable vertical structure. We propose a new hypothesis for the

mechanism of induced seismicity during fluid injection at the site, constrained by the present-day stress field, the pre-existing joint orientation in the host granite rock, and the focal mechanisms of the micro-earthquakes. The resulting phenomenological model is consistent with all of the know constraints, and involves aseismic slip on a set of optimally-oriented pre-existing joints that are 'unclamped' by an increase in pore pressure and concomitant decrease in normal stress, ultimately fed by fluid flow channelling along stress-aligned tensile cracks. This in turn induces seismic slip on new Riedel P-shear planes connecting the major shear slip surfaces. This hypothesis provides a new scenario to consider for risk assessment of projects involving geothermal energy extraction from jointed crystalline hot rocks, in Cornwall and elsewhere.

## Physics-based modelling of the 2016 Amatrice (central Italy) earthquake sequence

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On August 24th 2016 a normal faulting earthquake of Mw = 6.0 struck the Central Apennines (Italy) near Amatrice village, leading to 298 fatalities, extended building collapses and severe damage to cultural heritage sites. The earthquake sequence is characterized by several strong-felt events; the first large magnitude event was followed within 57 minutes by a Mw = 5.4 aftershock, a Mw = 5.4 event on October 26th followed by a Mw = 5.9 event, and a strong Mw = 6.5 earthquake that occurred near the city of Norcia on October 30th, the strongest seismic event in Italy in the last 35 years. Here, we examine how the space-time distribution of the seismicity was influenced by the multiple coseismic stress perturbations of the five main shocks in the surrounding crustal volume and on neighbouring active faults. We estimate the Coulomb stress changes (ΔCFF) on a 2x2 km spatial grid and through a homogeneously elastic half-space. We consider stress estimates at varying depths with 2 km spacing and effective friction coefficients (μ = 0, 0.2, 0.4, 0.6, 0.8). The dislocations of the five mainshocks are modelled assuming a uniform slip distribution with geometries derived from the best available focal mechanisms, and rupture length constrained by empirical scaling relations. For each grid node we adopt the maximum, minimum and average values of the geometric and kinematic fault parameters relative to the main composite seismogenic sources of the Central Apennines. The geometry and sense-of-slip of major active faults on the broader area are taken from the DISS active fault database for Italy. Our modelling results show that 80% of aftershocks of Mw > 2.5 concentrate to a NW-SE trending zone of cumulative stress increase, approximately 4 bar on average. Our study reveals a causal link between mainshocks since every new main shock occurred at high stress increase locations imparted by previous mainshocks. Furthermore, we notice that towards the NW propagation of the Colfiorito-Campotosto source zone, where the 1997 Mw = 6.1 Colfiorito sequence occurred, the positive stress changes are higher than those estimated for the SE region, where the 2009 Mw = 6.3 L'Aquila sequence evolved. Our model output is consistent with the observed spatio-temporal distribution of the seismicity, whose main events clearly migrated towards N-NW in the first two months with obvious implications for the short-term seismic hazard along the Central Apennines mountain chain. The recent 30th October Mw = 6.5 earthquake produced an increased positive stress change from 3 to 5 bar on neighbouring faults towards N and up to 16 bar near the first Mw = 6.0 epicentre, loading further the fault tips corresponding to Colfiorito and Campotosto active faults, without a strong effect on the Paganica fault, the causative fault of the 2009 L'Aquila earthquake.

### Multi-frequency Inversion of P-waves under America

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***AWE Grant Awardee***

Seismic tomography reconstructs the Earth's interior and helps us to understand the relationship between the behaviour of inaccessible regions and that of surface geology. However, in continental scale this relationship is less clear, due to the lack of well distributed stations. As USArrayTA has extended to the eastern border of the US, we are now able to image the entire continent with a reasonable resolution with the use of its high volume data acquired. This study aims to develop a new whole-mantle P-wave model of America utilizing high quality broadband records from the Incorporated Research Institutions for Seismology (IRIS) and other data centres supporting FDSN service up to 2016. P wave velocity structure of the mantle beneath America in eight frequency bands is reconstructed using a multi-frequency approach. The advantage of multi-frequency tomography is that by choosing different frequency bands, one can extract more information from waves. Thus, imaging small heterogeneities are possible, while ray theory fails to image small anomalies. This provides us a clearer insight into the tectonic implication of central and eastern parts of the continent. Besides, the suitable coverage in the US could lead to a better-determined inverse problem. So far, the Source Time Function (STF) estimation has been applied to IRIS/GSN broadband waveforms of ground displacements of 2074 earthquakes of magnitude greater than 5.8 occurring over the period of 2008-2016. Approximated STFs then has been used to measure P-wave travel time anomalies in eight frequency bands.

## Integrating outcomes from probabilistic and deterministic seismic hazard assessment

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Probabilistic seismic hazard assessment (PSHA), the most prominent method for seismic hazard assessment since the early 1970s, uses the widest possible amount of data, combining available seismological, geological and geophysical data to build up a model of the earthquake-producing processes in a region. A special case of PSHA is the deterministic seismic hazard assessment (DSHA) based on geological data and knowledge of active faults. The basic principle of DSHA is that if you can identify the nearest active fault to a particular site and calculate the largest earthquake that could possibly occur on that fault, you can then calculate the largest possible ground shaking at that site. Deterministic analyses of seismic hazard are generally based on discrete, single-valued models to arrive at scenario-like descriptions of seismic hazard (Reiter, 1990). PSHA and DSHA are usually used independently, with the former preferred in engineering and risk assessment applications and the latter being an appropriate tool for stakeholders engaged in policy making and community-based risk reduction activities. In this work I integrate the outcomes from DSHA and PSHA approaches from a single study area to combine the advantages of both approaches. The advantage of a PSHA is that it allows the uncertainties in input parameters (e.g. location and size of earthquakes and ground motion models) and frequency of earthquake occurrence to be incorporated, but the probabilistic dimension of PSHA can make decision-making difficult when the hazard results are characterized by large uncertainty bounds, sensitivity to outliers, and large differences between central estimates (i.e. mean, median and mode) (Reiter, 1990). The advantage of DSHA is that the output (i.e. earthquake scenarios) is clear and understandable to people who do not have a seismological background, but lacks any probabilistic dimension. I apply this approach to the Tien Shan region in Central Asia, an example of an active intra-continental belt, situated more than 1000 km from the suture between India and Asia. I use realistic (although simplified) fault rupture models based on field observations to characterize the sources of destructive historical earthquakes (i.e. 7.3 Ms 8 June 1887 Verny earthquake, 8.3 Mw 11 July 1889 Chilik earthquake, and 8.0 Ms 3 January 1911 Chon-Kemin earthquake) in

the region. Together with ground motion prediction equations, this allows us to develop ground shaking scenarios for the destructive earthquakes that occurred in the Northern Tien Shan. Using PSHA and the earthquake databases of the International Seismological Centre and the British Geological Survey, I associate the historical earthquakes in the Northern Tien Shan with a frequency of occurrence, and the ground shaking simulated in Almaty for those earthquakes with a return period. Furthermore, I disaggregate the hazard results to show the contribution of the historical earthquakes to the hazard in Almaty.

## Spectral Ground-motion Predictive Model for Algeria considering site effect based HVSR

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Local site conditions profoundly affect the ground motion record characteristics, and has an important impact on the accurate of the empirical ground motion prediction relations. Based on a large database containing 1289 records homogeneously processed with more than 600 recorded in Algeria and the rest from essentially Mediterranean region, this study aims to develop a spectral ground motion predictive model for Algeria which has experienced several destructive earthquakes in the past. As for Algerian tectonic environment, only shallow earthquakes were included. The data ranges are 5 to 150 Km for distance, and 3.0 to 7.8 for magnitude. The considered spectral attenuation model accounts for geometrical spreading, anelastic attenuation, and geological site conditions. The regression method, introduced by joyner and Boore (1981), is a two-step inversion [Fukushima and Tanaka, 1990; Fukushima and Tanaka, 1992]. The attenuation model describes the evolution of spectral acceleration according to magnitude, hypocentrale distance, and category of the site. The site classification is based on the predominant period computed using average horizontal to vertical response spectral ratio. Four site categories are defined according to Zhao et al. (2006) classification scheme. Because of the reduced number of records for very soft soil, we consider three soil type for the calculation of the empirical ground motion prediction relations: rock, firm and soft. Spectral attenuation laws were derived from 1289 horizontal components. The obtained results show that the standard deviation decreases compared to the original rock/soil classification scheme. The obtained site coefficients for stiff and soft soil type are in good agreement with those defined in EC-8. Also, the introduction of a more accuracy site classification leads to significantly lower prediction of average spectral acceleration at rock site. Moreover, in Algeria, unlike the seismic zones 3 and 2b, which are characterized by moderate to high seismic activity, for areas with low seismicity as it is the case for seismic zones 1 and 2a who represent a broad range of Algerian territory, considering a low magnitude equal to 5.0 leads to significantly higher prediction of average spectral acceleration.

**Relocating earthquake clusters across Iran**

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Accurate seismic event location is vital for the verification of the Comprehensive Nuclear-Test-Ban-Treaty (CTBT) and plays an important role in understanding the dynamic earth, and the seismogenic processes at work. Iran is one of the most seismically active areas in the world. Event location accuracy in Iran has been shown to have a large location bias of up to 20 km and has limited ground truth earthquake locations [International Association of Seismology and Physics of the Earth's Interior (IASPEI) reference event list hosted by the International Seismological Centre (ISC)]. Active faults in Iran are often only separated by 10-15 km, therefore detailed seismotectonic studies cannot be undertaken when global network locations contain large location biases. These biases are thought to be the result of a combination of inadequate standard 1-D velocity models that do not truly represent the 3-D structure of the Earth and a heterogeneous distribution of seismometers globally. When slip on a fault either ruptures the surface or causes the surface to deform, geodetic measurements such as Interferometric Synthetic Aperture Radar (InSAR) can be used to provide independent event locations. Such observations have also provided an assessment on the precision of global seismic event catalogues. We invert InSAR data associated with ground deformation from Iranian earthquakes to find the source mechanisms and determine an accurate hypocentre. We estimate earthquake depths by inverting the surface wave amplitude spectra or by picking the pP depth phase. We use arrival time information from the International Monitoring System (IMS) network as well as from Iranian stations (collected by the ISC). Using estimated depths and the InSAR inversion results to provide indirect evidence to fix the location of particular events, we perform relocations of clusters of events across Iran. We find significant differences (up to 30 km) in earthquake locations compared with both the Reviewed Event Bulletin (REB) and in country [International Institute for Seismology and Earthquake Engineering (IIEES) and the Institute of Geophysics of Tehran University (IGUT)] locations for different clusters across Iran. These relocated earthquake clusters allows us to improve our understanding of the seismotectonics in particular areas of Iran. The relocated events can also be used

to understand the accuracy of earthquake catalogues (e.g., ISC, REB, IIEES and IGUT) for this region and provide us with calibrated locations to test locations derived using other velocity models (e.g. LLNL-G3D).

**The use of real accelerograms as input to dynamic analysis**

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The evaluation of the structural response via temporal dynamic analysis requires some characterization of the seismic excitation, in term of accelerograms, which should reflect the seismic hazard as well as the site class. Usually in seismic codes, the signals that can be used are (i) artificial signals, (ii) simulated accelerograms and (iii) real records. Selecting, scaling and matching those signals are important, enabling structural response to be determined with better confidence and through fewer analyses than if unscaled accelerograms are employed. It is easier to use spectrum matching signals, obtained either by simulation or manipulation of real records but real recordings are the more attractive signals since accessible databases are available and only a limited number of criteria have to be considered in selection. This paper considers the response of several soil profiles to different input accelerograms (i) real ones, unscaled and (ii) selected, linearly scaled or spectrally matched ones using different techniques. The results obtained show the disparity of the responses. A critical analysis allowed us to promote the choice of real signals.

# Empirical relation scaling $I_0$, $M_d$ and $M_w$ for Algeria towards a homogenization of the seismic catalogue

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The Tell Atlas of Algeria is known to be an earthquake prone area which experienced many several earthquakes. All these events occurred along the Africa-Eurasia plate boundary collision zone. Evaluation of seismic hazard needs the compilation of homogenized earthquake catalog containing moment magnitude $M_w$, body-wave magnitude $m_b$ and surface-wave magnitude $M_s$. The actual Algerian catalog provides duration magnitudes $M_d$ and macroseismic intensities $I_0$.

In order to homogenize and complete our seismic catalog, we determined empirical relations for $M_d$ and $I_0$ calculated by CRAAG (Centre de Recherche en Astronomie, Astrophysique et Geophysique) in function of $M_w$, $M_s$, $m_b$ given by international seismological agencies (eg. ISC). To reach this objective, we construct a database to establish the relationship between the available magnitudes and intensity data using linear method. The results obtained and the reliability of the formulas are discussed. This will enable us to obtain a complete database regarding $M_w$ and complete magnitude parameter for past earthquakes to better evaluate seismic hazard within the Tell Atlas (Algeria) with several urbanized large cities such Algiers-capital city.

## AWE Blacknest archive of seismic recordings of presumed underground explosions, 1964- 1996

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Since the early 1960s Blacknest has been the UK centre for research into detecting and identifying underground explosions using seismology. Scientists there provided significant technical advice during the negotiations leading up to signing of the Comprehensive Test Ban Treaty in 1996. Some of the raw data behind the expertise came from the four seismometer arrays at Eskdalemuir (EKA), Yellowknife, Canada (YKA), Gauribidanur, India (GBA) and Warramunga, Australia (WRA), from which data have been stored since as far back as 1962. Analogue data have been digitised and digitial data transcribed to preserve them. The lack of data format standards at that time led to Blacknest developing its own. For the past seven years we have been assembling and reprocessing digitial and digitised records of presumed and announced explosions and earthquakes, to allow other institutions access to the data in standard formats and with basic metadata. Projects to digitise analogue tape and transcribe continuous digital data from old tapes have yielded datasets with potential for ambient noise studies as well as the analysis of signals that were not recognised at the time as being of interest.

# Maximum-likelihood magnitudes of announced underground nuclear tests by the Democratic People's Republic of Korea, 2006-2016

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The seismic disturbances caused by the five (2006-2016) announced nuclear tests by the Democratic People's Republic of Korea (DPRK) are of moderate magnitude (body-wave magnitude mb ~ 4-5) by global earthquake standards. An upward bias of network mean mb of low- to moderate-magnitude events is long established to be caused by the omission of stations where the signal was below noise level at the time of its arrival. This sampling bias can be overcome by maximum-likelihood methods in which either directly measured noise amplitudes or threshold levels determined by statistical analysis of bulletin amplitudes of other arrivals at non-recording stations are used to condition the probability of the network magnitude along with the actually measured station magnitudes. For the DPRK tests a joint maximum-likelihood inversion was run to deliver the magnitudes of the five events and station corrections at the CTBTO International Monitoring Network (IMS) stations. The effect of using auxiliary as well as primary stations was investigated. The resulting body-wave magnitude is compared with the network mean and maximum-likelihood magnitudes in the CTBTO Reviewed Event Bulletin.

## 1. Resolvability of regional density structure - a principal component approach to resolution analysis

**Agnieszka Plonka[1], A. Fichtner[2]**

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The seismic disturbances caused by the five (2006-2016) announced nuclear tests by the Democratic People's Republic of Korea (DPRK) are of moderate magnitude (body-wave magnitude mb ~ 4-5) by global earthquake standards. An upward bias of network mean mb of low- to moderate-magnitude events is long established to be caused by the omission of stations where the signal was below noise level at the time of its arrival. This sampling bias can be overcome by maximum-likelihood methods in which either directly measured noise amplitudes or threshold levels determined by statistical analysis of bulletin amplitudes of other arrivals at non-recording stations are used to condition the probability of the network magnitude along with the actually measured station magnitudes. For the DPRK tests a joint maximum-likelihood inversion was run to deliver the magnitudes of the five events and station corrections at the CTBTO International Monitoring Network (IMS) stations. The effect of using auxiliary as well as primary stations was investigated. The resulting body-wave magnitude is compared with the network mean and maximum-likelihood magnitudes in the CTBTO Reviewed Event Bulletin.

## Locating seismic sources with an automated multi-scale array-based detection and location scheme

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The ability to outline in fine detail the pattern of seismic energy release at different spatial and temporal scales is crucial for understanding the physics of deformation processes. Recent rapid densification of seismological monitoring systems, and continuously growing computational resources provide an opportunity to explore seismic sources at previously unknown scales. This, however, requires automated methods that can fully exploit complexity of seismic signals recorded across dense, large-scale seismic networks. We present a recently developed method called BackTrackBB, which allows to image the coherent energy radiation from seismic sources associated to different tectonic environments using continuous seismic records (Poiata et al. 2016). The method is a computationally efficient, array-based scheme performing simultaneous detection and location of seismic sources by exploiting the multi-scale frequency-selective coherence of signals' statistical features recorded across the stations of seismic network. The performance of the method in detecting, locating and characterizing seismic sources in complex tectonic environments is further discussed on the following case studies: (1) analysis of the 2013 seismic swarm of potentially induced earthquakes in southeastern Romania; (2) detection and location of tectonic tremor sources and low-frequency earthquakes during a tremor episode in southwestern Japan. The potential of extending the method to an automated system for seismic activity monitoring will be also discussed.

**Variations in lithospheric structure across the Indo-Eurasian collisional belt**

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The Himalayan Mountains and the Tibetan Plateau are the most spectacular present-day tectonic features on the continents. Tibet was formed by the successive collisions of several incoming continental blocks with southern Eurasia, the last of which was India. The collision of India with the Lasha terrain of southern Asia occurred during the mid-Eocene and has resulted in crustal thickening and the uplift of southern Tibet and the stacking of thrust sheets to its south, thus forming the Himalaya. The extensive geological and geophysical studies of the Tibetan Plateau over the past quarter of a century suggested that the relatively uniform surface structure of Tibet masks significant lateral variations in the crust and upper mantle structure. The deep geodynamic processes involved in the uplift and support of the Himalayas and Tibet are still unresolved. We use receiver functions and high frequency surface wave analysis to refine the crustal wavespeed structure across the whole collisional belt. Group velocity dispersion data from regional earthquakes and ambient noise cross-correlations plus teleseismic receiver functions shed new light on the crustal structure -- most interestingly, a mid-crustal low velocity layer (~10% decrease in wavespeed) which is observed throughout much of Tibet and which we attribute to radiogenic heating of the crust. Low frequency multi-mode surface wave analyses show that northern India and all of Tibet -- but not the southern portion of the Indian Shield -- are underlain by a thick, high-shear wavespeed lithospheric structure. These observations of the shear wavespeed structure provide significant constraints on our understanding of the evolution of the Indo-Eurasian collisional belt and offer clues as to processes occurring in ancient orogens.

## Seismic tomography: From damped least squares to transD

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Over the last four decades, seismic tomography has been the primary tool for revealing the heterogeneous nature of Earth's internal structure. From its origins in early active and passive source traveltime studies in the 1970s, seismic tomography has become increasingly sophisticated and powerful in response to advances in methodology, rapid improvements in computing power and growth in the availability of digital data. Today, we have reached a point where massive inverse problems involving millions of unknowns and tens of millions of data measurements can be tackled; where the entire waveform can be inverted rather than derivative components such as traveltime; where multiple datasets can be jointly inverted; and where various properties, seismic and otherwise, can be recovered. Early tomography applications tended to be formulated as linear inverse problems, which were solved using gradient-based or backprojection methods. When raytracing in laterally heterogeneous media became computationally tractable for predicting large datasets, iterative non-linear gradient-based techniques gradually became more popular. The workhorse of the gradient-based approach, whether for linear or iterative non-linear problems, is damped least squares (DLS) and its many variants, which essentially involves minimisation of an L2 misfit function via the solution of a large linear system of equations. An added bonus of this approach is that formal estimates of posterior covariance and resolution can be retrieved relatively easily. However, their usefulness in assessing solution robustness is limited due to a number of factors including poor knowledge of data errors and prior model constraints, ad hoc implicit and explicit regularisation, and non-linearity. Synthetic reconstruction tests, which can usually be readily applied to any tomographic problem, started to become popular in the 1980s. It is notable that their original intention was to provide summary information on formal estimates of model resolution for very large inverse problems. Today, despite massive increases in computing power, most tomography problems are formulated as linear or iterative non-linear inverse problems, and DLS-type methods remain the most common solution scheme. While this approach has revealed much about the internal structure of the Earth, inversion methods based on non-linear sampling are gradually becoming more tractable for problems of ever increasing size. These have the advantage of better exploring model space for data-fitting solutions, quantifying model uncertainty more rigorously, and largely dispensing with ad-hoc regularisation. So-called transdimensional (or transD) tomography is one of these new classes of solution method which is rapidly becoming popular. It is formulated in a Bayesian framework and uses a reversible-jump Markov-chain Monte-Carlo method to sample the posterior probability density function. This allows the number of model unknowns to itself be an unknown in the inversion, which means that the number and spatial distribution of model parameters becomes data driven, rather than imposed a priori. The method does not assume linearisation, and the final “solution” consists of an ensemble of data-satisfying models which can be interrogated for summary information. As well as describing this new method, I will also present several case studies from Australia which highlight its advantages compared to traditional DLS-type inversion schemes.

## Seismological research in Sweden: Current status and some highlights

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The centre for seismological research in Sweden is Uppsala University, where seismological activities started over 100 years ago. There are some relevant activities at other universities and authorities, but these are limited in volume. The Geophysics unit at Uppsala has recently expanded significantly and currently consists of about 70 researchers, including 20-30 PhD students. Of these, about one third are largely or completely focused on earthquake seismology, with most of the rest working on reflection seismology, deep drilling projects, electromagnetic methods, and the development of modelling and inversion codes. Current (2016-17) projects (mostly PhD projects) include: Statistical seismology; spatio-temporal patterns and foreshocks (Greece and Fennoscandia). Local source tomography of volcanoes (Iceland). Induced seismicity in geothermal fields (Iceland) and in enhanced geothermal systems (Sweden). Mining-induced seismicity (Sweden). High-resolution numerical modelling of stimulation of secondary faults close to a large event (Sweden). Methodologies for the analysis of volcanic tremor (Iceland). Ambient noise surface wave analyses, especially methodological development (Iceland and Sweden). Stress and slip modelling of large, interacting, events (Iran). Detection and analysis of micro-events in complex situations (Iceland and Sweden). Monitoring and analysis of neo-tectonic faults in Fennoscandia. Seismicity and seismic risk in Kenya. Detection and analysis of micro-earthquakes. This presentation will give a brief overview of current activities, and present a few very recent results in more detail, with focus on some of the remarkable aspects of Swedish seismicity and some novel recently developed analysis method.

## The Swedish National Seismological Network: Hazard assessment in a low-seismicity intraplate area

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Sweden, part of the ancient Baltic Shield, is a stable continental area and seismicity is low. Nevertheless, continuous seismological recording has been performed in Sweden since 1904. The registration system has evolved over time. Currently, there are about 65 permanent broad-band stations in operation, covering most of the country with a station spacing of the order of 70 km. The data is essentially complete to magnitude 0.5 within the network. Technically, the network uses the same system as is used in the Icelandic National Network, which was to a significant extent designed in Uppsala as part of a joint Nordic project. On both Iceland and in Sweden, reliable detection and analysis of very small events has been a major aim with the system design. The high sensitivity of the system is achievable because of Swedish geology, very careful site selection and installation, high sensitivity instruments and specially designed analysis algorithms. Focal mechanism information is calculated for all detected events. One significant practical operation remains identification and rejection of anthropogenic events, largely from the Swedish mining industry and infrastructure construction. This is dealt with using algorithm-supported operator interaction. The network is run by the Geophysics unit at Uppsala University. Direct financial support from the Government corresponds in total to the cost of 5-6 full time equivalent employees. This financing contributes to the costs of running the network, but the unit is also expected to perform as the Government's expert resource on geological hazards, actively interacting with Government units such as the foreign office, media, industry, and the general public. In addition, industry contributes long-term support equivalent to 2-3 full time employees, and there is a constant flow of funding for various related basic and applied research projects. Industry interest in seismicity is largely from the nuclear, mining and construction industries. While seismicity is low in Sweden, from solid palaeoseismological data it is known that very large earthquakes occurred about 10 000 years ago, at the end of the ice age, and that several of these neotectonic faults are still significantly seismically active. There are major dam complexes close to some of these faults. It is also known that seismicity is far from temporally stationary, with distinct and remarkable episodic seismicity patterns. Thus, assessment of seismic hazard is complex, and it appears that both more data and new methodologies may be necessary in order to robustly assess risk.

# Attenuation of seismic waves in southeast Iran (Gheshm region)

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An important parameter which directly affects the propagation of seismic waves either in earthquakes or explosions is attenuation coefficient, quality factor, of an area. Quality factor of seismic waves, Q, in the lithosphere at high frequencies (1 to 20 Hz) is one of the most useful parameters to explain attenuation of seismic waves as an important property for the study of earth structure which contains meaningful information even in short distances. Having such a parameter for an area helps us to guess the decreasing of the amplitude of a vibration and could be even useful while monitoring explosions. Many methods have been innovated measuring Q factor using natural and artificial data. In this research we determine Q factor for Gheshm region using “Sato method”. IIEES broad band network data are used doing this study. A network including 13 seismographs are installed in the area and using 112 recorded events during 3months, after Gheshm 2005 earthquake, the parameter is calculated. After processing we proposed a relation for Q in Gheshm region as Q=77f ^ 0.83, where “f” is frequency and the relation confirms that Q values are frequency dependent (increasing with frequency) in the media through which it propagates.

## Using diffractions as passive source wavefields: A traveltime moveout perspective

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Seismic diffraction occurs in arguably all complex tectonically active media and can be observed in particular in the context of crustal faults and in regions with discontinuous changes in elastic properties such as salt environments. Yet, since depth imaging methods such as Kirchhoff migration aim at collapsing the diffraction responses, they are still widely considered as an undesired portion of the wavefield. In addition, diffractions, due to strong geometrical spreading are general of much lower amplitudes and commonly masked by the historically favoured reflections. In the past decade however, diffractions have gained increased interest in the exploration community, because they are known to contain super-resolved information about the subsurface, i.e. structural information beyond the classical Rayleigh limit. In particular modified versions of the Kirchhoff integral have proven a reasonable choice for extracting and separating the generally very faint and subtle diffracted contributions from the dominant direct arrivals and directional reflections. Despite the success, these modified depth migration methods only perform well, when an accurate seismic velocity model is at hand. We suggest a fully data-driven strategy to identify and efficiently extract seismic diffractions in the time domain, that not only permits imaging, but also allows for the joint localization of the diffractor locations and the inversion of the traversed velocity model. Owing to their non-directional radiation, we argue that diffractive structures, from a traveltime moveout perspective, behave exactly as passive sources buried in the ground. Following this approach, we identify propagation symmetries and local passive source equivalent attributes, which can be measured in the data by deploying coherence-based traveltime moveout analysis. While in conventional beamforming, only the local slopes of the emerging wavefronts are estimated, we in addition make use of local wavefront curvature measurements, which can lead to a successful descrimination of reflections and diffractions, even when - as is the case in most academic expeditions - only single-channel or near-offset data is available. We suggest an atomatized workflow, in which first, the traveltime moveout analysis is used to extract the first and second-order wavefront attributes.

Based on these attributes, in the second step, we design filter functions that, like in surface-related multiple elimination, are used to enhance and adaptively subtract the generally dominating reflection foreground. In the resulting diffraction-only data, we again perform coherence analysis in order to arrive at estimates of local diffracted wavefront slopes and curvatures. These diffraction attributes are then fed into back-propagating wavefront tomography, leading to a joint diffractor location and velocity inversion without having to depend on an accurate starting model. We illustate the workflow and demonstate its applicability with two field data examples – one acquired in academia, the other by a contractor company for hydrocarbon exploration.

## Probabilistic seismic hazard assessment in low-to-moderate seismicity regions: outcome from the SIGMA research program

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SIGMA research & development program took place between 2011 and mid-2016. The main objectives were to improve the knowledge of data, methodologies and tools to better quantify and reduce the epistemic uncertainties of the seismic hazard models. Two sites, South-eastern France and Northern Italy, were selected to assess the improvement in the seismic hazard components during the course of the project.

This study presents the final PSHA model performed for the South-Eastern France case study. This PSHA model integrates the relevant scientific progress made in the different SIGMA work packages during the last five years: 1) a new earthquake catalogue for France covering instrumental and historical periods, 2) a set of ground motion prediction equations (GMPEs) developed from global and regional data, 3) a new methodology to evaluate the maximum magnitude for moderate seismicity regions, 4) incorporation of area sources models, smoothed seismicity, 3D faults models. The magnitude-frequency distributions, maximum magnitude, faults slip rate and style-of-faulting are considered as additional source of epistemic uncertainties.

The hazard results are displayed at 20 selected sites in terms of UHS at two selected return periods (475 years and 10,000 years). In order to evaluate the impact of the new hazard model, we compare the results with existing models developed at the French territory scale in the framework of the first generation of models supporting the Eurocode 8 enforcement, (MEDD 2002 and AFPS06) and at the European scale (within the SHARE project), highlighting significant discrepancies at short return periods.

**Fully probabilistic seismic source inversion**

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Seismic source inversion is a non-linear problem in seismology where not just the earthquake parameters themselves but also estimates of their uncertainties are of great practical importance. We have developed a method of fully Bayesian inference for source parameters, based on measurements of waveform cross-correlation between broadband, teleseismic body-wave observations and their modelled counterparts. This approach yields not only depth and moment tensor estimates but also source time functions. These unknowns are parameterised efficiently by harnessing as prior knowledge solutions from a large number of non-Bayesian inversions. The source time function is expressed as a weighted sum of a small number of empirical orthogonal functions, which were derived from a catalogue of >1000 source time functions (STFs) by a principal component analysis. We use a likelihood model based on the cross-correlation misfit between observed and predicted waveforms. The resulting ensemble of solutions provides full uncertainty and covariance information for the source parameters, and permits propagating these source uncertainties into travel time estimates used for seismic tomography. The computational effort is such that routine, global estimation of earthquake mechanisms and source time functions from teleseismic broadband waveforms is feasible. A prerequisite for Bayesian inference is the proper characterisation of the noise afflicting the measurements. We show that, for realistic broadband body-wave seismograms, the systematic error due to an incomplete physical model affects waveform misfits more strongly than random, ambient background noise. In this situation, the waveform cross-correlation coefficient CC, or rather its decorrelation $D = 1 - CC$, performs more robustly as a misfit criterion than ℓp norms, more commonly used as sample-by-sample measures of misfit based on distances between individual time samples. >From a set of over 900 user-supervised, deterministic earthquake source solutions treated as a quality-controlled reference, we derive the noise distribution on signal

decorrelation D of the broadband seismogram fits between observed and modelled waveforms. The noise on D is found to approximately follow a log-normal distribution, a fortunate fact that readily accommodates the formulation of an empirical likelihood function for D for our multivariate problem. The first and second moments of this multivariate distribution are shown to depend mostly on the signal-to-noise ratio (SNR) of the CC measurements and on the back-azimuthal distances of seismic stations.

## Seismic Signals from Digital Rocks

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Carbonates hold approximately 60% of the world's oil and 40% of the world's gas reserves (Schlumberger, 2007), yet are relatively poorly understood in terms of their elastic properties. This is partly due to the complexity of the pore structure and the fabrics that form in carbonates during their formation, including the primary deposition by sedimentation and/or by precipitation at the surface, as well as secondary precipitation and dissolution reactions at depth. This makes it difficult to develop simple rock physics models for their geophysical properties, notably the relationship between bulk seismic velocity and hydraulic properties such as porosity and permeability. Here we seek to understand how the elastic properties, such as P and S wave velocities, relate to micro-structural properties of the rocks, and specifically how elastic properties change when external conditions change (e.g., increasing effective pressure during reservoir depletion). We examine the detailed nature of wave propagation in complex carbonates by linking elastic properties such as seismic velocity, with detailed rock micro-structure information, using high resolution x-ray micro-tomography and numerical modelling of wave propagation. This approach enables new experiments to be conducted numerically, where geological processes such as dissolution, cementation or fracturing, are simulated by changing properties of the images. The effect of these processes on seismic properties can then be calculated or simulated, for example uniform cementation, or elastic pore closure. These methods can then be benchmarked with laboratory results by performing experiments investigating the relationship between seismic velocity and changes in fluid pressure, and differential stress, and comparing pre- and post-deformational micro-tomography scans. We also present Coda Wave Interferometry (CWI) as an appropriate method (for laboratory and numerical experiments) for detecting very small fractional changes in the bulk velocity of the medium. This method uses multiply-scattered waves, which sample the same parts of the medium many times and are therefore more sensitive to changes in velocity, compared to using the direct-wave or primary reflection arrivals which typically only sample along a single ray path once. We demonstrate that this allows us to observe much smaller changes in a medium than was possible previously. The methods presented are applicable in any context where time-lapse seismic monitoring occurs, not only for oil and gas reservoirs, but carbon storage and sequestration sites, geothermal sites, and groundwater aquifers.

## Estimating the complete stress tensor field from microearthquake observations

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The upper crust in seismicly active areas has had thousands of major earthquakes and is therefore quite fractured and deforming by frictional slip, for instance microearthquakes. Each microEQ shows that the Coulomb Failure Stress (CFS) has increased and reached zero for the slip direction on the fracture. We know however also that all the thousands other fractures within the microEQ volume all have negative CFS in all directions. The simplest approximation for including this information is to assume that the Coulomb failure criterion for homogeneous rock is valid also for the fractured rock. By this the directions of the three principal stresses will be given by the microEQ fault plane solution (FPS), 3 constraints on the stress tensor causing the slip. By assuming that CFS=0 MPa for the FPS we get a fourth constraint. To achieve this we must relate the water pressure (we assume a wet crust) to the lithostatic stress, here we assume that the water pressure is as small as possible to avoid squeezing out. A fifth constraint is achieved by assuming that the vertical stress equals the lithostatic stress which is well supported by rock stress measurements. The sixth constraint is achieved by minimizing the deviatoric elastic deformation energy, the "nature" avoids "overkill". By these assumptions all 6 elements of the stress tensor causing the microEQ can be determined. The method was presented 2006 and has since then been applied to hundred thousands microEQs in Iceland, and to induced seismicity in Swedish mines, and to induced seismicity at Geysir, USA, and in geothermic sites in Iceland. As each microearthquake is a complete measurements of the stress tensor the method can be used both for mapping the stress tensor field as well as monitoring the crustal stresses. Note, when we know the stress tensor field the instability (CFS-value) for any fracture will also be known. This makes the method especially valuable for improving earthquake warnings. Several such examples will be presented from Iceland with the largest EQs having M=6.6 in June 2000. The stress monitoring with use of this method is implemented by IMO in Reykjavik for the Southern Iceland Seismic Zone. Examples will be shown. It is obvious that the method requires microEQs, with no microEQs nothing will be known. However, most of the larger Icelandic EQs do have foreshocks. But, sometimes they are quite small with even negative magnitudes but often there are hundreds of them. When we do have foreshocks the stress monitoring seems to be quite valuable, increasing CFS values are then observed in the hypocentral area. I strongly recommend geophysisists to look more into that value of knowing the crustal stresses. I think that one reason why the stresses so long have been overseen are due to the misunderstanding that the FPS only puts weak constraint on the stress tensor. However, that is only so if the earthquake volume only contains one (!) fracture, the fault. For the crust in a seismicly active region that never occurrs. The block volumes in such a crust are quite small.

**Ice fabric in an Antarctic ice stream interpreted from seismic anisotropy**

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It has long been known that glacial ice is anisotropic. Crystal alignment during ice compaction and flow forms "ice fabrics" which significantly affect the mechanical properties of the ice. However, numerical models used to predict the evolution of ice flow in key regions such as Greenland and Antarctica do not effectively take anisotropy into account, due to a lack of in-situ estimates of ice fabric to drive them. This is a particular problem in fast-flowing ice regions, such as ice streams, where it is challenging to obtain ice samples. Here we present new measurements of a clear anisotropic ice fabric in a fast moving (377 $ma^{-1}$) ice stream in West Antarctica. We use ∼6000 measurements of shear wave splitting observed in microseismic signals from the bed of Rutford Ice Stream, to show that the ice in this area is dominated by a previously unobserved type of partial girdle fabric. This fabric has a strong directional contrast in mechanical properties, shearing 9.1 times more easily along the ice flow direction than across flow. This observation is likely to be widespread and representative of other ice streams and large glaciers. Ice streams are the key outlet pathways for ice sheets and therefore an understanding of how best to model ice flow in these regions is essential to accurately predict the future stability of the cryosphere. This study is the first conclusive study of which we are aware that provides a robust model of ice stream fabric using shear wave splitting in microseismic data, providing key results for data-driven ice flow modelling.

**Bolide airbursts as a seismic source for the 2018 Mars InSight mission**

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In 2018, NASA will launch InSight, a single-station suite of geophysical instruments, designed to characterise the martian interior. We investigate the seismo-acoustic signal generated by a bolide entering the martian atmosphere and exploding in a terminal airburst, and assess this phenomenon as a potential observable for the SEIS seismic payload. Terrestrial analogue data from four recent events are used to identify diagnostic airburst characteristics in both the time and frequency domain. In order to estimate a potential number of detectable events for InSight, we first model the impactor source population from observations made on the Earth, scaled for planetary radius, entry velocity and source density. We go on to calculate a range of potential airbursts from the larger incident impactor population. We estimate there to be ~1000 events of this nature per year on Mars. To then derive a detectable number of airbursts for InSight, we scale this number according to atmospheric attenuation, air-to-ground coupling inefficiencies and by instrument capability for SEIS. We predict between 10-200 detectable events per year for InSight.

## The ISC datasets and services to seismology

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The main mission of the International Seismological Centre (ISC) is to provide the definitive parametric information on the recent and past earthquakes and other seismic events by collecting, processing and integrating seismic bulletins from ~130 networks worldwide.

The ISC Bulletin is the most complete global long-term source of seismic bulletin information covering the period 1904-2017 and containing almost 6 millions of seismic events with associated 150 millions of seismic arrivals recorded at approximately 16 thousands of seismic stations worldwide.

To assist a wide range of users working in different research areas, the ISC has also developed several subsets and extensions of the ISC Bulletin. The ISC-EHB dataset provides a high-precision view of seismicity based on the selection of well-recorded seismic events; it is used by those studying the inner structure of the Earth as well those working in geology and tectonics. The ISC also maintains the IASPEI Reference Event List (GT) used for calibration of newly developed velocity models and earthquake location methods. The ISC-GEM catalogue is a highly homogeneous dataset of moderate-to-large earthquakes designed for use in global and regional studies of seismic hazard and risk. The ISC Event Bibliography is an interactive facility that enables searches for references to scientific articles devoted to specific natural and anthropogenic seismic events that occurred within a region and time period of interest. The CTBTO Link to the ISC database is another dedicated service for those monitoring nuclear explosions in the context of the Comprehensive nuclear Test Ban Treaty (CTBT).

## The feasibility of detecting CO2 leaks using passive seismic monitoring

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The Aquistore project in Saskatchewan, Canada provides the carbon dioxide (CO2) storage site for the world's first combined commercial power plant carbon capture and storage (CCS) project. CO2 injection at a depth of 3.2 km has been on-going since April 2015 and a permanent near-surface geophone array provides passive seismic monitoring (PSM). Using fluid flow modelling of a leak of single-phase CO2 through a vertical fault, we find that seismicity is expected once the CO2 reaches shallow depths (<500m) because the fluid pressure is predicted to exceed the formation fracture pressure. The conclusion we reach is that there would be time of the order of days for mitigation measures (e.g., evacuation of people) if the fault aperture were <10-5m. We also use data from the geophone array to investigate whether ambient noise interferometry (ANI) and a tomographic inversion for Rayleigh wave group-velocity maps could provide a suitable CO2 leakage detection tool. To assess the repeatability of the method we conduct, for the first time, a time-lapse ambient noise tomography survey of a CO2 storage site to cover time periods preceding and following injection start-up. Sensitivity analysis results indicate that usable surface wave data derived from the current array configuration are sensitive to depths of up to ~400m. We do not expect to observe any changes due to CO2 migration at such shallow depths and the estimated seismic velocities agree to within 0.07km/s. The group travel-time picking errors are mostly 5–15% but at 400m a change in seismic velocities of 3.5% is predicted with CO2 saturation at this depth, insufficient precision to resolve such a small change in velocity. In the event of a CO2 leak at the Aquistore site, PSM is most likely to provide early-warning through the detection of fluid-induced seismic events (i.e., microseismicity). The geology, the array configuration, and the group travel-time picking uncertainties prevent the use of ambient noise Rayleigh wave tomography to detect velocity changes due to CO2 saturation. However, the resulting map of 3D near-surface velocities is useful for near-surface static corrections when using

seismic reflection surveys to image the reservoir. In general, further studies such as this one are required to determine the applicability of ANI for leak detection at other $CO_2$ storage sites.

## Upper crustal structure of the North Anatolian Fault Zone from ambient seismic noise surface wave tomography

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The advent of seismic techniques that utilise the ambient seismic noise field has revolutionised the potential for imaging the Earth's lithosphere. Instead of being constrained by the irregular distribution of earthquake sources, seismic sampling is only dependent on seismic station distribution. Cross-correlation of the ambient noise field between two stations allows us retrieve the Green's Function between virtual seismic sources and receivers at arbitrary locations. Here, we use data from a dense seismic array (Dense Array for Northern Anatolia - DANA) deployed across the North Anatolian Fault Zone (NAFZ) in the region of the 1999 magnitude 7.6 Izmit earthquake in western Turkey. The NAFZ is a major strike-slip system that extends ~1200 km across northern Turkey and continues to pose a high level of seismic hazard, in particular to the mega-city of Istanbul. We obtain maps of group velocity variation using surface wave tomography applied to short period (1- 6 s) Rayleigh and Love waves to construct high-resolution images of surface wave group velocity variation in the upper 10 km of the NAFZ. The average surface wave group velocities in the region vary between 1.8 km/s at 1.5 s period, to 2.2 km/s at 6 s period. The signatures of both the northern and southern branches of the NAFZ are clearly associated with strong gradients in surface wave group velocity. To the north of the NAFZ, we observe low surface wave group velocities (~ 1.2 km/s) associated with the unconsolidated sediments of the Adapazari basin, and blocks of weathered terrigenous clastic sediments. To the south, we detect high velocities (~ 2.5 km/s) associated with a shallow crystalline basement, in particular a block of metamorphosed schists and marbles that bound the northern branch of the NAFZ, as well as a potential granitic intrusion at depth.

## Slab Behaviour in The Mantle Transition Zone

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The behaviour of subducted oceanic lithosphere in the Mantle Transition Zone (MTZ) remains poorly understood. Controls on slab mass transfer from upper to lower mantle are a further unknown. Seismic tomography models consistently exhibit fast velocity anomalies that widen approaching 670km depth. Rheological mechanisms, ranging from vertical piling to lateral buckling, have been invoked to explain this ‘slab thickening’. Robust tomography models of the MTZ are thus critical to improve our understanding of subduction.

Japan is a perfect case study to investigate this. Here, slab stagnation in the MTZ contrasts between the Honshu and Northern Bonin arcs, with varying slab dip. Additionally, the distribution of seismic stations around Japan provides strong regional coverage, with a sufficient number of intersecting ray paths and wide back-azimuthal range.

Triplicated S-waves sample the MTZ strongly and should be utilised to maximise resolution for this depth window. We aim to jointly invert these with higher mode surface waves using regional finite-frequency tomography, yielding gun-to-tape depth resolution for the entire upper mantle. Multi-frequency travel times for both regional and teleseismic S-waves will be measured with a matched filter approach, with predicted and observed waveforms then compared by cross-correlation, for a suite of frequency bands. To compute synthetic seismograms, we will use fully numerical forward modelling of the seismic wavefield for a spherically symmetric Earth to 1s dominant period. Looking ahead, Japan offers the opportunity to compare inversions incorporating triplicated S-waves with other, full-waveform inversions, performed for the region.

**Multifrequency measurements of P waves on ocean bottom seismometers in the Indian Ocean**

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From 2011 to 2014, the RHUM-RUM project (Reunion Hotspot Upper Mantle – Reunions Unterer Mantel) instrumented a 2000 km x 2000 km area of the Indian Ocean seafloor, islands and Madagascar with broadband seismometers and hydrophones. The central component was a 13-month deployment of 57 German and French Ocean Bottom Seismometers (OBS) in 2300-5600 m depth. This was supplemented by 2-3 years deployments of 37 island stations on Reunion, Mauritius, Rodrigues, the southern Seychelles, the Iles Eparses and southern Madagascar. Two partner projects contributed another 30+ stations on Madagascar. Our ultimate objective is multifrequency waveform tomography of the entire mantle column beneath the Reunion hotspot. Ideally, we would use all passbands that efficiently transmit body waves but this meets practical limits in the noise characteristics of ocean-bottom recordings in particular. More than 200 teleseismic events during the 13-month long deployment yielded usable measurements. We present our methods, discuss data yield and quality of ocean-bottom versus land seismometers, and of OBS versus broadband hydrophones. Above and below the microseismic noise band, data yields are higher than within it, especially for OBS. The OBS were afflicted by relatively high self-noise compared and the hydrophones functioned particularly reliably but their waveforms are relatively more challenging to model due to reverberations in the water column. We obtain ~25000 combined cross-correlations measurements that should be usable in multifrequency P-wave tomography, in passbands between 30 s and 2.7 s dominant period. The measurements for permanent and temporal land stations show high quality, as quantified by high cross correlation factors. However, because of the microseismic and stationary noise, correlation of the OBS data shows lower values of cross correlation compared to land stations. Hydrophones worked more reliably but contain strong reverberations from the water column so that currently fewer data are usable than from the seismometers. Here we present preliminary results of the P-wave inversion based on multifrequency traveltime observations, obtained by cross-correlation of observed with predicted waveforms. The latter are synthesised from fully numerical Green’s functions and carefully

estimated, broadband source time functions. Work is ongoing on including hydrophone data and embedding our regional data-set to a global P-wave inversion.

**Updating of a PSHA based on Bayesian inference with historical macroseismic intensities**

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Since the basic work of Cornell, many studies have been conducted in order to evaluate the probabilistic seismic hazard (PSHA) at a given site or at a regional scale. In general, results of such studies are used as inputs for regulatory hazard maps or for risk assessments. Such approaches are nowadays considered as well established and come more and more used worldwide, generally in addition to deterministic approaches.

Nevertheless, some discrepancies have been observed recently in some PSHA, especially from studies conducted in areas with low to moderate seismicity. The lessons learnt from these results lead to conclude that, due to uncertainties inherent to such a domain (for example, the ground-motion prediction equations used in computing the hazard), some deterministic choices have to be made and, depending on expert judgments, may lead to strong differences in terms of seismic motion evaluation.

In this context, the objective of this paper is to present a methodology that can be used to take into consideration historical observations (such as macroseismic Intensities) in order to reduce epistemic uncertainties in a probabilistic seismic hazard assessment (PSHA). The method developed here is based on a Bayesian inference technique that is used in order to quantify the likelihood of the prior estimation and finally, update the PSHA.

Hazard curves (rate of occurrence of PGA), output of a given PSHA, are transformed into macroseismic Intensity through “PGA- to-intensity” relationships. Random and epistemic uncertainties included in such relationships are propagated in the overall updating process, as well as the random occurrence of events, over the period of observation. The period of observation under consideration is the completeness period for each intensity data set. The updating process is developed at a regional scale over a significant number of stations. The potential correlation between points of observation is also discussed and accounted for.

Finally, a case of application is proposed on the French metropolitan territory to demonstrate the efficiency of this updating method and draw perspectives for further applications.

**Focal depths and mechanisms of induced earthquakes in the 2013 seismic sequence near the CASTOR Underground Gas, northeast coast of Spain**

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During September-October of 2013, an intense swarm of earthquakes occurred off the east coast of Spain associated with the injection of the base gas in an offshore underground gas storage. After the end of the injection operations, three moderate-sized earthquakes ($M_w$ 4.1-4.0) occurred that were widely felt by the nearby population and which led to the indefinite shut-down of the facility. Here we investigate the source parameters (focal depth and mechanism) of the largest earthquakes in the sequence in order to identify the faults reactivated by the gas injection, and to help understand the processes that caused the earthquakes. Our waveform modeling results indicate that the largest earthquakes occurred at depths of 6-8 km beneath the sea floor, significantly deeper than the injection depth (~ 1800 m). Although we cannot undoubtedly discriminate the fault planes from the two nodal planes, most evidence seems to favor a NW-SE fault plane. We propose that the gas injection reactivated unmapped faults in the (Paleozoic?) basement, with regional orientation inherited from the opening of the Valencia Trough.

# ISC-EHB: Reconstructing the EHB earthquake database

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The EHB database is a dataset of teleseismically well constrained events that are selected from the International Seismological Centre (ISC) Bulletin and relocated using procedures described by Engdahl, Van der Hilst & Buland (1998). It is useful for global seismicity and high frequency tomographic inversions, but currently ends in 2008. We aim to expand and recreate the EHB, in collaboration with the ISC, to produce the ISC-EHB. We begin with events in 2000-2014 and apply new and more rigorous procedures for event selection, data preparation, processing and relocation.

Events are only selected from the ISC Bulletin if they have more than 15 teleseismic (> 280) time defining stations, with a secondary teleseismic azimuth gap of < 1800, and a defining prime magnitude > 3.75 (Di Giacomo & Storchak, 2016). These criteria minimize the location bias produced by 3D Earth structure, and select many events that are relatively well located in any given region.

There are four processing steps; (1) EHB software relocates all the events using ISC starting location and depths; (2) Near station and secondary phase arrival residuals are reviewed and a depth is adopted or assigned according to best fit, and in some instances depths may be reassigned based on other sources (e.g., USGS broadband depths); (3) All events are relocated with their new depths and plotted in subduction zone cross sections, along with events from the ISC-GEM catalogue for comparison; (4) These plots are used to confirm or modify weakly constrained depths.

The new ISC-EHB database will be available online in catalogue and bulletin form via the ISC. It will now include maps and cross sections of subduction zone seismicity. Here we present maps and cross sections for events in 2000-2003.

## Stress drops for the M ≥ 4.0 earthquake catalogue of the Blanco Oceanic Transform Fault

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We present initial results in estimating stress drops of M ≥ 4.0 earthquakes on the Blanco Oceanic Transform Fault, off the coast of Oregon. We plan to examine how these stress drops vary spatially and temporally, particularly in foreshocks, aftershocks, and swarms. We estimate stress drops on the Blanco fault using a phase coherence method that evaluates phase differences between station records for two collocated earthquakes. These phase differences depend on the spatial extents of the two collocated earthquakes. If the energy of an earthquake is generated over a large rupture area, then different stations will see different source time functions as the distance from the slipping locations to the stations varies throughout the rupture. The phase difference is most pronounced at frequencies higher than the reciprocal of the seismic travel time across the earthquake rupture length. By cross correlating between station records for collocated earthquakes, we isolate frequency domain phase differences between earthquake source time functions, giving us a falloff in the phase coherence spectrum. The falloff frequency corresponds to the rupture length of the larger earthquake in the pair and thus the stress drop. We present falloff frequencies for several pairs of earthquakes finding realistic rupture lengths. We demonstrate the reliability of this method for the Blanco fault using multiple collocated pairs with one common earthquake finding consistent rupture lengths across most pairs.

## Global review of induced and triggered earthquakes

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Natural processes associated with very small incremental stress changes can modulate the spatial and temporal occurrence of earthquakes. These processes include tectonic stress changes, the migration of fluids in the crust, Earth tides, surface ice and snow loading, heavy rain, atmospheric pressure, sediment unloading and groundwater loss. It is thus unsurprising that large anthropogenic projects which may induce stress changes of a similar size also modulate seismicity. As human development accelerates and industrial projects become larger in scale and more numerous, the number of such cases is increasing. That mining and water-reservoir impoundment can induce earthquakes has been accepted for several decades. Now, concern is growing about earthquakes induced by activities such as hydraulic fracturing for shale gas extraction and waste water disposal via injection into boreholes. As hydrocarbon reservoirs enter their secondary and tertiary phases of production, seismicity may also increase there. The full extent of human activities thought to induce earthquakes is, however, much wider than generally appreciated. We have assembled as near complete a catalogue as possible of cases of earthquakes postulated to have been induced by human activity. Our database contains a total of >700 cases and is probably the largest compilation made to date. We include all cases where reasonable arguments have been made for anthropogenic induction, even where these have been challenged in later publications. Our database presents the results of our search but leaves judgment about the merits of individual cases to the user. We categorise the induced earthquakes based on the likely project which resulted in induction. In some cases, categorisation of a particular case is tentative because more than one anthropogenic activity may have preceded or been ongoing at the time of the relevant earthquakes, e.g., oil production and brine injections. We present a first analysis of the data in our database and comment on some related issues with which scientists are currently grappling.

## Global seismic tomography using Backus-Gilbert inversion

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The discrete theory of Backus-Gilbert (B-G), solving all at once the linear problems of model estimation and appraisal, aims at evaluating weighted averages of the true model parameters. We introduce and adapt to seismic tomography the SOLA method, an alternative B-G formulation, more computationally efficient and versatile, and show that the SOLA method can successfully be applied to global-scale S-wave tomography.

## Analysis of different statistical methods to estimate and represent Mmax in PSHA based on the truncated GR model

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It is generally recognized that the accurate and statistically and physically consistent estimation of the maximum magnitude Mmax is not straightforward. The task is even more difficult in moderate to low seismicity areas where databases are sparse, where information on active faults is missing and where only few larger earthquakes have been recorded. However, the definition and estimation of Mmax becomes increasingly more important for longer return periods that are relevant for the safety analysis of nuclear installations. In general, the Gutenberg Richter relation yielding an exponential distribution of earthquakes magnitudes is adopted. The exponential distribution is unbounded with no upper limit which is not satisfactory from a physical point of view. Since the energy released by rupture is finite, the maximum magnitude also has to be limited by an upper value. Various methods to evaluate Mmax have been proposed in the literature since the first developments of PSHA (Cornell, 1968) which can be mainly categorized as physical (based on geological, structural or geophysical properties), statistical (in particular more recent works of Kijko et al., Pisarenko et al.) and mixed approaches (e.g. the EPRI method based on Bayesian updating of prior distribution of Mmax). Moreover, the uncertainty in data, models and statistical estimations leads to consider not only one single value but a distribution of Mmax. This work proposes to compare the performance of different methods and ways to represent Mmax in the framework of the truncated Gutenberg-Richter model by means of statistical data analysis. In particular, statistical theory of extremes, Bayesian updating and more classical frequentist approaches will be applied by using simulated earthquakes catalogues. We furthermore analyze the possibility to work with the distribution of Mmax on a time interval rather than with its absolute value. This approach could detract importance from Mmax used in the truncated GR model but to better controlled quantities.

**A time-dependent seismicity model for south-western British Columbia, Canada**

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The Cascadia subduction zone of the Pacific Northwest potentially can host megathrust subduction earthquakes with moment magnitude greater than 8, followed by a large number of aftershocks. The triggered moderate aftershocks at shallow crustal depths can result in significant damages to buildings and infrastructures. In this study, south-western British Columbia, Canada is selected as a target region to assess the triggering of moderate-to-large aftershocks at shallow crustal depths due to Mw 8-9 earthquakes from the Cascadia subduction zone using the epidemic-type aftershock sequence (ETAS) model. The ETAS model is a stochastic spatiotemporal branching point-process model of seismicity, and its parameters that describe the productivity and spatiotemporal distribution of triggered earthquakes can be estimated by historical earthquake events. Although the ETAS model has been successfully implemented in Japan, Taiwan, New Zealand, and California, such an application has not been conducted for south-western British Columbia. This is because seismic activities in south-western British Columbia are relatively quiet and no major earthquake has occurred since the last megathrust event in 1700. This means that the ETAS parameters for the megathrust subduction earthquakes in Cascadia, affecting on crustal seismicity, need to be estimated by analysing seismicity data from other subduction zones (Japan, Indonesia, and Chile) globally. The validity of the estimated ETAS parameters is investigated by simulating historical megathrust subduction events (e.g., 2011 Tohoku earthquake), and then comparing forecasted occurrence rates (i.e. spatiotemporal seismicity) with observed rates. The standard error of each parameter in the ETAS model is estimated by simulations of synthetic catalogues and the estimation of the ETAS parameters. Different sets of ETAS parameters are selected from the global databases to simulate time-dependent megathrust subduction earthquakes with moderate-to-large aftershocks for British Columbia. Quantitative comparisons of the selected ETAS parameters are conducted to show the variability and sensitivity. In addition, despite lack of major earthquakes in south-western British Columbia, some small (Mw 5.0-5.9) and moderate (Mw 6.0-

6.9) crustal earthquakes were recorded. To investigate the difference of spatiotemporal productivities of shallow crustal earthquakes between the Cascadia subduction zone and other subduction zones, the ETAS model is fitted into a local database in Cascadia and selected earthquake datasets from the global database. To reduce the bias, crustal earthquakes with identical magnitude ranges are considered between the local database and the selected earthquake dataset. Moreover, the ground motion prediction equations (GMPEs) can be incorporated with the ETAS model for south-western British Columbia and soil map information to estimate the scenario-based ground motion maps in the future study.

## Yields, source time functions and depths of North Korean announced nuclear tests

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Using the cube-root scaling law for explosive sources, I estimate the yields and source time functions of announced North Korean underground nuclear tests directly from seismograms recorded in China, Japan and Australia. This method is compared with the conventional approach. The conventional approach estimates yields based on body-wave magnitude mb and two parameters that depend on the path between the source and the receiver. In practice this means that sources at a particular site, say Nevada Test Site (NTS), or Semipalatinsk Test Site (STS), need to be calibrated. An explosion at NTS gives a smaller mb than an explosion of the same yield at STS. The corresponding calibration for the North Korean Test Site (NKTS) is not available, so estimation of yield at NKTS is a problem. In the conventional approach source time functions are not derived directly from the data. They are estimated using models that make assumptions about the compressional stress function at the source and the elastic constants of the medium in which the source is emplaced. My method requires two events at the same source location and eliminates the path effect between source and receiver by finding a filter that shapes the seismogram of the smaller event to the seismogram of the larger. If the noise is small, the convolution of the filter with the source time function of the smaller event yields the source time function of the larger event. The two source time functions are also related by a well-known scaling law in which the injected volume is proportional to the yield and the time constant is proportional to the cube-root of the yield. The convolutional relationship and the scaling law are two independent equations that can be solved for the two source time functions. The path effect includes scattering from the Earth's surface above the source. The sources are not at the same depth and this scattering does not cancel. A compensating filter is obtained by inspection of the spectral notches of the seismograms. This filter varies with direction from the source. Where a seismogram is a measurement of particle velocity at the receiver, the recovered source time function is the time derivative of the volume injection function at the source. Its integral is the volume injection function, also known as the reduced displacement potential. Calibration of the yield is performed using published

measurements of explosions at NTS made with buried near-field instruments. From the shape of the source time functions, it appears that the North Korean tests were performed in granite. The time constant of each function determines the yield. Current estimates of the yields of the 2009 and 2013 events are 7.8 kt and 17 kt, respectively.

# GDI Protocol

## ULTRA LOW LATENCY TRANSMISSION

### A rapid data transmission protocol that dramatically reduces latency, ideal for earthquake early warning systems.

GDI uses a flexible packetisation scheme for true, real-time transmission that can deliver waveforms, sample by sample, as they are acquired by the datalogger.

By adapting its transmission to the available communications bandwidth GDI achieves the fastest possible speed for data flow.

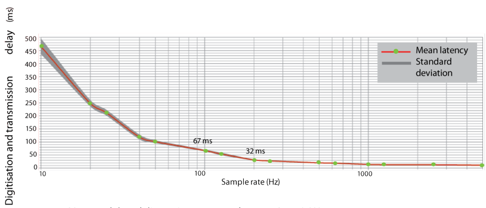
Traditional delays associated with protocols with fixed length packets such as SEEDlink (miniSEED packets) are overcome. In addition, as the packet header is significantly smaller than with SEEDlink (4 bytes as opposed to 64 bytes in SEEDlink), bandwidth requirements are reduced.

Unlike SEEDlink protocol, GDI also delivers per-channel metadata in SEED format and machine readable State of Health (SoH) information.

#### GDI available as free-licence source code

GDI source code is available as a free download for further development or integration into existing EEW networks, visit www.guralp.com for further details.

In addition, through partnership with Gempa, GDI protocol is also supported via a plug-in to the CAPS module of SeisCompPro for simple integration into existing siesmic monitoring infrastructure.




Measured data delivery times vs. sample rate using a LAN

Download the free-licence GDI source code here:

http://git.guralp.com

For more information see the GDI project wiki here:

http://git.guralp.com/open-source/gdi_simple_client/wikis/home

### Key features

- Free-licence source code for incorporation into your EEW network
- Supported via a plug-in for the CAPS module of SeisCompPro
- Rapid data transmission for earthquake early warning systems on all scales
- Bandwidth-adaptive packetisation scheme drives efficient data flow
- Responsive sample-by-sample streaming dispatches data instantly
- Delivers per-channel metadata in SEED format and machine readable State of Health (SoH)
- Significantly reduced packet headers for higher transmission efficiency
- Already available, in combination with low latency causal filtering, in Guralp Minimus digitiser - for data latency of ~40 ms

#### GDI and the Güralp Minimus

The greatest benefit of GDI is achieved when it is combined with low latency filtering, such as the causal filtering in the Güralp Minimus digitiser.
In this example, digitisation and transmission can be achieved in ~40 ms, significantly less than the data latencies of 1 s, typically achieved with SEEDlink.

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