BSM2024

British Seismology Meeting
25th-27th March, Reading, UK

Abstract Book

Invited Talks .... p. 1

Oral Presentations .... p. 7

Poster Presentations .... p. 48

International Seismological Centre

Organized by the ISC with support and sponsorship from:

BGA British Geophysical Association

AWE

Royal Astronomical Society

GaiaCode

nanometrics

STRYDE

Raspberry Shake® Watch the Earth Move

SMARTSOLO SCIENTIFIC

güralp

Invited Talk

Characterising small coastal and underwater seismic sources using International Monitoring System and local seismic network data

R. Heyburn[1], D. Bowers[1], D. N. Green[1], A. Nippress[1], S. N. Nippress[1], and N. D. Selby[1]

[1] *AWE Blacknest, Brimpton Common, Reading, UK*

As well as detecting signals from underground and atmospheric nuclear test explosions, the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO) is designed to detect signals from explosions detonated in the water. To do this, the IMS uses both seismometer stations on land to detect seismic signals and acoustic-to-seismic conversions, and a now complete network of 6 underwater hydrophone arrays which can detect acoustic waves in the oceans. Explosions detonated in the water typically generate higher amplitude seismic signals than similar sized underground explosions, and acoustic waves from underwater events can also propagate over long distances in the Sound Fixing and Ranging Channel of the oceans with very little attenuation. The IMS can therefore often be used to detect, locate and characterise a variety of underwater anthropogenic sources with seismic magnitudes well below those expected for a conventional nuclear test explosion. In this study we present an overview of results from studies of a range of unusual seismic sources in the water that we have analysed in recent years. These include, submarine disasters, naval explosions, and gas pipeline ruptures. Results show that data from the IMS, and the increasingly extensive network of local and regional distance seismic stations which are openly available to researchers, can be a powerful tool for detecting, locating and characterising such sources.

Understanding North Sea seismicity to gain stress field information and de-risk large-scale CO_2 injections

Daniela Kühn[1], Tom Kettlety[2], Evgeniia Martuganova[3], Annie Jerkins[1], Joseph Asplet[2], Bettina Goertz-Allmann[1], Johannes Schweitzer[1], Brian Baptie[4], Trine Dahl-Jensen[5], Peter Voss[5], Mark Fellgett[6], John Hopper[5], Chen Huang[1], Brian Carlton, Anna Maria Dichiarante[1], Nadège Langet[1], Elin Skurtveit[7]

[1] *NORSAR, Kjeller, Norway*
[2] *University of Oxford, Oxford, UK*
[3] *TU Delft, Delft, Netherlands*
[4] *BGS, Edinburgh, UK*
[5] *GEUS, Copenhagen, Denmark*
[6] *NGI, Oslo, Norway*
[7] *BGS, Keyworth, UK*

Carbon capture and storage technologies are an essential part of EU's decarbonisation efforts. Combined with sustainable energy resources, they are necessary to move Europe towards a net zero carbon emissions economy. Currently, several Mt-scale CO_2 storage projects are being developed in the North Sea. Containment risk evaluation includes analysing tectonic earthquake patterns to potentially map faults, reveal their orientation and failure style, invert for stress directions and at later stages, enable the discrimination of natural and induced seismicity. In addition, seismological information may contribute to the geomechanical understanding of the reservoir and caprock response to large-scale CO_2 injection over time.

A wealth of data exists from various European seismological agencies, but much of it has not been analysed collectively. Within the framework of the ACT project SHARP Storage, an extensive unique earthquake bulletin was compiled using seismicity data from all relevant data centres. Preliminary processing included duplicate removal and explosion identification. The magnitude of completeness of this data set varies both spatially and temporally. The most seismically active regions in the study area are the Viking and Central grabens. Coastal areas are populated with more events than the central part of the North Sea due to the denser distribution of seismic stations onshore allowing for the detection of smaller ($M<3$) magnitude events. Data sets are planned to being made public after finalising the project.

For events occurring after 1990 and possessing magnitudes larger than $M > 3.5$, waveforms are currently being collected as a basis for further analysis, including event relocation and magnitude homogenisation. Inverted moment tensors, shear-wave splitting measurements, and stress drop analysis will be compared to and complement a review of borehole stress measurements to better gauge the present-day stress field and enhance seismic hazard assessments. Ground motion prediction equations (GMPEs) are being derived for the onshore regions nearest the development CO_2 storage projects, and an updated probabilistic seismic hazard analysis is being carried out on a regional scale.

3D & 4D Variational Bayesian Full Waveform Inversion

Andrew Curtis[1], Xin Zang[2], Angus Lomas[3], Muhong Zhou[3], York Zheng[3]

[1] *University of Edinburg, Edinburg , UK*
[2] *China University of Geosciences, Beijing, China*
[3] *BP, Sunbury, UK*

Seismic Tomography is a method to image the Earth's subsurface using acoustic and elastic waves. In order to better interpret the resulting images it is important to assess imaging uncertainties, but this is hard to achieve. Monte Carlo random sampling methods are often applied for this purpose but the 'curse of dimensionality' makes them computationally intractable for high-dimensional parameter spaces. To extend uncertainty analysis to larger systems, variational inference methods developed recently in the machine learning community are introduced to seismic tomography. In contrast to random sampling, variational methods solve an optimization problem yet still provide probabilistic results. Variational inference is applied to solve two types of tomographic problems: full waveform inversion (FWI), and time-dependent (known as 4D) FWI. Three different variational methods are tested: automatic differential variational inference (ADVI) and both deterministic and stochastic versions of Stein variational gradient descent (SVGD). ADVI provides a robust mean velocity model but biased uncertainties, whereas deterministic SVGD produces an accurate match to the results of Monte Carlo analysis, but at a fraction of the computational cost. SVGD is significantly easier to parallelize, and for very large problems can be run in minibatch mode which is impossible using Monte Carlo methods without incurring probabilistic errors. Stochastic SVGD is shown to be the only method that may be capable of providing useable results for 3D FWI problems. The 3D solution is verified independently using our recently developed extension to ADVI. Variational methods have been extended to time-dependent monitoring problems of the type expected to be encountered in CO2 or Hydrogen storage applications. Similar methods can be used to extend probabilistic analysis to other nonlinear Geophysical inverse problems, and to higher dimensional tomographic systems than is currently thought possible.

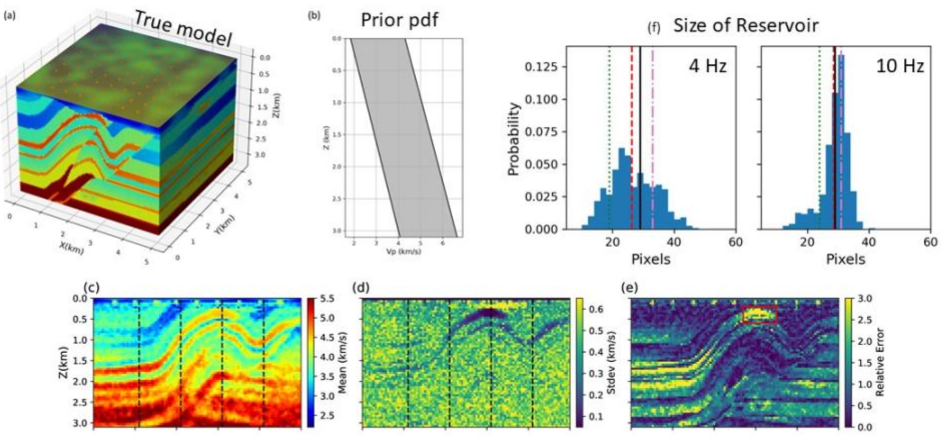


Figure: (a) 3D synthetic model. (b) Uniform prior probability density function. (c),(d),(e): Respectively the mean, standard deviation and relative error (difference between true and mean models, divided by the standard deviation) across central vertical slice in x-z plane. (f) Results of an interrogation problem to answer the question, "*How large is this storage reservoir?*" given probabilistic FWI results, using two different wavelet central frequencies: black line indicates the correct value, red line is the statistically optimal estimate.

A patchy core-mantle boundary

Sanne Cottaar [1], Carl Martin[2], Lisanne Jagt[1], Zhi Li[3], Stuart Russell[1,4]

[1] *University of Cambridge, Cambridge, UK*
[2] *Utrecht University, Utrecht, Netherlands*
[3] *Peking University, Beijing, China*
[4] *Universität Münster, Münster, Germany*

Ultra-low velocity zones (ULVZs) are anomalous patches of extremely slow seismic velocities - reduced up to 30% for shear waves- discovered on the boundary between the Earth's core and mantle. Mapping of ULVZs is done with various seismic phases that reflect, refract, and diffract on the core-mantle boundary, and which provide variable constraints on ULVZs. Only a small number of studies have constrained the full dimensions of these zones using core-diffracted phases, and find extremely widespread zones near various major hotspots. These zones are suggestive of a potentially separate category of "mega-ULVZs".
In my talk I will show evidence using Sdiff postcursors for the mega-ULVZs underlying Hawaii and Galapagos. Next, I will present our new Bayesian mapping method which allows us to use a larger data set to map the Hawaiian mega-ULVZ. I will also show evidence for layering within the Hawaiian ULVZ, and the first evidence of postcursors in Pdiff. There will be thousands of waveforms in this talk!

Contributions of autonomous seismo-acoustic floats in the oceans to earthquake location and structural studies of the solid earth

Karin Sigloch[1], Dalija Namjesnik[1], Sébastien Bonnieux[1], Joel Simon[2], Tom Garth[3], James Harris[3], Dmitry Storchak[3], Yann Hello[1], Frederik Simons[2]

[1] *Géoazur lab, Université Côte d'Azur, CNRS, Observatoire Côte d'Azur, IRD. Sophia Antipolis, France*
[2] *Princeton University, Princeton, New Jersey, U.S.A.*
[3] *International Seismological Centre, Thatcham, UK*

Géoazur research lab has been designing seismo-acoustic floats that are meant to fill seismology's instrumentation gap in the oceans, and has been building them together with OSEAN, a small engineering firm. Once deployed from a ship of opportunity, a "MERMAID" float drifts passively in the currents at ~1500 m water depth. An embedded algorithm constantly scans for earthquake signals, i.e., seismic waves that were converted to acoustic upon hitting the seafloor from below. If a sufficiently pertinent signal is detected, the float rises to the surface to send its position and hydrogram home via Iridium satellite connection. It then sinks back to resume its listening position, each float carrying batteries for ~5 years of autonomous operation, or about 250 rise-sink cycles once a week. Crucially, no recovery is required, eliminating the need for scarce ship time and rendering this instrumentation concept scalable. The vision is to deploy thousands of floats, following the example of physical oceanography who have covered the oceans with a fleet of ~4000 "Argo" profiling floats.

Around 80 "Mermaid" floats are in operation, most of them in the South Pacific as part of the international SPPIM experiment, which is working towards a whole-mantle tomography as its central result. We present the data set acquired by SPPIM since 2018, and the results of a complementary use case of this data set. In collaboration with the ISC and Princeton University, we have investigated the improvements that the "Mermaid" traveltime picks can bring to the ISC's ability to locate distant, regional and local earthquakes in the South Pacific region.

Imaging the deep structure of continental shear zones: a review of Faultlab North Anatolian Fault zone findings with the DANA seismological network

Cornwell, D.G [1], Papaleo, E. [1], Thompson, D. A.[1], Rost, S.[2], Houseman, G. A.[2], Kahraman, M.[3], Turkelli, N.[3], Teoman, U.[3], Altuncu Poyraz, S.[3], Gülen, L. [4] and Utkucu, M.[4],

[1] *School of Geosciences, University of Aberdeen, Aberdeen, AB24 3UE, UK*
[2] *Institute of Geophysics & Tectonics, University of Leeds, Leeds, LS2 9JT, UK*
[3] *Kandilli Observatory, Bogazici University, Geophysics, Istanbul, Turkey.*
[4]*Sakarya University, Geophysics, Sakarya, Turkey.*

The Dense Array for Northern Anatolia (DANA), Türkiye, a rectangular seismometer array spanning the NAFZ with 66 stations at a nominal inter-station spacing of 7 km and 7 additional stations further afield, was deployed from May 2012 to October 2013 as part of the multi-disciplinary Faultlab project. The aim was to image the deep structure of a continental shear zone, the north Anatolian fault zone (NAFZ), near the epicentres of two large earthquakes that occurred in 1999 at Izmit (M7.5) and Düzce (M7.2), and where estimates of present-day slip rate are 20-25 mm/yr. Through a variety of seismological (and complementary) analysis methods, the DANA datatset has been used to define the complex lithospheric geology that hosts the NAFZ, demonstrate the structure of the two NAFZ branches and their seismic and aseismic deformation, and redefine deep shear zone models in unprecedented detail. Its unique location and configuration have also made it popular to develop new seismological techniques. This talk reviews the DANA deployment and findings, their implications, and applications to recent large shear zone seismic events, including the 2020 M6.8 and 2023 M7.8 and M7.5 earthquakes as associated with the Eastern Anatolian Fault (EAF).

Re-analysis of historical data using machine learning

Stuart Nippress[1], Marta Pienkowska[2]

[1] *AWE Blacknest, Brimpton Common, Reading, UK, RG7 4RS*
[2] *ETH Zürich, Institut für Geophysik, Sonneggstrasse 5, 8092 Zürich, Switzerland*

Over the last decade there has been a international effort to find methods to recover and digitize recordings from historical earthquakes and explosions that occurred during the 1950's through to the 1980's. Making these recordings accessible in digital format offers opportunities for a new generation of researchers to study what signatures are encoded in the data, to help characterise noise and seismicity in regions of low seismicity and to apply state-of-the-art techniques and methods to historical data.

Machine learning (ML) is a collection of methods used to develop understanding and predictive capability by learning relationships embedded in data. ML techniques are becoming increasingly widespread in seismology, with applications ranging from identifying unseen signals and patterns to extracting features that might improve our understanding of the underlying physical processes.

Cross-correlation is often used to investigate waveform similarity and is also used to perform clustering of seismic events. However, the cross-correlation coefficient used to separate clusters of events is a personal arbitrary choice, so that it varies between studies, with window length and the frequency band used for filtering.

In this study we apply ML clustering techniques to historical earthquake and explosion teleseismic stacked waveform data recorded at seismic arrays in the UK (EKA), Canada (YKA), Australia (WRA) and India (GBA). In particular we use two unsupervised algorithms to cluster waveforms using shape-based clustering: kernel K-means and K-shape. The clustering algorithms are efficient (run-time of a few minutes on a standard laptop for a few hundred waveforms), produce similar clusters, are easy to code and freely available. They clearly split waveforms into distinct clusters that are spatially related, even when waveform differences are subtle. The fact that these event locations in each cluster are in very close proximity suggests that near-source effects (depth and topography) have a much greater influence on waveform shape at large distances than receiver-side or propagation path effects.

Seismic Data Archive in the United Kingdom to support Nuclear Test Monitoring

Peter Bartholomew and the Forensic Seismology Team

United Kingdom National Data Centre for the Comprehensive Nuclear-Test-Ban Treaty,
AWE Blacknest, Reading, RG7 4RS, UK

In 1961, AWE Blacknest became the home of Forensic Seismology in the UK, with the aim of developing and maintaining a capability to provide seismological advice to the UK government. During the 1960s the group set up a seismometer array in Scotland and worked with host countries to set up arrays in Canada, Australia (now both IMS stations), India and Brazil. AWE Blacknest has continuous data archives from these sites dating back to 1961 on a mix of paper helicorder records (seismic and infrasound traces), analogue FM-encoded tape and digital tape. From 2006-15 Blacknest developed and ran an extensive programme to overcome the ageing issues presented by vintage magnetic media condition and formats, and recovered and digitised the tapes, putting the continuous data on to modern computer storage systems. Since the 1990s data have been directly recorded to digital storage systems. Historically only events of interest, including data recorded from suspected nuclear explosions, were extracted, and Blacknest is running a programme of analysing these events and preparing the data and analysis in a form for public release. I will present on the work undertaken to develop the programme, data recovery and digitization methods from magnetic media, and the modern storage systems Blacknest use for serving seismic data. This will also include analysis work and the data inventories that Blacknest is making available.

Source Analysis of Industrial and Forensic Events

Michael E. Pasyanos[1], Keehoon Kim[1], and Gene A. Ichinose[1]

[1] *Lawrence Livermore National Laboratory, Livermore, California, USA*

We have developed several methods for the analysis of non-traditional seismic sources, and have applied them to a variety of industrial and forensic events. For treaty monitoring purposes, it is important to properly identify and characterize some of these exotic sources since, like nuclear tests, they are generally shallow and can fail traditional discriminants like m_b:M_S. These methods include yield estimation using full waveform envelopes, spectral infrasound yield estimation, joint seismo-acoustic yield estimation, and full moment tensor methods for event identification and yield estimation. Ideally, identification methods not only discriminate in a binary sense between two end members (e.g., m_b:M_S or high-frequency P/S as a discriminant between earthquakes and explosions), but allow for other potential source types, such as collapses. We also seek to relate observed seismic and geophysical parameters to physical properties such as seismic moment (for earthquakes), explosive yield (for explosions), and cavity volume (for collapses). We have applied these methods to number of events including underground, near surface, and atmospheric explosions, and mine-related and explosion-related collapses. In particular, we will be discussing: 1) recent chemical explosions at the Nevada National Security Site (NNSS), 2) several mine collapses from around the world, and 3) the 20 April 2023 SpaceX Starship Explosion in the atmosphere.

Seismological evaluation of the events in connection with the leaks in the Nord Stream 1 and 2 gas pipelines on 26 September 2022

Lars Ceranna, Stefanie Donner, Peter Gaebler, Nicolai Gestermann, Gernot Hartmann, Patrick Hupe, Christoph Pilger, Thomas Plenefisch, Klaus Stammler, Andreas Steinberg*

* The order of the authors is alphabetical and does not represent a ranking of the individual contributions to this study

Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

On 26 September 2022, seismic events were detected and localized in the Baltic Sea near the Danish island of Bornholm, which can be temporally and spatially linked to leakages in the Nord Stream 1 and Nord Stream 2 gas pipelines. To investigate these events seismologically, we use data from the following station networks: Swedish National Seismic Network, Danish Seismological Network, GEOFON Seismic Network, Polish Seismological Network, German Regional Seismological Network and associated stations as well as four arrays of the International Monitoring System of the CTBTO - (FINES, ARCES, NOA, HFS). The first event with a magnitude Mw 2.3 occurred at 00:03 UTC 37 km east-southeast of Bornholm. The determined location and the origin time of the event are consistent with data of the pressure decrease on one of the Nord Stream 2 pipelines. Another sequence of events occurred 17 hours later at 17:03 UTC around 60 km north-east of Bornholm with a maximum magnitude of Mw 2.7. It consists of three closely successive, but separable, single events. This sequence led to a complex wave field of overlapping seismic wave trains. Using relative localisations and the gas pressure inside the pipeline recorded at the landing site in Germany, we can assign the epicentres of the three events to the locations of the leaks in the pipelines of Nord Stream 1 and 2.

Based on comparable events in the region, which include both tectonic earthquakes and explosions, the explosive character of the investigated Nord Stream events can be verified. Nevertheless, these events differ in their frequency content from (ammunition) blasts in the Baltic Sea. Our modelling shows that the measured seismic signals can be adequately explained by an instantaneous gas release on the sea floor similar to an airgun. Synthetic seismograms for such a source and a subsurface model adapted for the study area show high consistency with the measured signals. Based on the released energy and the characteristics of the recorded waveforms, we conclude that the impulsive gas release from the burst gas pipes constitutes the dominant part of the signal source.

Infrasound signals associated with the destruction of the Nord Stream pipelines were recorded at two stations (I26DE in the Bavarian Forest and IKUDE near Kühlungsborn) in Germany. Particularly after the event sequence at 17:03 UTC, distinctive signals were registered whose characteristics indicate an explosive event with subsequent gas leakage at the surface.

Risk related red-light thresholds for induced seismicity in the UK.

Ryan Schultz[1], Brian Baptie[2], Ben Edwards[3], Stefan Wiemer[1]

[1] *Swiss Seismological Service, ETH Zürich, Zürich, Switzerland*
[2] *British Geological Survey, Edinburgh, United Kingdom*
[3] *University of Liverpool, Liverpool, United Kingdom,*

Traffic Light Protocols (TLPs) are one of the most widely implemented means of attempting to mitigate the risk of induced earthquakes from hydraulic fracturing (HF) or other operations that involve subsurface injection. TLPs are essentially control systems that allow for low levels of induced seismicity but set a stopping point (red-light) for operations to reduce the probability of events that may result in a concern. The red-light threshold can be defined by different metrics but is often defined by a specific earthquake magnitude. Here, we model the risks of induced earthquakes from HF operations across the UK for different red-light threshold magnitudes in terms of three risk metrics: nuisance impacts, building damage, and chance of fatality. These risk metrics/tolerances are then combined to determine the red-light threshold for when an HF operation should stop. This risk-based approach allows red light thresholds to be chosen based on tolerance for risk, in a transparent manner, allowing for a fairer TLP design.

Our approach to estimating a red-light threshold based on risk evaluation consists of the following steps: 1) determining the largest magnitude event following HF operations at a specific site for a given red-light threshold, 2) estimating the resulting ground motions from such an event, and 3) calculating the resulting seismic risks. We use Monte Carlo perturbations to capture the variability within risk evaluations. These steps are repeated for different potential HF well locations across the UK. Prior cases of HF induced earthquakes in the UK are used to infer appropriate tolerances to each of our risk metrics.

Our results suggest that acceptable red-light thresholds in the UK should lie in the range 1.2-2.5 ML and should change with location, primarily due to exposure from ground shaking varying with the distribution of population density. Nuisance and damage are likely the most important of the risk metrics considered because they result in the lowest red-light magnitudes. We also discuss how our approach could be used to choose HF locations and adapt to real-time information. The results also show how the risk of induced earthquakes from other energy technologies such as deep geothermal or carbon/hydrogen storage, could be managed in future.

A new seismic hazard model for the offshore regions around the United Kingdom

Ilaria Mosca[1], Brian Baptie[1]

[1] *British Geological Survey, Edinburgh, UK*

The presence of historical seismicity, including the largest recorded earthquake in the United Kingdom (UK), near offshore carbon capture and storage (CCS) areas suggests that robust estimates of earthquake hazard are essential for the planning and design of offshore critical infrastructure. Although updated seismic hazard maps for the UK were published in 2020 to inform the National Annex to Eurocode 8 (earthquake-resistant design of structures) (Mosca et al., 2022), these maps do not extend offshore and the most recent hazard maps for the offshore regions around the UK were published in 2002 (EQE International Ltd, 2002). Since then, there have been significant developments in best practices for seismic hazard assessment, in particular how to model the ground shaking produced by potential, future earthquakes and capture its uncertainties. Furthermore, to meet the government target of at least one low-carbon cluster by 2030, the UK continental shelf and in particular the North Sea region has a strategic role with an increasing number of operating and proposed offshore CCS areas.

The goal of the project was to develop a robust seismic hazard model and accompanying hazard maps for the UK offshore Exclusive Economic Zone using the latest available data and recent advances in seismic hazard methodology. We have also estimated site-specific hazard estimates for selected CCS sites, i.e. Endurance and Acorn sites, and the planned North West CCS cluster in Liverpool Bay.

New seismic hazard maps for the UK offshore region will support UK decarbonisation by providing owners and operators of offshore structures with robust estimates of seismic hazard in the vicinity of new and existing sites. This will enable informed decisions for the seismic actions to consider in the structural design of offshore structures. The results will also inform regulatory decisions to ensure safe operating practices in the industry and help identify areas of higher hazard where further site-specific studies might be needed. Finally, it will provide a robust baseline for tectonic seismic activity in the North Sea that can be used to help discriminate any seismicity induced by operations, such as CCS, in the event it occurs.

Seismic surveys to inform heat-flow experiments in a fractured chalk aquifer, Berkshire, UK

Katerina Kyrkou[1], Adam Booth[1], Fleur Loveridge[2], Emma Smith[1], Joseph Kelly[2], Andy Nowacki [1], Jonathan Chambers[3], Yin Jeh Ngui[3], David Boon[3], Edward Hough[3], Oliver Kuras[3]

[1] *University of Leeds, School of Earth and Environment, UK*
[2] *University of Leeds, School of Civil Engineering, UK*
[3] *British Geological Survey, UK*

Urban geothermal solutions to heating and cooling have developed slowly in the UK, partly due to limited understanding of subsurface heat flow regimes and how stored heat might be sustainably utilised and managed within heterogeneous aquifers. Understanding heat flow within various aquifers is the goal of the *SmartRes* project, in which heat exchange trials will be conducted at two UK sites.

To provide context for heat flow experiments in a fractured chalk aquifer, seismic surveys were acquired at Trumplett's Farm, a groundwater abstraction and monitoring site near Reading (Berkshire, UK). Here, groundwater flow is primarily within a fracture network, likely in an active zone within the upper 10 m of the saturated chalk. Seismic surveys were acquired to assess differences in chalk composition and any anisotropic expression of fracturing. The surveys recorded energy generated with an impact source at surface geophones (24 cabled GEODE, and 20 nodal Smart-Solo, geophones) and hydrophone strings, deployed to 100 m depth in boreholes drilled at the site. Smart-Solo nodes were deployed in a ~10 x 5 m grid at the site, with cabled geophones occupying lines between boreholes, with geophone intervals of <2 m. Nodal geophones recorded passively throughout the 3-day deployment and will be analysed using ambient noise correlation to evaluate anisotropy. The remaining data have provided preliminary insight into velocity structure via MASW (Multichannel Analysis of Surface Waves), P-wave refraction velocities, and vertical seismic profiles (VSPs).

Preliminary MASW analyses suggest shear wave velocity (Vs) ranges from 250-600 m/s in the uppermost 1.5 m, but that estimation is challenging given poor dispersion imaging of the fundamental mode. Different source-receiver offsets were tested to eliminate mode superposition, but the best dispersion curves are observed for zero-offset shots. Data were processed in a commercially available software with relatively limited freedom to adjust inversion parameters. Further analysis will use the MuLTI code, to undertake a constrained Monte Carlo inversion approach.

The deeper chalk was imaged in VSPs, indicating reflective P-wave horizons at 52 and 69 m depth, separating material with interval velocities of ~2100 m/s, ~2500 m/s and ~3000 m/s. This initial imaging required aggressive frequency-wavenumber filtering to suppress direct waves in the water column and will be refined with a fibre-optic distributed acoustic sensing (DAS) deployment at the site. Additionally, a thermal response test (TRT) will be undertaken, monitored using an optimised BGS PRIME electrical tomography array and distributed temperature sensing (DTS).

Impacts of deep learning to detect induced seismicity: a case study from Preston New Road, UK

Cindy S. Y. Lim[1,2], Sacha Lapins[1], Margarita Segou[2], Maximilian Werner[1]

[1] *School of Earth Sciences, University of Bristol, Bristol, UK*
[2] *British Geological Survey, Edinburgh, UK*

Deep learning phase pickers, such as PhaseNet, have emerged as efficient and valuable tools for automated phase picking. However, the potential impacts of machine learning (ML) enhanced phase detection on induced microseismicity (Mw < 0) are largely unexplored. This study addresses a critical research gap by investigating the implications of ML-enhanced phase detection for small magnitude events, contributing to our understanding of induced seismicity at unconventional exploration sites.

PhaseNet demonstrates precise phase picking when applied to a high-frequency (2000 Hz) borehole seismic dataset from the Preston New Road shale gas exploration site (PNR-1z) in the UK. Despite being trained on 100 Hz data, PhaseNet detects over 52,000 earthquakes (of which over 15,800 are newly identified) in a 3-month period. In comparison, the well operator's prior method, a more computationally intensive space-time migration approach known as Coalescence Microseismic Mapping, detected over 38,000 induced events within the -2.8 < Mw < 1.1 magnitude range.

Our study addresses challenges in magnitude estimation due to waveform clipping and borehole resonance frequencies by calibrating a linear coda duration-moment magnitude scale for larger, clipped event waveforms and the new events. By deriving the source properties of the newly ML-enhanced catalogue, we demonstrate that off-the-shelf PhaseNet detects numerous new small events (Mw < -0.5). The increased count of lower magnitude events results in denser sampling of magnitude distributions and a lower magnitude of completeness, which affects Gutenberg-Richter b-value estimation. Additionally, the higher event count will enhance the identification of event clusters. These findings have implications for improving seismic hazard assessments and offer opportunities to investigate the spatio-temporal evolution of induced seismicity in higher resolution.

19th and 20th century damaging earthquakes in the Hainaut coal basin of Belgium: triggered or natural?

Koen Van Noten[1], Thierry Camelbeeck[1], Thomas Lecocq[1], Kris Vanneste[1], Ben Neefs[1]

[1] *Royal Observatory of Belgium, Brussels, Belgium*

Several billion tons of Westphalian coal have been mined in the Hainaut province in Belgium for almost two centuries. Concurrent with mining, a considerable seismic activity occurred from the end of the 19th century until the late 20th century. This seismicity (~135 events) is the second largest source of seismic hazard in NW Europe. Five seismic events (Mw~4.0) locally caused moderate damage to buildings with maximum intensity VII on the EMS-98 scale. For decades, the origin of this seismicity and its potential link with coal extraction was disputed due to uncertainties in earthquake location and depth. To tackle this discussion, we re-evaluated the seismic catalogue and reviewed a century of data collected by official macroseismic surveys held by the Royal Observatory of Belgium, press reports, and early instrumental seismological records.

For pre- (1887-1911) and early-instrumental (1911-1965) periods, magnitude, epicentral intensity, location, and depth of 77 seismic events were updated by revisiting macroseismic data. The intensity dataset shows that inside the Carboniferous coal basin intensity attenuates much faster than in the surrounding Palaeozoic Brabant and Ardenne basements due to the (fractured) characteristics of coal. Using the improved intensity dataset, we modelled a new Hainaut intensity attenuation relation linking magnitude, epicentral intensity and focal depth. This new model shows that current hazard maps overestimate ground motion levels in the Hainaut area due to the use of inadequate ground motion prediction equations (GMPEs). By comparing intensity data and published GMPEs, more suitable GMPEs were selected to reduce the impact of this seismicity on hazard calculations.

For the instrumental period during which only few seismic stations were available (1965-1983), we developed a relative multiple events location method to improve earthquake parameters of closely located earthquakes in the Hainaut coal basin. Relocation of 58 events confirms the shallow depth (between one and six km) of the events established by the macroseismic results. Remarkably, after coal mining stopped in the late seventies, only microseismicity remained, with only deep and low-magnitude events recorded by the (since 1985) expanded Belgian Seismic Network.

Our new catalogue provides arguments that support a triggered mechanism, rather than a natural cause, for a century of seismicity. These arguments are (i) the spatial connection between earthquake epicentres and mines, (ii) the (very) shallow depth of seismicity relocated inside the Carboniferous, and (iii) the mostly reverse fault mechanisms supporting normal stress reduction caused by extraction of huge volumes of coal. Is this a unique causal relation or a common observation in the world?

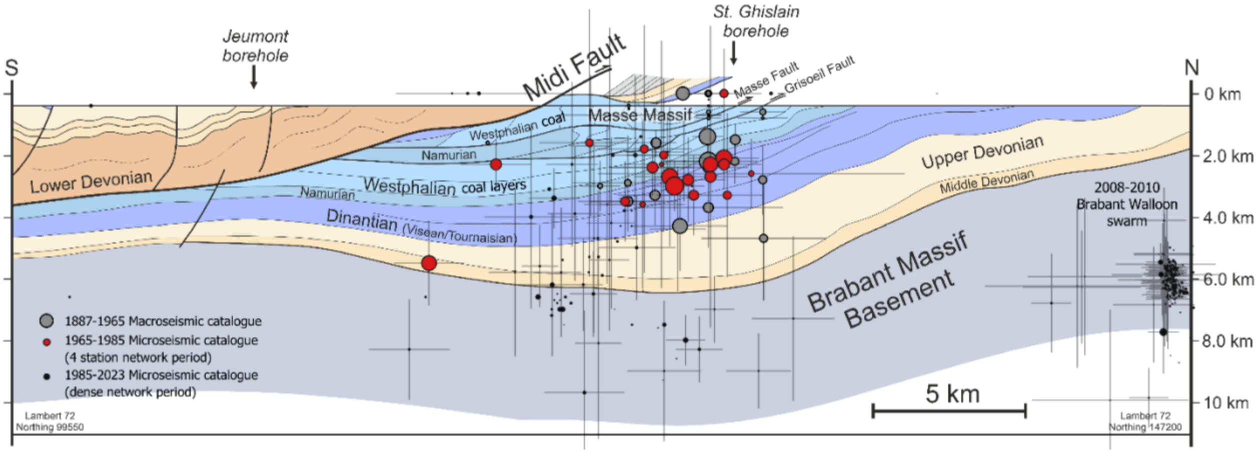


Figure 1: Hainaut coal basin cross-section and relocated earthquakes from pre- and early-instrumental (grey dots), and poorly-instrumented (red) periods. Black dots show post-mining seismicity measured by the fully operational network.

Seismic anisotropy as a measure of in-situ stress for safe CO_2 storage

Joseph Asplet[1], Mark Felgett[2], Tom Kettlety[1], Richard Luckett[2], Mike Kendall[1], Daniela Kuehn[3]

[1] *University of Oxford, Oxford, UK*
[2] *British Geological Survey, UK*
[3] *NORSAR, Norway*

Geological carbon storage is an essential part of the UK and EU's long-term net zero strategy. With several CO_2 injection projects being developed in the Southern North Sea and the East Irish sea, it is important that we develop the tools to monitor these projects and to understand and monitor containment risks. Accurately measuring the ambient stress field of the CO_2 reservoir, caprocks and underlying basement is one important strand of monitoring CO_2 injection and storage. Improved constraints on the stress field will improve geotechnical assessments of caprock integrity, models of fault development and risk modelling. We show how seismic anisotropy, observed by measuring shear-wave splitting of direct S phases, can be used as a measure of the in-situ stress field.

Seismic anisotropy is a well-known measure of order within materials. In crustal rocks the preferential growth and alignment of fractures and microcracks is known to be an efficient mechanism for generating seismic anisotropy, particularly in the case of saturated fractures (Crampin, 1999). These fractures are preferentially oriented with the in-situ S_{Hmax}. Shear-wave splitting fast polarisation directions correspond to fracture orientation, assuming near-vertical fractures, and therefore also can act as a proxy for S_{Hmax}. Furthermore, path-normalised shear-wave splitting delays times have the potential to be used to estimate the ratio of S_{Hmin} / S_{Hmax}, which control fracture density, length, and aspect ratio. We demonstrate this using forward models based on squirt flow in fluid-filled fractures (Chapman, 2003).

We measure shear-wave splitting for 772 earthquakes that occurred across the UK, from 2010-2022. Using this new shear-wave splitting dataset we show how seismic anisotropy can be used to quantify in-situ stress. Most of the data is recorded by stations monitoring Preston New Road, Lancashire stages 1 and 2 and the 2019 Newdigate, Surrey earthquake sequence. These dense datasets allow us to demonstrate the potential for shear-wave splitting measurements to provide constraints on horizontal stress orientations at a significantly greater spatial resolution than borehole measurements. For Preston New Road we find fast polarisation directions that agree with existing interpretations of S_{Hmax} orientation derived from borehole breakout analysis (Clarke et al., 2019), along with intriguing signals of time-varying anisotropy during and following injection. At Newdigate, we compare shear-wave splitting measurements to new borehole breakout analysis for 20 wells across the Weald basin and find a sharp change in the local orientation of S_{Hmax} suggesting previously unmapped local-scale complexity in the stress field.

Station Statistics Obtained from Parametric Data Reported to the ISC

Ryan Gallacher[1], James Harris[1], Natalia Poiata[1]

[1] *International Seismological Centre, Thatcham, UK*

The International Seismological Centre (ISC) receives phase picks from stations throughout the globe, including some phases picked by multiple agencies at the same stations. The approximately 20 million phases reported to the ISC every year form the perfect dataset to evaluate the performance of stations over time. A simple statistic used for evaluating station performance is the phase residual at the station for all reviewed events. Changes in the calculated phase residual at the stations can be displayed by epicentral distance, by azimuth or over the operational life of the station. This information can also be shown in a geographic form to identify tectonic features that may influence the phase residuals. It is also possible to use the reported magnitude information to identify variations and discrepancies in reported magnitude from the individual station and from multiple reporters. This can be achieved by comparing the reported station magnitude and the ISC network magnitude for all events. The relative difference between these magnitudes can be evaluated either over time or geographically to identify patterns and changes. Differences in S-P arrival time plotted with epicentral distance is another instructive statistic that can be used for identifying outlier events or tectonic features. We intend to provide examples of stations showing variations in phase residuals, magnitudes and S-P arrival time. We will demonstrate how this information can be used to identify problems with events, stations or reporters. Further given the recent transition at the ISC to utilising FDSN station information we will also explain how IR and FDSN stations are matched.

Successful Deployment of an 18km SMART Cable with Force-Feedback Seismometer and Accelerometers in the Mediterranean Sea

John O'Neill[1], Bruce Nicholson[1], Neil Watkiss[1], Federica Restelli[1], Giuditta Marinaro[2], Francesco Simeone[2] & Davide Embriaco[2].

[1] *Güralp Systems Ltd, UK*
[2] *Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy*

Autonomous Ocean Bottom Seismometer (OBS) deployments have often involved a degree of "drop-and-hope" due to the inherent lack of seismic data communication during installation as well as waiting extended periods before data collection. Cabled solutions provide real-time data during and immediately after deployment, sometimes with opportunity to adjust the instrument before it is left to operate remotely. However, cabled solutions are inherently financially and logistically challenging both in terms of seismic hardware and arguably more significantly, deployment hardware (ships, ROVs, cables etc.). The geographical reach of these experiments is also often limited to within a few hundred kilometres of the coast. These constraints often mean cabled OBS are beyond the scope of most scientific bodies.

Güralp Systems, in collaboration with INGV, has successfully manufactured and demonstrated a method of reducing financial and logistical constraints and extending geographical range by utilising force-feedback seismic instrumentation in cabled OBS systems. The recent successful deployment of the InSEA Wet Demo SMART (Science Monitoring And Reliable Telecommunications) cable displays a world first in how science can partner with industry to achieve this.

SMART cables are primarily telecommunication cables that secondarily serve as hosts for scientific monitoring equipment. Commercial viability for these systems relies on the cable being laid as if the science element did not exist, thereby minimising additional deployment costs and reducing barriers to cooperation with cable laying companies. GSL and INGV deployed 3 seismometer-accelerometer pairs housed inline repeaters along the 21km cable length using standard cable-laying techniques to show proof of concept.

This pioneering installation using telecommunication cables marks a significant step towards drastically improving local knowledge of inaccessible oceanic regions as well as global azimuthal coverage for teleseismic events, all in real time.

Seismic noise interferometry for phase transmission fibre optics

Sixtine Dromigny[1], Andreas Fichtner[2], Daniel Bowden[2], Dominik Hussman[3]

[1] *University of Oxford, Oxford, UK*
[2] *ETH Zurich, Zurich, CH*
[3] *Federal Institute of Metrology (METAS), Bern, CH*

The phase change of a light pulse travelling in a fibre optic cable is related to the change of the refractive index of the light pulse, the fibre's curvature and the strain applied on the fibre.
Based on this relationship, through the cross-correlation of the phase change of a light pulse at two different curvature points on the fibre, earthquake propagation can be monitored on a range of thousands of kilometres.
We investigate if this new measuring method can be used to monitor seismic noise as well, turning the random noise into a deterministic signal, useful for seismic tomography. For this, we describe the auto-correlation equation of the signal, and with an illustrated example, we show that the auto-correlation of random noise sources results in a deterministic signal, for which we can interpret travel-times of seismic waves.
We also discuss the potential of a concrete application of the new measuring technology, in cooperation with Switzerland's Federal Institute of Metrology (METAS) using their fibre optic cable network. This network sends an optical frequency to Swiss universities' laboratories for time calibration. However, any displacement of the fibre causes the frequency to change, and therefore must be corrected for. We analyse the auto-correlation of the measured phase noise correction and discuss potential interpretation of the results.

A New Approach to Infrasound Sensor Design

Rademacher H[1], Güralp CM[1], Minchinton P[1], McGowan M[1]

[1] *Gaiacode Ltd, Dickers Farm, Bramley Road, Silchester, RG7 2LU United Kingdom*

Current infrasound sensor designs have shortcomings inherent in their open-loop arrangement. Among them are the limited dynamic range, the lack of linearity of the response function over the desired frequency range and – may be most importantly – the fact that such sensors can only be calibrated in the laboratory and not under real conditions in the field.

Here we present a novel infrasound sensor design, which overcomes these and other shortcomings. At the core of our new sensor lies a feedback loop. It is based on a proven technology already applied in many sensor and control systems, particularly relevant for Earth science in the design and manufacturing of high fidelity broadband seismic sensors.

The new infrasound sensor uses a precision bellow, which deflects in response to pressure variations or atmospheric infrasound waves. The movement of the bellow in single degree of deflection is measured with a differential capacitive displacement transducer. Its circuitry is a Blumlein bridge arrangement operating at a frequency of 45 KHz and a driver signal amplitude of 20 V. The transducer's output signal is then synchronously fed back to the regular linearised magnetic force transducer after passing through a Proportional Integral and Differential (PID) controller.

This design increases the bandwidth of the sensor to five decades, from 2.7 mHz to more than 200 Hz. At the same time the response of the sensor is essentially flat over the entire frequency range with only minor variations of less than +/- 0.1 dB. We measured the dynamic range of the sensor to be in excess of 155 dB, a significant increase compared to current open loop systems.
The infrasound sensors theoretical transfer function is compared to practical measurements providing sensors characteristics including its detection levels over the complete frequency response.

The system calibration is carried out analogously to the calibration of broadband seismic sensors. We inject a known calibration signal (either sinusoidal, square wave or broadband noise) directly into the feedback force transducer. This setup allows the calibration of the infrasound sensor in the laboratory as well as after deployment in a field station.

Application of PhaseNet to a National Seismic Network

Richard Luckett[1]

[1] *British Geological Survey, Edinburgh, UK*

Machine learning is increasingly used in seismology for a number of tasks and has proven to be very useful in this field. Some of the most generally employed algorithms are those included in QuakeFlow, an earthquake monitoring workflow developed at Stanford University. Foremost of these in the literature is PhaseNet (Zhu and Beroza, 2019) a deep-neural-network based seismic arrival picker.

The BGS is responsible for detecting and cataloguing earthquakes throughout the UK and maintains a network of about 60 seismic stations deployed across the country for this purpose. Currently detection completeness varies between 2.0 ML and 2.5 ML, depending on location. This talk describes an experiment to discover if the use of PhaseNet could reduce the magnitude of completeness for the UK. This was done by applying the algorithm retrospectively to large volumes of waveform data from the national network. The phase association algorithm included in QuakeFlow, GaMMA (Gaussian Mixture Model Associator, Zhu et al., 2022) is also considered in this context and its performance compared with that of other available association algorithms.

In addition, PhaseNet was used to repick data from two local networks surrounding sources of induced seismicity. These are the GWATT seismic network surrounding the United Downs Deep Geothermal Power (UDDGP) drilling project in Cornwall and a surface network designed to record hydrofracturing induced seismicity near Blackpool. In the case of the Blackpool data this is particularly interesting because a catalogue exists of events recorded by an extremely sensitive downhole array. This allows additional earthquakes detected by PhaseNet to be evaluated in a precise way.

Zhu, W and Beroza, G (2019). PhaseNet: A deep-neural-network-based seismic arrival-time picking method. Geophysical Journal International, 216.

Zhu, W, McBrearty, I, Mousavi, S, Ellsworth, W and Beroza, G (2022). Earthquake phase association using a Bayesian Gaussian Mixture Model. Journal of Geophysical Research: Solid Earth, 127.

Estimating seismic attenuation, site corrections and geometrical spreading from large seismic catalogues using linearised spectral ratios and regression regularisation paths

Sacha Lapins[1]

[1] *University of Bristol, Bristol, UK*

Estimating source parameters from earthquake signals requires discriminating source properties (e.g., corner frequency and radiation pattern) from path, site and geometrical spreading effects. Commonly used seismic source models (e.g., Brune and Boatwright models) incorporate nonlinear combinations of these terms, making it challenging to estimate and isolate these effects from individual event spectra. This is particularly true for low magnitude seismicity (M<3) where signal-to-noise levels are low, instrument bandwidth can be limiting, and the spectral decay resulting from attenuation and source corner frequency strongly trade-off with each other.

Here, I present a linearised spectral ratio approach for simultaneously estimating all non-source-dependent terms (i.e., quality factor Q, geometrical spreading, and site-specific κ_0 and constant/average corrections) from large catalogues of low-magnitude seismicity. Under the assumption of constant corner frequency for any given event, inter-station spectral ratios are used to cancel this term from source model equations, leaving only the contribution of path, site and spreading effects to estimate. Large systems of linearised spectral ratio equations are then constructed for subsequent regression, each incorporating many events (e.g., 50–100 events) and all available pairwise station combinations. An iterative regularised regression procedure is then used, where the strength of the parameter regularisation is gradually annealed to zero, encouraging the regression algorithm to first estimate ‘global’ site and spreading terms (i.e., those assumed to be constant over all events) before estimating the more variable Q attenuation terms for each source-receiver pair. Lastly, distributions are generated for the maximum likelihood estimates of each term by repeatedly applying this approach to subsets of large seismic catalogues (such as those produced by machine learning phase arrival detection models), providing more robust final estimates and uncertainty quantification.

I demonstrate this approach on a machine-learning-derived catalogue of seismicity from Nabro volcano in Eritrea, comprising nearly 34,000 events. The resulting estimates are compared against some commonly assumed values (e.g., for average radiation pattern and geometrical spreading) and other inferred geophysical properties at Nabro, providing interesting insights into the subsurface properties beneath this volcano. The results also highlight important considerations regarding the use of ‘textbook’ values and assumptions of frequency dependence/independence for some source model parameters.

Automatic relocation of intermediate-depth earthquakes using adaptive teleseismic arrays

Alice Blackwell[1], Timothy Craig[1], Sebastian Rost[1]

[1] *University of Leeds, Leeds, UK*

Intermediate-depth earthquakes, accommodating intra-slab deformation, typically occur within subduction zone settings at depths between 60-300 km. High magnitude, intermediate-depth events can pose a significant hazard to populations, and increase the risk of damaged infrastructure, injury and fatality. Despite improvements in recorded seismic data density and quality, the distribution and controls of these events remain poorly understood. Depth phases (near-source surface reflections, e.g. pP and sP) are crucial for the accurate determination of earthquake source depth using global seismic data. However, they suffer from poor signal-to-noise ratios in the P-wave coda. This reduces the ability to systematically measure differential travel times to the corresponding direct arrival, particularly for the frequent lower-magnitude seismicity which highlights considerable seismogenic regions of the subducted slabs.

To address this limitation, we have developed an automated approach to group globally distributed stations at teleseismic distances into ad-hoc arrays with apertures of 2.5°, before optimising and applying phase-weighted beamforming techniques to each array. Resultant vespagrams allow automated picking algorithms to determine differential arrival times between the depth phases (pP, sP) and their corresponding direct P arrival. These are subsequently used to invert for a new hypocentre location. These will allow new comparisons and insights into the governing controls on the distribution of earthquakes in subducted slabs. We demonstrate this method by relocating intermediate depth events associated with northern Chile and the Peruvian flat slab regions of the subducting Nazca plate.

Solving the elastic wave equation with physics-informed neural network

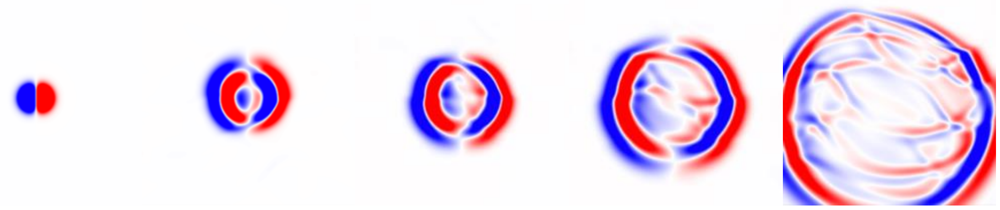
Davide Staub[1], Siddhartha Mishra[1], Ben Moseley[1]

[1] *ETH Zürich, Zürich, Switzerland*

Physics-Informed Neural Networks (PINNs) have recently emerged as a promising approach for solving Partial Differential Equations (PDEs), offering a mesh free alternative that integrates physical principals into the learning process. This presents a new paradigm compared to traditional discretization methods and purely data-driven machine learning techniques. While promising, PINNs are not a panacea; they inherit challenges such as spectral bias and unstable convergence. Moreover, their potential in seismology remains largely unexplored.

In this work we provide a robust and critical assessment of PINNs for solving the elastic wave equation in seismology. We investigate the performance of PINNs on problems with varying degrees of complexity, across various seismic sources and parameter models, from constant to highly heterogeneous settings. A pivotal aspect of our work involves investigating whether embedding physical principles directly into the network architecture enhances convergence and accuracy. We test an extensive range of neural architecture designs, from unrestricted, uninformed PINNs to highly specialized ones, finding that integrating understanding of wave physics into the network design significantly improves accuracy. For instance, introducing a custom wavelet or planewave layer, coupled with encoder and decoder layers, consistently yields a relative L2 error approximately half that of the standard PINN, as evidenced across numerous experiments. We further demonstrate that this novel architecture enhances accuracy when applied to the acoustic wave equation, underlying the versatility of our network.

Another key contribution of our research is the successful conditioning of PINNs on seismic source locations. This advancement is vital for seismology applications, where traditionally, thousands of seismic simulations are run to assess various potential source locations. By conditioning PINNs on the source location, the network learns solutions for a class of problems, not just a single setting. Once trained, this method significantly outperforms traditional numerical methods, such as Finite Difference (FD) methods, in terms of simulation speed. The capability of conditioned PINNs to infer the wavefield for countless source location in a single forward pass, signifies a considerable advancement towards rapid seismic hazard detection and seismic analysis.



Propagation of an elastic wave through a layered solid medium, generated by a planewave-PINN

Pushing our data to the limit and no further: constraining Earth properties using Backus-Gilbert inferences

Paula Koelemeijer[1,2], Federica Restelli[2], Adrian Mag Marin[2], Franck Latallerie[2], Andrew Walker[2], Christophe Zaroli[3]

[1] *Department of Earth Sciences, University of Oxford, Oxford, UK*
[2] *Department of Earth Sciences, Royal Holloway University of London, Egham, UK*
[3] *Institut Terre et Environnement de Strasbourg, Université de Strasbourg, Strasbourg, France*

Seismic tomography models are routinely developed and interpreted in terms of Earth composition and dynamics. However, without information on both the uncertainties and the resolution of seismic tomography models, we should remain cautious with our interpretations. This is particularly important when interpreting relationships between velocities, such as the ratio between anomalies in Vs and Vp. To jointly interpret such variations, it is essential for them to share the same local resolution.

To overcome these issues, we utilise Backus-Gilbert based methods. These inference methods enable us to retrieve local model properties with the associated uncertainties. We specify *a priori* information on the resolution through target kernels, thus obtaining an implicit control on the resulting model resolution. Specifically, we develop global models of Vs and Vp with the same local resolution using normal mode observations. Furthermore, we constrain the structure of the upper mantle in the Pacific with 3D surface wave tomography, while we also advance Backus-Gilbert methods to constrain properties of discontinuities inside the Earth. These different applications illustrate the advantages of Backus-Gilbert inferences for constraining Earth properties.

Oral Presentation

Vp/Vs tomography in South-East Asia using SOLA-Backus-Gilbert inversion

Emile Serra[1], Christophe Zaroli[1], Sophie Lambotte[1], Paula Koelemeijer[2,3]
[1] *Institut Terre et Environnement de Strasbourg, Université de Strasbourg, France*
[2] *Department of Earth Sciences, University of Oxford, Oxford, UK*
[3] *Department of Earth Sciences, Royal Holloway University of London, Egham, UK*

The ratio of seismic velocity variations (R=dlnVs/dlnVp) is an important physical parameter to study the thermochemical properties of the subsurface. When obtained through the division of two independent models of Vs and Vp variation, a few issues emerge. Firstly, the two models must share the same local resolution. Secondly, the division itself must be possible. For a given location in our tomography models, the division involves 4 parameters: dlnVs, dlnVp and their uncertainties (if assumed gaussian). However, the probability function describing the division of these two Gaussian distributions, the Hinkley distribution, does not necessarily resemble a Gaussian distribution itself and it is likely very different compared to the direct division of dlnVs and dlnVp.
Thanks to a SOLA-Backus-Gilbert inversion approach, performed in the South-East Asia region, we are able to develop models of dlnVs and dlnVp with similar local resolution. We propose a method to use the Hinkley distribution to determine better estimates of the R value, bonded with a "quality parameter" that indicates the confidence of the dlnVs/dlnVp value. Thanks to the Hinkley function, we are also able to obtain an estimate of the uncertainty on the dlnVs/dlnVp division. In a similar way, we also investigate the dlnVp/dlnVs (1/R) ratio. We show that, in most cases, either R or 1/R is relevant (i.e. Gaussian). Thus, the two ratios are complementary, and worth being both considered in physical interpretations. In conclusion, with the SOLA-Backus-Gilbert approach, we are able to generate four models (dlnVp, dlnVs, dlnVs/dlnVp and dlnVp/dlnVs), with their respective uncertainties, each having similar local resolutions.

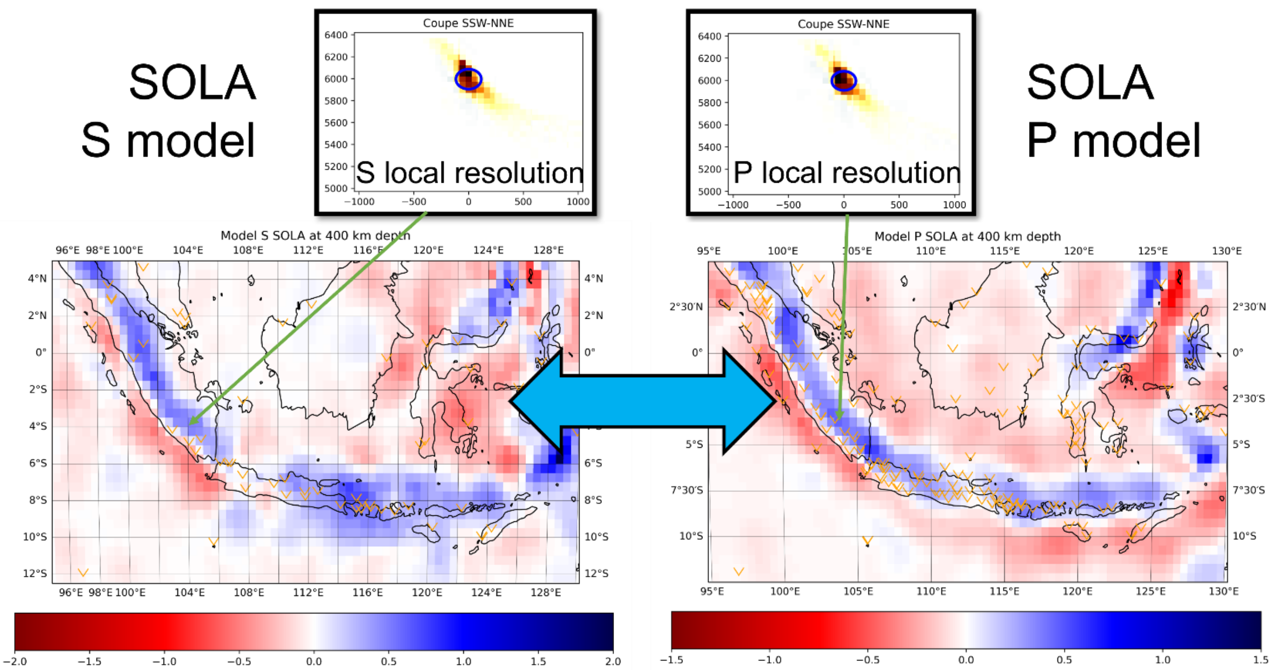


Fig 1. dlnVp (right) and dlnVs (left) tomography of the South-East Asia using SOLA. In the top, the local resolutions of the dlnVp and dlnVs of the cell shown with the arrow. The goal is to get the R(=dlnVs/dlnVp) ratio of the cells with similar local resolutions.

A search for dilation in low frequency earthquake waveforms

Jessica C. Hawthorne[1], Amanda M. Thomas[2], Lois Papin[2], Hui Huang[3], S. Jordan, M. Cavendish[4]

[1] *University of Oxford, Oxford, UK*
[2] *University of Oregon, Eugene, Oregon, USA*
[2] *Tongji University, Shanghai, China*
[3] *University of Nottingham, Nottingham, UK*

The fault zone process that creates slow earthquakes remains unclear, but one proposed mechanism to limit slip speeds depends on shear-induced dilatancy and the resulting pore pressure changes. This process would imply that the fault zone dilates during slow earthquakes. So in this study, we search for the signature of dilation in the focal mechanisms of tremor's low frequency earthquakes (LFEs).

It is, however, difficult to directly observe dilation in LFE waveforms. The paths travelled by LFEs' 1-10 Hz seismic waves are complex, and Earth structure is poorly known at the short wavelengths of interest. This complexity makes it difficult to disentangle path effects from source properties. Thus we look for differences in the seismic waves created by two groups of LFEs: groups of events that are in the same location but occur at different times. The earlier events are smaller and thought to rupture through more solid, low-permeability fault rock and thus may have large dilation, while the later events rupture areas that have recently slipped and thus may have smaller dilation.

In our initial analysis, we stack and analyse waveforms of LFEs identified in Cascadia by Bostock et al (2015). However, we identify no significant difference in the waveforms or any significant trends in the polarisation of the difference. Preliminary results suggest that the early and late LFEs have waveforms that differ by less than 1-2%.

That zero to minimal difference could indicate that there is no dilation. Perhaps early and late LFEs are exclusively shear slip, and shear-induced dilatancy does not limit LFE slip speeds. However, it is also possible that dilation is simply small. The early, potentially large-dilation LFEs could have a dilation-to-shear slip moment ratio of 0.05, and the later, potentially small-dilation LFEs have a dilation-to-shear ratio of 0.04. Such dilation would be large enough to significantly affect LFE slip rates but would not be visible with our current data and techniques.

In our continuing work, then, we seek to decrease the uncertainty in our observations by identifying and stacking more LFEs and by extracting more information from seismograms including many LFEs.

Deep long-period earthquakes at Alaskan Volcanoes and their relations to fluid/magmatic transport

Zilin SONG[1,2], Yen Joe TAN[1], Diana C. ROMAN[3]

[1] *Chinese University of Hong Kong, Hong Kong, China*
[2] *University of Edinburgh, Edinburgh, UK*
[3]*Carnegie Institution for Science, Washington D.C., USA*

Deep long-period earthquakes (DLPs) have been detected in the vicinity of volcanoes, with depth raging from the lower crust down to the upper mantle. The predominant low-frequency energy in their seismic signals differentiates DLPs from regular volcano-tectonic earthquakes (VTs). Due to their correlation with impending eruptions, DLPs are also considered as potential eruption precursors. However, waveforms of DLPs are characterized by emergent phase arrivals which poses challenges for detection using conventional data processing procedures. The specific mechanism of DLP also remains elusive. Therefore, in this study, we first apply the frequency index (FI) to classify earthquakes into high-frequency VTs and long-period events (LPs) at 10 Alaskan Volcanos, where the largest number of DLPs have been reported. Results indicate a consistent distinction in FI values (~-1) between VTs and LPs across different volcanoes. Given the detection of VTs below the shallow magma reservoir, along with their co-location with DLPs, we propose that source effects play a primary role in the genesis of DLPs. We further analyse 13 years of continuous waveforms at 10 Alaskan Volcanoes by cross-correlation-based detection methods to detect more DLPs. It provides ~40, 000 DLP detections which leads to an average reduction of 0.6 M_L in magnitude completeness of DLP catalogue. Eventually, we determine approximately 50,000 LPs, with repetitive LPs detected above and near the magma reservoir. It implies the involvement of destructive source processes during DLPs occurrence. Further, we observe a negative correlation (R^2=0.81) between Moho depth and magmatic water content along the mid-east Aleutian volcanic arc, indicating a shorter magmatic transport distance from mantle melts to the reservoir as magmatic water content increases. Compared to the common depth of DLPs, where DLPs occur most frequently beneath each volcano in our study, we find positive relations (R^2=0.58) between magmatic travel distance and the distance from the Moho to the DLP common depth. In comparison, we also analyse the correlation between the DLP common depth and longitude as kinematic parameters of plate motion along Aleutian trench vary systematically from west to east. No correlation is detected (R^2=0), suggesting that DLP genesis at Alaskan volcanoes is primarily driven by magmatic transport processes instead of plate motions.

Evidence for crustal melt lens beneath Changbaishan volcanic field

Weiqian Yu[1,2], Wei Wei[1], James O.S. Hammond[3], Cunrui Han[3], Jiandong Xu[2]

[1]*State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China*
[2]*Jilin Changbaishan Volcano National Observation and Research Station, Institute of Geology, China Earthquake Administration, Beijing 100029, China*
[3]*School of Natural Sciences, Birkbeck, University of London, London WC1E 7HX, UK*

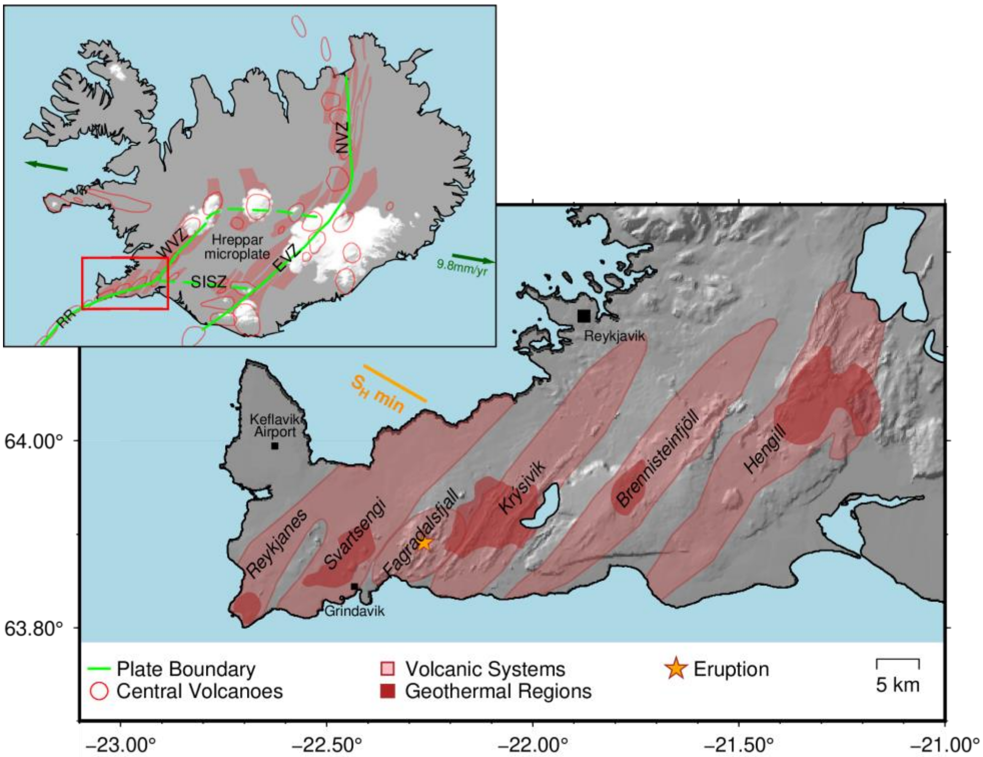
Changbaishan volcanic field (CBVF), located on the border of China and the Democratic People's Republic of Korea (DPRK) is famous for intense volcanism in Cenozoic with three similar polygenetic volcanoes (Wangtian'e-WTE, Namphothe-NPT and Tianchi-TCV) and over 200 monogenetic volcanoes. TCV is the only activate volcano of the three, known for the 'Millennium Eruption', dated to 946 Common Era and is often named Changbaishan (or Mount Paektu/Baekdu in DPRK). Here we refer to it as TCV to distinguish the specific volcano from the wider CBVF region. Many studies show evidence for partial melt beneath the volcano, but details on the structure of the magmatic system are lacking due to a lack of data in the region. In this study, we obtained a high-resolution crust and upper mantle shear wave velocity (Vs) model beneath the CBVF by ambient noise tomography and receiver functions using a new dense seismic array. The absence of velocity anomalies beneath WTE and NPT suggest a lack of magma within the crust. However our models reveal two low velocity anomalies in the upper crust below TCV. The shallowest one (<4km) overlaps with petrological estimates of the assembly depth of erupted rhyolite magma reservoir and depth inferred for hydrothermal reservoir from recently MT study. This may be associated with saline fluids and/or a magma reservoir. A second one is located at depths between 7 and 14 km with a lateral extent of ~30 km. This low velocity anomaly is interpreted to be the main magma reservoir with an estimated melt fraction of 4 %-12 % that could feed the surface volcanism and hydrothermal activities. This double layered low velocity anomalies is in agreement with the observations of volcanic seismicity, ground deformation and volcanic gas geochemistry during the 2002-2006 volcanic unrest. Underlying the deeper low velocity zone in the lower crust is a region of faster velocity compared to the surrounding region. In the bottom of lower crust and uppermost mantle, our Vs model shows low velocities close to the Moho beneath TCV. This is likely the source of partial melt that supplies the volcano. We proposed that magma from the mantle continues to intrude into the lower crust, where through reactive transport it migrates to form a basaltic magma reservoirs beneath CBVF, leaving behind a chemically differentiated crust with faster seismic velocities.

Seismic Crustal Structure of the Reykjanes Peninsular, SW Iceland

Jennifer Jenkins[1], Tim Greenfield[2], Joseph Fone[2], Armin Dalkhani[3], Thorbjorg Agustdottir[4], Nicholas Rawlinson[2], Gylfi Páll Hersir[4], Egill Árni Gudnason[4], Josef Horálek[5], Anne Obermann[6], Torsten Dahm[7], Claus Milkerei[7]

[1] *Durham University, Durham, UK;* [2] *University of Cambridge, Cambridge, UK;* [3] *University of Deflt, Netherlands;* [4] *Iceland Geosurvey ISOR, Reykjavik, Iceland, UK;* [5] *Czech Academy of Science, Prague, Czechia,;* [6] *ETH, Zurich, Switzerland;* [7] *GFZ, Potsdam, Germany*

The Reykjanes Peninsular in Iceland is a transtenstional rift system representing an on-land continuation of the Mid-Atlantic ridge. Across the peninsular are six active volcanic systems with associated geothermal regions. Since 2020 ongoing seismic and volcanic unrest, including 4 volcanic eruptions to date have brought significant attention, and an increase in seismic monitoring to the region. Utilising the vast increase in the number of local seismometers we use, to image large scale crustal velocity structure and crustal thickness variation across this area of active crustal formation.
Interstation surface wave dispersion curves are derived from ambient noise cross-correlations between current co-recording stations, and combined with data from previous small-scale studies to generation regional Rayleigh wave phase velocity maps. These are sampled and combined with a newly generated teleseimic receiver function dataset and jointly inverted for shear-wave velocity structure down to 50 km depth. Individual velocity models are combined into a regional 3D model of the area, which is interpreted in terms of local surface structure and seismicity as well as regional tectonics and petrology results, to provide big-picture context for the ongoing volcanic unrest.



The Moho and lithosphere-asthenosphere boundary below the Turkana Depression, East Africa: evidence from project TRAILS

Ian D. Bastow[1], Rita Kounoudis[1,2], Christopher S. Ogden[1,3], Cynthia J. Ebinger[4], Saskia D.B. Goes[1], Martin Musila[4], Atalay Ayele[5], Pengzhe Zhou[1]

[1] *Imperial College, London, UK*
[2] *The University of Oxford, UK*
[3] *AWE Blacknest, UK*
[4] *The University of Tulane, USA*
[5] *The University of Addis Ababa, Ethiopia*

The Turkana Depression is a broad (~500km-wide), topographically-subdued (~0.5km), region between the elevated Ethiopian (~1.5km) and East African Plateaus (~2.5km). The Depression is unique in East Africa for being host to a NW-SE-trending failed Mesozoic (Anza) rift system through which the near-orthogonal, N-S-trending East African Rift subsequently developed. Whether the Depression's low-lying nature is a result of a significantly thinned crust instigated by its multiple rifting phases, or instead due to a lack of dynamic mantle support is debated. Also poorly understood is the extent to which Cenozoic rifting and magmatism have developed across the Depression during the linkage of other comparatively narrow East African Rift zones to the north and south. Utilising data from the 2019-2021 Turkana Rift Arrays Investigating Lithospheric Structure project and surrounding networks, receiver function analysis and its joint inversion with surface-waves [2], are used to probe Moho architecture and the lithosphere-asthenosphere system.

Receiver function results [1] reveal a thinned crust (20-25km) throughout the Depression: 10-20km thinner than the Ethiopian Plateau and Tanzania Craton. The Depression's low elevations are thus likely an isostatic response from a thinned crust and not a lack of mantle dynamic support. High associated crustal stretching factors ($\beta<2.1$) and low bulk crustal Vp/Vs ratios (1.74) point to a crust largely unmodified by voluminous magma-assisted rifting and widespread flood basalt magmatism. Cenozoic extension has thus largely been dominated by faulting and plate stretching, rather than magma intrusion, which is likely an incipient process, operating directly below Lake Turkana. At mantle lithospheric depths, joint inversion (and travel-time tomography [3]) reveals a clearly identifiable, high shear-wavespeed mantle lithospheric lid, an observation that has proven elusive across the heavily melt-infiltrated MER and Ethiopian Plateau. The thermal state of the mantle is also explored through thermodynamic conversions of shear-wavespeeds to temperature, illuminating elevated asthenospheric temperatures below a relatively thermally un-altered mantle lithosphere. Any dynamic support below the Depression is thus likely asthenosphere-derived.

[1] Ogden, C. et al., (2023), The development of multiple phases of superposed rifting in the Turkana Depression, East Africa…, Earth Planet. Sci. Lett., 609, 118,088, doi:10.1016/j.epsl.2023.118088.
[2] Kounoudis, R. et al., (2023), The development of rifting and magmatism in the multiply-rifted Turkana Depression, east Africa:…, Earth Planet. Sci. Lett., doi:10.1016/j.epsl.2023.118386.
[3] Boyce, A., et al., (2023), Mantle wavespeed and discontinuity structure below East Africa:…, Geochem. Geophys. Geosyst., 24 (8), e2022GC010,775, doi:10.1029/2022GC010775.

Insights on the African upper mantle from Quasi-Love wave scattering

Thomas A. J. Merry[1,2], Caroline Eakin[1]

[1] *Australian National University, Canberra, Australia*
[2] *University of Cambridge, Cambridge, UK*

Diverse upper mantle processes take place beneath the African plate. The continent hosts several cratonic roots, active and magmatic continental rifting, abundant intra-plate volcanism, such as at the Cameroon Volcanic Line, as well as several oceanic hot spots offshore. Relatively small-scale mantle convection processes, some possibly related to lithospheric thickness variations, have been proposed to account for patterns of volcanism and topography. A key constraint on these features and processes can be found via seismic anisotropy, but limited coverage of seismic stations across the continent has resulted in sparse observations. Quasi-Love waves, which are produced by scattering of Love to Rayleigh energy by lateral gradients in upper mantle seismic anisotropy, can provide information about seismic anisotropy well away from seismic stations. We catalogue observations of Quasi-Love waves across the region and back-project to the scattering points to reveal locations of lateral gradients in upper mantle seismic anisotropy. With periods of 100–150 s, the scattered waves are primarily sensitive to the 100–200 km depth range. Quasi-Love wave scattering is found to occur at craton edges, likely due to the contrast between lithospheric and asthenospheric anisotropy, as well as within the vicinity of ancient orogenic belts, indicating changes in fossilised lithospheric anisotropy that records past collisional events. Scattering also occurs in regions below thin lithosphere, suggesting deviations in asthenospheric flow patterns (such as localised upwellings) potentially induced by topographical variations in the lithosphere-asthenosphere boundary above. This occurs in areas such as the East African Rift, beneath oceanic hotspot tracks, and the Cameroon Volcanic Line. Quasi-Love scattering is abundant in the Indian Ocean and Madagascar, consistent with small-scale dynamic processes in the asthenosphere that likely relate to the complex rifting history of this ocean basin and the dispersed microcontinents within.

3D imaging of Rayleigh wave mantle attenuation with uncertainty quantification

William Sturgeon[1], Ana M.G. Ferreira[1]

[1] *University College London, UK*

We present global 2-D maps of frequency-dependent attenuation based on a huge dataset of ~10 million Rayleigh wave amplitude measurements. We incorporate fundamental mode and up to 4th overtone measurements over a period range of 35-275 s to ensure sensitivity in both the uppermost mantle and in the transition zone. In order to isolate intrinsic anelastic attenuation structure, we account for source, path and receiver effects on the amplitude data. Most prominently, we account for focusing/defocusing effects along the ray-path using complementary phase velocity maps. Following the removal of outliers based on strict data selection criteria, the resulting dataset is inverted using a least-squares approach along with a thorough exploration of model regularisation.

Our maps show a strong correlation between attenuation and surface tectonics up to periods of T~100 s, with low attenuation beneath the continents and high attenuation beneath the oceans. Our maps also show a commonly observed age progression trend in ocean basins, with lower attenuation beneath older oceanic crust. The East Pacific Rise, western North American and hotspots correlate with high attenuation up to T~100s, but then correspond to low attenuation regions at periods greater than T~180 s. As to be expected, uncertainties are higher in regions of poor data coverage (e.g., southern hemisphere and oceans).

We then, for the first time, invert frequency-dependent Q-curves for 1D profiles of shear-attenuation using the Monte-Carlo based Neighbourhood Algorithm. We discuss the implications of our resulting 3D model in terms of mantle temperature, composition melt and water anomalies.

The UPFLOW experiment: Peeking from the sea floor to the deep mantle with an ∼1,500 km aperture array of 50 ocean bottom seismometers in the mid-Atlantic

Ana M. G. Ferreira[1,2], Maria Tsekhmistrenko[1,2], Miguel Miranda[3], the UPFLOW team

[1] *University College London, Department of Earth Sciences, UK*
[2] *ERP, Earth Rover Program, UK*
[3]*Air Centre, Atlantic International Centre, Portugal*

Imaging deep upward mantle flow is key for understanding global mantle flow and to link the Earth's deep interior with the surface. Yet, plume-like mantle upwellings that connect the deepest mantle to the surface are poorly understood. As part of the UPFLOW project funded by the European Research Council (2021-2025) we conducted the largest and longest amphibian passive seismic experiment done so far in the Atlantic. We focused on the Azores-Madeira-Canary Islands region, which is a unique natural laboratory with multiple upwellings that are poorly understood. UPFLOW deployed 50 and recovered 49 ocean bottom seismometers (OBSs) in a ∼1,000×2,000 km^2 area starting in July 2021 for ∼13 months, with an average station spacing of ∼200 km. We present initial results from multi-frequency (T~2.7 – 30 s) teleseismic body P-wave tomography combining over 5 million global measurements from the ISC database with over 100,000 measurements from the UPFLOW project and surrounding permanent and temporary land stations, which greatly enhance the data coverage and resolution in the study region. We interpret our results in terms of possible lateral connections between mantle upwelling beneath the Canaries and the Azores archipelago and discuss their geodynamical implications.

Determining subsurface temperature & lithospheric structure from joint geophysical-petrological inversion: A case study from Ireland

Emma L. Chambers[1], Javier Fullea[2], Sergei Lebedev[1,3], Raffaele Bonadio[1,3], Duygu Kiyan[1], Chris J. Bean[1], Pat Meere[4], Yihe Xu[1,3], Brian M. O'Reilly[1]

[1] *Dublin Institute for Advanced Studies, Dublin, Ireland*
[2] *Universidad Complutense de Madrid, Madrid, Spain*
[3] *University of Cambridge, Cambridge, UK*
[4] *University College Cork, Cork, Ireland*

High-quality maps of the geothermal gradient and temperature are essential when assessing the geothermal potential of a region. However, determining geothermal potential is a challenge when direct measurements of in situ temperature and thermal property information are sparse, as is the case in Ireland. In addition, individual geophysical methods are sensitive to a range of parameters, not solely temperature. We develop a novel approach to determine the geothermal gradient using a joint geophysical-petrological thermochemical inversion (Chambers et al. *Tectonophysics,* 2023 & Fullea et al. *GJI,* 2021), which requires seismic surface wave data, thermal property data, and additional geophysical and petrophysical datasets. The multi-parameter models produced by the integrated inversions fit the surface-wave, heat flow and additional data, revealing the temperature, lithospheric structure and geothermal gradient within the crust and mantle.

Here we present the new methodology and resulting models of Ireland's subsurface temperature. Our new methodology produces results comparable to past temperature and geophysical measures. Importantly, the maps are within error of direct borehole temperature measurements, providing confidence in the results. Lithospheric and crustal thickness play a key control on the temperature gradient with areas of thinner lithosphere resulting in elevated geotherms. In some locations we observe geotherms elevated beyond expectations which result from high radiogenic heat production from granitic and muddy limestone rocks. This new methodology provides a robust workflow for determining the geothermal potential in areas with limited direct measurements. The final temperature model updates previous maps of Ireland and will be used for future geothermal exploration and utilisation.

The DIG project is funded by the Sustainable Energy Authority of Ireland under the SEAI Research, Development & Demonstration Funding Programme 2019 (grant number 19/RDD/522) and by the Geological Survey Ireland.

Seismic Thermography, or the importance of inverting for what we really want to know

Sergei Lebedev[1], Javier Fullea[2], Yihe Xu[1], Raffaele Bonadio[1]

[1] *University of Cambridge, Cambridge, UK*
[2] *Universidad Complutense de Madrid, Madrid, Spain*

What is next in seismic tomography? A key future direction, as we argue in this presentation, is the inversion of seismic data directly for temperature within the Earth. We term this emerging branch of seismic imaging Seismic Thermography. Variations in temperature are of great interest because they indicate the thickness and, consequently, mechanical strength of the lithosphere and density variations and convection patterns in the sub-lithospheric mantle. Seismic tomography maps seismic-velocity variations in the mantle, which depend on temperature. Temperatures and, for example, the lithospheric structure and thickness are, thus, often inferred from tomography. Tomographic models, however, are non-unique solutions of inverse problems, regularized to ensure model smoothness or small model norm, not plausible temperature distributions. For example, lithospheric geotherms computed from seismic-velocity models typically display unrealistic oscillations, with improbable temperature decreases with depth within shallow mantle lithosphere.

It is more accurate to invert seismic data directly for temperature and avoid the errors due to the intermediate-model non-uniqueness. Because seismic-velocity sensitivity to composition is weaker than to temperature, we can use computational petrology and thermodynamic databases to invert seismic data primarily for temperature, with reasonable assumptions on composition and other relevant properties and with additional inversion parameters such as anisotropy.

We apply thus defined Seismic Thermography to the thermal imaging of the lithosphere, asthenosphere and the lithospheric thickness using surface waves. Conductive geotherms and standard compositions fit the data from Precambrian continents and from Britain and Ireland, which we use as examples. Exotic compositions and temperature profiles can also be mapped, when required by the data, using specially defined components of the parameterisation. The accuracy of the models depends critically on the accuracy of the extraction of structural information from the seismic data. Random errors have little effect but correlated errors of even a small portion of 1% can affect the models strongly.

Seismic Thermography builds on the techniques of seismic tomography and relies on computational petrology but it is emerging as a field with its own scope of goals, technical challenges and methods. It is producing increasingly accurate models of the Earth and important inferences on its dynamics and evolution.

More equitable recruitment of PhD students in geophysics

Benjamin Fernando[1], Sam Giles[2], Natasha Dowey[3], Christopher Aiden-Lee Jackson[4], Anya Lawrence[2], Munira Raji[5], Rebecca Williams[6], Jenni Barclay[7], Louisa Brotherson[8], Ethny Childs[9], Jacqueline Houghton[10], Anjana Khatwa[11], Alicia Newton[12], Keely Mills[13], Francisca Rockey[14], Steven Rogers[15], Catherine Souch[16]

[1]Johns Hopkins University, Baltimore, United States; [2]University of Birmingham, United Kingdom; [3]Sheffield Hallam University, United Kingdom; [4]Imperial College London, United Kingdom; [5]University of Plymouth, United Kingdom; [6]University of Hull, United Kingdom; [7]University of East Anglia, United Kingdom; [8]University of Liverpool, United Kingdom; [9]Institute of Environmental Sciences, United Kingdom; [10]University of Leeds, United Kingdom; [11]Wessex Museums, United Kingdom; [12]The Geological Society Of London, United Kingdom; [13]Loughborough University, United Kingdom; [14]Black Geographers, London, United Kingdom; [15]Keele University, United Kingdom; [16]Royal Geographical Society, United Kingdom

Within the UK geosciences community, students of colour are substantially under-represented at both undergraduate and postgraduate levels[1]. Geophysics is no exception[2].

Progress toward addressing this is frustratingly slow[3]. As part of the Equator project [4], we worked with NERC, university departments, and students themselves to identify evidence-based, scalable, and practicable suggestions for addressing this imbalance.

We find three areas where improvement is most significantly needed:

(1) – the way in which PhD programs are advertised,
(2) – the way in which interviews take place, and
(3) - the way in which applications are evaluated and ranked.

In each area, we propose actionable goals requiring short, medium, and long term efforts. These approximately correspond to areas which are within the power of individual supervisors, departments, and funding bodies to address respectively.

This presentation will focus on actionable items which are particularly relevant to seismology, given the high proportion of PhD students recruited from other disciplines.

[1] Fernando et al, Strategies for making geoscience PhD recruitment more equitable, Nature Geoscience (2023)
[2] The Demographics and research interests of the UK Astronomy and Geophysics communities in 2016, Royal Astronomical Society Report (2016)
[3] Dowey et al, A UK perspective on tackling the geoscience racial diversity crisis in the Global North, Nature Geoscience (2021)
[4] Dowey et al, The Equator Project – Full Report Preprint, https://doi.org/10.31223/X5793T (2022).

Panel discussion: How do we promote geophysics at highschool Level?

Jennifer Jenkins[1]

[1]*Durham University, Durham, UK*

Geophysics is an exciting, relevant subject. There are good career opportunities and a demand for geophysics graduates by industry. Geophysics skills are needed to facilitate a green energy transition and are directly relevant to achieving multiple Sustainable Development Goals. And yet UK geophysics courses have low-uptake, to the extent that some institutions are considering closing down courses. Why is this? It's likely numerous factors contribute, but a key issue is a lack of awareness or understanding of what geophysics is at high school level.

In this panel session a group of representatives including teachers, academics and industry representatives will discuss the current situation of geophysics undergraduate degrees, think about the reasons behind low-application rates and consider how we can best engage with schools to reach and inspire the next generation of geophysicists.

Forecasting Coastal Cliff Collapse using Distributed Sensing

Jess Johnson[1], Lidong Bie[1], Dominic Seager[1], Harry Whitelam[1], Ben McLeod[1], Nick Griffin[1], David Ciplic[1], Thomas Easton[1], Matthew Hatherly[1], Theo Graham[1], Rebecca Gorman[1], Ricky Herd[1]

[1] *University of East Anglia, Norwich, UK*

Coastal erosion is widespread and around 28% of the English and Welsh coastline experiences erosion rates of at least 10 cm/year [1]. Environmental change due to a changing climate will almost certainly lead to a significant increase in these erosion rates. For cliff coasts, much existing protection is expected to be abandoned [2]. Cliff-top communities will have to live with increased erosion risk, making it crucial to understand erosional processes, including how and when they might threaten cliff-top buildings and other infrastructure, to facilitate sustainable management of defences and other resources.

The stretch of coastline on the North Norfolk Coast has some of the highest rates of retreat in Europe. Across England, the Environment Agency estimates that roughly 2,700 homes and businesses will be vulnerable to coastal erosion in the next 50 years. Local authorities are trying to address this challenge. However, it is currently difficult to forecast where and when hazardous collapses will occur, rendering management and mitigation of the risk extremely challenging.

Traditional methods of subsurface monitoring are restricted in either time or space. Distributed Sensing is a new technology that utilises optical fibre. Our system includes a distributed acoustic sensor (DAS) to record high-frequency ground motion, distributed strain sensor (DSS) to record slower ground deformation, and distributed temperature sensor (DTS) to capture temperature profiles and variations. The interrogator sends a series of pulses into the fibre at up to 100 kHz and records the return of the naturally occurring scattered signal [3]. In doing this, the distributed sensor measures at all points along the fibre, with samples as closely spaced as 25 cm. In Summer of 2023, we deployed 2 km of fibre optic cable on the North Norfolk Coast to monitor coastal processes.

Using machine learning techniques, we plan on constructing a database of micro-earthquakes associated with subsurface cracking and rockfalls and create a local magnitude scale related to the volume of rock affected along with a real-time map to show regions that are more seismically active and therefore more likely to see movement. We will also use ambient noise from the nearby crashing waves to tomographically monitor the geomechanical properties of the subsurface as they evolve [4]. Strain and temperature monitoring give real-time information about deformation within the cliff structure.

[1] E. P. Evans et al., "Foresight flood and coastal defence project: scientific summary: volume I, future risks and their drivers" (London, 2004).
[2] Committee on Climate Change, "Managing the coast in a changing climate" (2018).
[3] N. J. Lindsey et al., Geophys. Res. Lett., doi:10.1002/2017GL075722 (2017)
[4] B. Fores, C. et al., Monitoring Saturation Changes with Ambient Seismic Noise and Gravimetry in a Karst Environment. Vadose Zo. J. 17, 170163 (2018).

How An Extraordinary Tsunamigenic Rockslide Into a Greenland Fjord Seismically Rang The Earth For 9 Days

Stephen P. Hicks[1], Kristian Svennevig[2], Thomas Forbriger[3], Thomas Lecocq[4], Rudolf Widmer-Schnidrig[5], Anne Mangeney[6], Clément Hibert[7], and the rest of the *SlideSurfSeis* working group (investigating landslide-tsunami-seismic interactions and surface - Solid Earth coupling in the Greenland fjords)

[1] *University College London, London, UK*
[2] *Geological Survey of Denmark and Greenland, Denmark*
[3] *Geophysical Institute, Karlsruhe Institute of Technology (KIT), Germany*
[4] *Seismology - Gravimetry, Royal Observatory of Belgium, Brussels, Belgium*
[5] *Institute of Geodesy, University of Stuttgart, Germany*
[6] *Université Paris Cité, Institut de physique du globe de Paris, CNRS, Paris F-75005, France*
[7] *Institut Terre et Environnement de Strasbourg (ITES), CNRS UMR 7063, Université de Strasbourg, Strasbourg, France*

Climate change is preconditioning large landslides in polar regions due to glacial thinning / debuttressing. Tsunamigenic landslides have occurred recently in Greenland, especially in the western fjords, but none are known from the east coast. It remains an open question as to what physical mechanisms might contribute to this regional difference, and whether observational biases play a role. On 16 September 2023, we observed an unprecedented up to 9-day-long global 10.88 mHz (92 s) monochromatic very-long period (VLP) seismic signal, originating from East Greenland.

Using a combination of on-the-ground photos, satellite imagery, and inversion of seismic waveforms, we demonstrate how this event started with a 25 M m^3 glacial thinning-induced rockslide on a mountain high above Dickson Fjord. The landslide then travelled down a steep gully glacier, entraining ice, and then impacting the water in the fjord, which triggered a 200 m high tsunami, as shown by after-event imagery and local tide gauge data. Local-lying cultural sites, which were destroyed by the tsunami, show that this tsunami went unprecedented for at least a century. Simulations show the tsunami stabilized into a 5 m high seiche, oscillating with a frequency of 12.45 mHz (80 s).

Emerging from the coda of the high-frequency landslide signal, we discovered a globally detectable VLP seismic signal lasting for many days. Analysis of the VLP surface waves' duration, amplitude, and polarisation show that a radiation pattern that can be modelled using a single-force source oriented perpendicular to the long-axis of Dickson Fjord, and together with the fundamental frequency of 10.88 mHz, we suggest that the seismic signal comes from a fjord-perpendicular seiche. However, the observed ultra-slow decay reflects an enigmatic component of the VLP surface waves that may relate to a currently unknown force-feedback mechanism.

Seismic tracking of the OSIRIS-REx re-entry

Benjamin Fernando[1], Constantinos Charalambous[2], Christelle Saliby[3], Eleanor K. Sansom[4], Carene Larmat[5], David Buttsworth[6], Daniel C. Hicks[7], Roy Johnson[8], Kevin Lewis[1], Meaghan McCleary[9], Giuseppe Petricca[10], Nick Schmerr[11], Fabian Zander[6]

[1]*Department of Earth and Planetary Sciences, Johns Hopkins University*; [2]*Department of Electrical and Electronic Engineering, Imperial College London*; [3]*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur*; [4]*School of Earth and Planetary Science, Curtin University*; [5]*Los Alamos National Laboratory*; [6]*Institute for Advanced Engineering and Space Sciences, University of Southern Queensland*; [7]*United States Department of Defence (KBR Consultant)*; [8]*NASA Ames Research Center*; [9]*NASA Langley Research Center*; [10]*Raspberry Shake, S.A., Panama*; [11]*Department of Geology, University of Maryland, College Park*

The atmospheric re-entry of the OSIRIS-REx spacecraft in September 2023 provided a rare opportunity to test and calibrate seismoacoustic techniques used to track and localise meteoroids entering the Earth's atmosphere. We will present some of the highlights of this deployment.

We undertook a field campaign near the point of the capsule's peak heating in northern Nevada, with the aim of recording both the hypersonic shockwave and its coupling into the ground. This made use of an array of conventional three-component geophones as well as a novel deployment of a fully off-grid, live-streaming Raspberry PiShake for educational purposes.

Both sets of sensors recorded the double-peaked 'N-wave' (a rapid overpressure followed by a rapid underpressure) characteristic of non-linear acoustic propagation. They also recorded the lower-frequency rumbling induced in the sub-surface by the airwave.

The co-location of a pressure sensor on the PiShake enabled us to constrain the air-to-ground coupling factor ($4x10^{-6}$ m/s/Pa), a key parameter which determines the amount of energy transmitted into the ground during atmospheric explosions and hence the far-field seismic shaking from meteoroid re-entries.

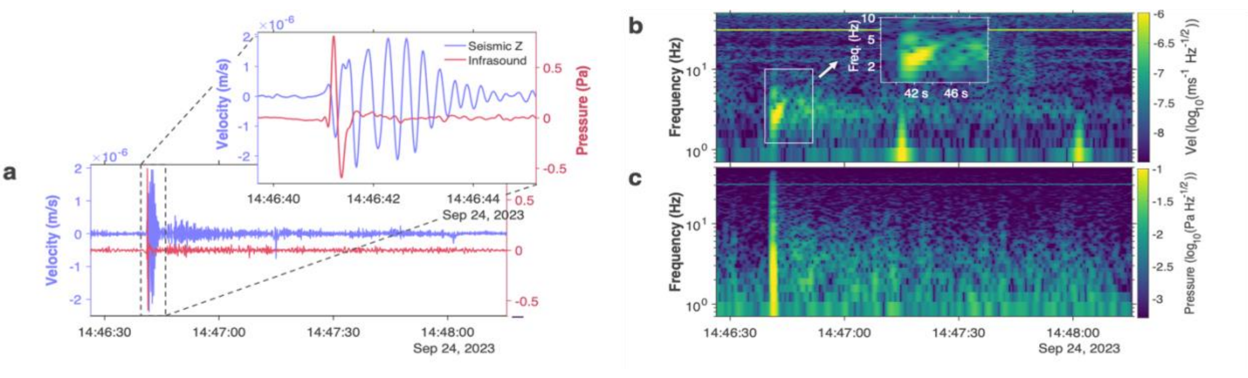


Figure 1: Seismic (blue trace, top spectrogram) and acoustic (red trace, bottom spectrogram) recorded by the Raspberry PiShake. The sonic boom is visible as a sharp pulse around 14:46:45, followed in the seismic data by a chirp signature.

A Description of the Continuous Seismic Dataset Recorded by InSight on Mars

Anna Horleston[1], E. Barrett[2], S. Ceylan[3], C. Charalambous[4], J.F. Clinton[3], N. Dahmen[3], S. Edgington[2], F. Euchner[3], D. Giardini[3], T. Kawamura[5], D. Kim[4], V. Lekic[6], P. Lognonné[5], T. Nebut[5], M. Panning[2], C. Pardo[5], W.T. Pike[4], L. Pou[2], N.C. Schmerr[6], S.C. Stähler[3], E. Stough[2], C. Yana[7], G. Zenhäusern[3]

[1] University of Bristol, Bristol, UK; [2]JPL, Pasadena, USA; [3]ETH Zurich, Zurich, Switzerland; [4]Imperial College London, London, UK; [5]Université Paris Cité, Institut de Physique de Globe de Paris, CNRS, Paris, France; [6]University of Maryland, Maryland, USA; [7]CNES, Toulouse, France

From November 2018 to December 2022, InSight was operational on the surface of Mars. Throughout the mission, SEIS (the Seismic Experiment for Interior Structure) (Lognonné et al., 2019) recorded a near-continuous dataset at sampling rates ranging from 2 sps to 100 sps. Over 1300 marsquakes were catalogued by the Marsquake Service (InSight Marsquake Service, 2023) and the entire dataset and marsquake catalogue are publicly available from various sources (InSight Mars SEIS Data Service, 2019; see below for further details).

However, throughout the mission, many operational procedures associated with the InSight spacecraft system were performed that impact the continuous seismic signal recorded. These include (but are not limited to) operations to bury the seismic tether, to clean dust from the solar panels and hammering with the heat-flow probe. All these activities required changes to the recording state of the seismometers and created unique non-seismic signals. To fully utilise the continuous dataset these signals need to be understood for what they are and not misinterpreted as signals from other sources on the planet (Ceylan et al., 2021; Kim et al., 2021).

In this presentation we give examples of these activities and the seismic signatures they generate. We will share a preliminary catalogue which, when finalised, will be published so that the continuous seismic dataset from Mars is fully accessible, without ambiguity, to future generations of researchers.

Lognonné P., et al., (2019), Space Sci Rev, 215(12), https://doi.org/10.1007/s11214-018-0574-6
InSight Marsquake Service (2023). Mars Seismic Catalogue, InSight Mission; V14 2023-04-1. ETHZ, IPGP, JPL, ICL, Univ. Bristol, https://doi.org/10.12686/a21
InSight Mars SEIS Data Service. (2019). SEIS raw data, InSight mission. IPGP, JPL, CNES, ETHZ, ICL, MPS, ISAE-Supaero, LPG, MFSC. https://doi.org/10.18715/SEIS.INSIGHT.XB_2016
Ceylan, S., et al., (2021), PEPI, 310, https://doi.org/10.1016/j.pepi.2020.106597
Kim, D., et al., (2021), Bulletin of the Seismological Society of America, 111(6), 2982-3002

Data availability: All raw waveform data is available through the InSight Mars SEIS Data Service at IPGP, IRIS-DMC and NASA PDS.

Recent Aftershock Sequences Reported to the ISC

Tom Garth[1], Ryan Gallacher[1], Burak Sakarya[1]

[1] *International Seismological Centre, Thatcham, UK*

The ISC reviews and finalises earthquake locations globally, producing the ISC-bulletin twenty-four months behind real time. This delay allows earthquake parametric data to be gathered from as many different sources as possible, before producing the final earthquake locations based on data from ~150 agencies in ~100 different countries

In the 14 months prior to this meeting, there have been several significant earthquakes impacting many thousands of lives. Here we consider the data that has been contributed to the ISC, and is available in the pre-review ISC-bulletin for three of these earthquake sequences. These include the Turkish, Moroccan, and Afghan seismic sequences of 2023. In this pre-reviewed part of the ISC-bulletin, the reported phase data have been grouped by event but have not yet been evaluated. Thus the earthquake has not yet been relocated by the ISC. The most reliable locations can come from either local agencies (such as the extremely well instrumented Turkey sequence) or agencies with a global coverage (such as the NEIC or IDC) depending on the remoteness of the region and density of instrumentation.

Secondly, we consider three earthquake sequences that occurred in the most recent complete year of the ISC bulletin. These are the Mw 8.1 Tonga earthquake, the South Sandwich Island sequence and the Mw 8.2 Alaskan earthquake. In each of these cases, the seismic phase data from each of the reporting agencies has been combined, and the main-shocks and recorded after-shocks (with magnitudes above ~3.5 mb) have been relocated and reviewed by the ISC analysis team.

To explore each of these sequences we use the newly developed ISC-MATLAB toolbox, a freely available toolbox that downloads and displays the richness of the ISC-bulletin in easily manipulated MATLAB data structures. We plot the spatial distribution of the earthquake sequences, compare the locations reported by different agencies, assess the completeness of the catalogues and plot the varying seismicity rates and aftershock decay rates of the sequences.

Discussion on the recent large earthquakes and tectonic environment in Menyuan, Qinghai, China

Anhui Sun[1], Chao Ren[1], Weitao Wang[2], Yuan Gao[1], Guofeng Zhao[3, 4]

[1] *Key Laboratory of Earthquake Prediction, Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, China*
[2] *Institute of Geophysics, China Earthquake Administration, Beijing, China*
[3] *China Earthquake Networks Center, Beijing, China*
[4] *National Earthquake Data Center, Beijing, China*

Two large earthquakes struck Menyuan County, Qinghai Province, China in the past decade, a reverse *M*s 6.4 event on 01/21/2016 and a strike-slip *M*s 6.9 event on 01/8/2022. Seismic phases of the 2016 earthquake sequence are automatically picked with the help of three deep learning models (BRNN, EQTransformer, PhaseNet) on waveform data from dense ChinArrayII, and the relocated catalog is obtained on the optimized local 1-D initial model after REAL phase association, which reduces the root-mean-square residual of travel time by up to 41%. Without foreshock activity in the twenty days before the mainshock, the 2016 *M*s 6.4 earthquake sequence is thus considered a mainshock-aftershock type. The aftershock distribution suggests the geometer of the seismogenic fault plane is relatively upright at shallow depths while southwest-dipping with about 40° in the deep and intersecting the Lenglongling fault (LF), the regional section of the left-lateral strike-slip Haiyuan fault, at a depth of 13-17 km. With a comprehensive analysis of geodesy and focal mechanisms, the seismogenic fault is inferred to be a blind secondary fault on the north of LF. The 2016 event's seismogenic fault plane geometry complexity, medium properties, and energy release of the intersection zones might hinder the 2022 strike-slip earthquake from rupturing eastward further along the LF.

Distributions of seismic parameters (*a*, *b*, *a*/*b*) of the LF zones around the focal area indicate low-*b*, low-*a*, and high-*a*/*b* values before the 2022 *M*s 6.9 earthquake, which may reflect the tectonic state of low seismicity by locking and accumulating stress for a large potential earthquake. Using the reviewed travel times of local earthquakes after 1980 recorded by regional permanent seismic stations and temporary seismic arrays, we presented tomographic images, including seismic velocity (*V*p and *V*s), Poisson's ratio (σ), and estimated structures of crack density (ε) and saturation rate (ξ), around the focal area with a horizontal resolution of 0.3°. The two earthquakes are located close to the high-velocity marginal zones where *V*p and *V*s change sharply, as well as σ and ξ indicating. Broader and larger surface ruptures on the north of the LF were revealed by field survey after the 2022 earthquake, where crack density was much higher than that on the south of the LF in the shallow crust, and caused infrastructural damage to the Lanxin high-speed railway and tunnel nearby.

*This work was partially supported by grants from the National Natural Science Foundation of China (41974050) and the Key Laboratory of Earthquake Forecasting (CEAIEF2023030104)

A Decade of Prospective Evaluations of One-Day Seismicity Forecasts for California

José A. Bayona[1], Marcus Herrmann[2], William H. Savran[3], Pablo Iturrieta[4], Fabio Silva[5], Warner Marzocchi[2], Philip J. Maechling[5] and Maximilian J. Werner[1]

[1] *University of Bristol, Bristol, UK,* [2] *University of Naples, Naples, Italy*
[3] *University of Nevada, Nevada, USA,* [4] *GFZ German Research Centre for Geosciences, Potsdam, Germany,* [5] *Statewide California Earthquake Center, California, USA*

Aftershock and seismicity forecasting systems are now operationalised by state agencies in the USA, New Zealand, Italy, and Switzerland. They provide valuable situational awareness to disaster responders, and decision makers at local and national levels. To ensure best available science is provided, the underlying forecast models require rigorous validation and benchmarking. The Collaboratory for the Study of Earthquake Predictability (CSEP) is a global community of researchers whose mission is to advance earthquake predictability research through the prospective evaluation of forecast models. One of CSEP's major multi-institutional achievements is the development and operation of 25 time-dependent forecasting models that include the types used by agencies today for real-time forecasting. Between 2007 and 2018, these models generated an unprecedented database of nearly 50,000 one-day seismicity forecasts for California, providing a unique opportunity to assess fundamental questions about what controls earthquake occurrences in a truly prospective manner (i.e., using data collected after forecasts were made), and to benchmark operational models. Here, we statistically evaluate these models against $M_w \geq 3.95$ earthquakes observed in California between August 1, 2007 to August 30, 2018. The dataset includes notable sequences, including the 2010 M_w 6.5 Ferndale, 2010 M_w 7.2 El Mayor-Cucapah, 2014 M_w 6.0 South Napa, and 2014 M_w 6.8 Mendocino sequences, as well as the Brawley M_w 5.0+ earthquake swarm of 2012. The results show that, on a daily basis, most models either overestimate or underestimate the number of target earthquakes during periods of low and high seismicity, respectively, but provide cumulative earthquake rates that are broadly consistent with the observations over more than a decade. Furthermore, different flavours of popular clustering models generate spatial forecasts that are daily and cumulatively consistent with the spatial distribution of most observed epicenters, endorsing the use of these models for short-term earthquake forecasting. These results provide valuable lessons for the next generation of forecast models and operational systems.

Dynamic Effects on the Slip Distribution of the 2023 Kahramanmaraş Earthquake

Nurcan Meral Özel[1], Yasemin Korkusuz Öztürk[1], Ali Özgün Konca[1], Jean-Paul Ampuero[2], Elif Oral[3]

[1]Boğaziçi University, Kandilli Observatory and Earthquake Research Institute, Department of Geophysics, 34684, Cengelkoy, Istanbul, Turkey
[2] Institut de Recherche pour le Développement Chaire d'Excellence - Université Côte d'Azur, France
[3]California Institute of Technology, Pasadena, California, 91125, USA

The 6th of February 2023 Mw7.8 Kahramanmaraş earthquake initiated on a splay fault called Narli and proceeded along the East Anatolian Fault (EAF) bilaterally. The earthquake ruptured a long seismic gap of the EAF and the Amanos Fault which connects to the Cyprus Arc offshore. A total of more than 300 km rupture caused more than 50.000 deaths, so it is the deadliest event of the last century in Turkey. Our initial dynamic rupture simulations and recent studies verify that the rupture speed is faster toward northeast and slower toward southwest, as an indicator of the dynamic triggering at the NNE and static trigger to the SSW. In addition, dynamic overshoot might be the reason for very large destruction at the NNE of the junction (Pazarcık) between the Narlı Fault (NF) and the EAF. Therefore, understanding of the effect of the Narlı Splay Fault seems crucial, as nobody expected that the EAF would have been triggered dynamically by a splay fault. Hence, the question 'could the slip distribution become less if the earthquake started on the EAF?' arises. Therefore, we aim to understand the dynamic effects on the slip distribution of the 6th of February 2023 Kahramanmaraş earthquake by performing dynamic earthquake rupture simulations for not only the already occurred Kahramanmaraş earthquake, but also for previously possible different rupture initiation conditions by starting the earthquake on different segments of the EAF, using the Finite Element code PyLith. We first, generate realistic dynamic rupture simulations and validate with near field observational data, and then we initiate the Kahramanmaraş earthquake at the southern end of the Pütürge segment, northern part of the Erkenek segment and at Pazarcık (near the north eastern part of the Narlı-EAF junction). Our initial results demonstrate that if the earthquake initiated on the Pazarcık segment of the EAF, the rupture might have not enter into the NF. Also, higher initial stress excess might have required for the EAF initiation of the rupture which might be the reason for the splay fault triggering. Consequently, we aim to understand super-shear and sub-shear rupture velocity behavior of the EAF and dynamics of the Kahramanmaras earthquakes and stress transfer to neighboring faults which are significant in order to comprehend the potential of possible destructive earthquakes in the East Anatolian region, and generation of damage, shaking and PGA distribution scenarios.

The ISC as a Long-term Facility Hosted by the UK for International Seismology

Dmitry A. Storchak, James Harris, Domenico Di Giacomo, and the ISC Team

International Seismological Centre (ISC), Thatcham, UK

The International Seismological Centre (ISC) is a long-term facility that the UK hosts for international Seismology. The main mission of the ISC is to produce the most complete and continuous Bulletin of instrumentally recorded seismicity on a global scale. We explain the recent ISC efforts in constraining the depths of moderate to large seismic events by taking the depth phase arrival time measurements from the waveforms freely available on-line and building Probabilistic Point Source Model solutions (ISC-PPSM). We also lay out the plans of extending the Bulletin with earthquake solutions and station readings in the early instrumental period (1904-1963). We discuss the future of the International Seismograph Station Registry (IR) and its place within the FDSN registry of seismic networks.

In addition, we briefly describe several specially designed data products that stemmed from the ISC Bulletin and allowed ISC to assist several different areas of research. These products include ISC-EHB dataset (1964-2021), ISC-GEM catalogue (1904-2019), IASPEI GT List (1959-2020), and the ISC Event Bibliography (1904-2024). We also describe several supplementary ISC services: the Seismological Dataset Repository, the Electronic Archive of Printed Station/Network Bulletins, and the International Seismological Contacts.

Evidence for mantle upwelling beneath Iceland from shear-wave splitting

Lovella B. Mojet de Koe[1], James O. S. Hammond[1]

[1] *Birkbeck, University of London, UK*

Iceland, situated on the mid-Atlantic ridge in the North Atlantic displays more volcanic activity than expected from conventional mid-ocean ridge processes. Despite extensive study the origin of the additional volcanism remains controversial. Seismic tomography studies have suggested a plume structure is the main cause, but the non-uniqueness of the results from this method have fuelled ongoing debates. Alternative explanations including the influence of shallow plate tectonic effects are also advanced. One aspect that fuels this debate are measurements of shear-wave splitting. These show strong horizontal alignment of olivine, linked with horizontal flow, providing limited evidence for vertical flow associated with a mantle upwelling.

In this study we revisit shear wave splitting across Iceland to investigate mantle flow. By analysing over one hundred earthquakes at station BORG, we show evidence for an absence of shear-wave splitting (null measurements) for a wide range of back azimuths. Other seismic stations in the region have recorded less data, meaning splitting results are limited, but most areas of Iceland are consistent with null measurements except the eastern rift zone, which shows fast directions perpendicular to the rift axis. It suggests that vertical flow beneath the island driven by mantle upwelling is a plausible mechanism to cause anisotropy, with some local deviations that require further study.

Waveform tomography of the upper mantle beneath the North Atlantic region using regional seafloor and global data

Janneke de Laat[1], Sergei Lebedev[1], Raffaele Bonadio[1], Maria Thsekhmistrenko[2], Nicolas Celli[3], and the The SEA-SEIS Team*
*The SEA-SEIS Team: Chris Bean, Mick Smyth, Clare Horan, Louise Collins, Martin Mallhoff, Arne Schwenk, Clara Gomez Garcia, Laura Berdi, David Stalling, Daniel Farrell, Ee Liang Chua, Chiara Civiero, David Craig.

[1] Department of Earth Sciences, University of Cambridge, Cambridge, UK
[2] Department of Earth Sciences, University College London, London, UK
[3] Dublin Institute for Advanced Studies, Dublin, Ireland

The Iceland hotspot and its interaction with the Mid-Atlantic Ridge have strongly influenced the structure and evolution of the North Atlantic region. The Iceland hotspot has been linked to the presence of the underlying Iceland plume, rising from the deep mantle below Iceland. Due to the sparsity of the seismic data coverage in the North Atlantic Ocean, the structure and dynamics of the underlying plume, as well as its influence on the surrounding North Atlantic region, remain a topic of debate. As part of the project SEA-SEIS (Structure, Evolution And Seismicity of the Irish offshore), a network of ocean bottom seismometers was deployed across a large part of the North Atlantic Ocean—from Ireland and Britain to near Iceland—in September, 2018. Over a period of 19 months, they recorded seismic data on the seafloor. 14 OBSs were retrieved in May 2020, of which 12 successfully recorded 19 months of seismic data. The data was thoroughly preprocessed, including the reduction of compliance and tilt noise on the vertical-component waveforms of teleseismic events. These waveforms were individually inverted for surface, S- and multiple S-waves using the Automated Multimode Inversion (AMI), extracting structural information on the lithosphere and underlying mantle.

Here, we combine this new seafloor seismic data with a massive global dataset of waveform fits for almost 1.5 million seismograms, with the coverage maximised in the hemisphere around the North Atlantic, and compute a new seismic waveform tomography model of the North Atlantic upper mantle: *NA24.* The tomography reveals both the S-wave velocity and the azimuthal anisotropy structure below the Iceland hotspot, the adjacent mid-ocean ridge, and the entire North Atlantic region at a new level of detail. It shows low seismic velocities below Iceland and the adjacent Reykjanes Ridge and Kolbeinsey Ridge down to ~260 km depth, below which they merge into one low-velocity body located west of Iceland at around 330 km depth. In the transition zone, the low-velocity body is present below eastern Greenland. This observation implies that the Iceland plume is located below eastern Greenland in the transition zone, moving eastward as it rises in the upper mantle. In the shallow upper mantle, a strong ridge-parallel azimuthal anisotropy structure is revealed along the full length of the Reykjanes Ridge. This implies a strong channelled horizontal flow from the Iceland plume towards the south below the ridge axis, while any sign of a radial outward flow of the plume is absent.

Poster # 3

Growing an ocean island: high-precision seismicity reveals a multi-faceted magma intrusion during the 2022 São Jorge, Azores seismic crisis

Stephen P. Hicks[1], Pablo J. Gonzalez[2], Rui Fernandes[3], Ana Ferreira[1], Ricardo Ramalho[4], Neil Mitchell[5], Anthony Lomax[6], Fernando Carrilho[7], Susana Custodio[8], Nuno Dias[8], João Fontiela[9], Virgilio Mendes[8], Arturo Montalvo Garcia, The Sao Jorge 2022 seismic crisis investigation team

[1] *University College London, London, UK*; [2] *Consejo Superior de Investigaciones Científicas, Instituto de Productos Naturales y Agrobiología (IPNA-CSIC), Spain*; [3]*University of Beira Interior, Portugal*; [4] *Cardiff University, Cardiff, UK*; [5] *University of Manchester, Manchester, UK*; [6] *ALomax Scientific, France*; [7] *Instituto Portugues do Mar e da Atmosfera, Portugal*; [8] *IDL - Instituto Dom Luiz, Universidade de Lisboa, Portugal*; [9] *Institute of Earth Sciences, University of Évora, Portugal*; [10] *Instituto de Investigação em Vulcanologia e Avaliação de Riscos, Azores, Portugal*

The central islands of the Azores Archipelago in the North Atlantic straddle a diffuse zone of dextral transtension between the African and Eurasian plates, providing an ideal setting for studying the interplay between tectonics and magmatism. São Jorge is a narrow island dominated by a westward progression of past basaltic fissure eruptions, where fault zones act as volcanic rifts. After two inland eruptions with significant socioeconomic impact in 1580 and 1808, the most recent probable eruption occurred offshore in 1964, after 2 years of seismic activity. In March 2022, a seismic crisis began on São Jorge (magnitudes up to M_L 3.8).

Our analyses of InSAR and GNSS data are consistent with a dike intrusion that stalled at 2 km depth below sea level. Here, we use seismicity to probe the space-time evolution of the intrusion. The unique geography and near-coastal position of seismicity yield inherently uncertain locations. To address this, we supplemented on-land stations with 6 ocean-bottom seismometers (OBSs) around the island later in the crisis. We use NLL-SSST-coherence, a location method ideal for changing station density, to exploit later OBS data to form robust source-specific station terms that allow precise relocation of the earlier part of the seismic sequence when coverage was sparser. In a final step, we combine waveform coherence and location uncertainty stacks to enhance hypocenter location precision to <100m.

Relocations of ~12,000 earthquakes show precursory, weak seismicity that started ~6 months before, starting offshore, south of São Jorge before migrating to shallower depth beneath the centre of the island. The main seismic crisis on 19 March 2022 started at shallower (<8 km) depth and moved north-westward and deeper before concentrating in the central zone at ~10 km depth. Intriguingly, nearly all the seismicity is located west of and deeper than the modelled dike intrusion, suggesting the intrusion was largely aseismic. Nevertheless, the agreement between the strike of the dike and the seismicity lineations suggests that the pre-existing Pico do Carvão Fault Zone guided melt ascent in the crust. However, moment tensors from polarity and waveform inversion show double-couple left-lateral strike-slip faulting along planes striking obliquely (by ~20°) to the dike and seismicity lineation, evidencing high fluid/melt pressures. The overall *b*-value is high (~2).

Interpreting both the seismicity and near-field GNSS displacements, we discuss the intrusion's evolution along the preexisting fault zone, particularly focussing on potential magmatic inflow and drainage beneath the main dike intrusion.

A detailed view of the magmatic plumbing system beneath Askja Volcano, Iceland, from ambient noise tomography

Joseph Fone[1], Tom Winder[2,1], Nicholas Rawlinson[1], Robert White[1], Bryndis Brandsdottir[2]

[1] *University of Cambridge, Cambridge, UK*
[2] *University of Iceland, Reykjavík, Iceland*

The volcano Askja in the Northern Volcanic Zone (NVZ) of Iceland last erupted in 1961 and has been steadily deflating from the 1970s until August 2021 when GPS and InSAR measurements confirmed that it had begun re-inflating. The NVZ has hosted a network of seismic stations operated by the University of Cambridge Volcano Seismology group since 2006. In the summer of 2023, this network has been augmented by 12 three component nodes that will record for ~2 months in addition to 10 broadband instruments that will be left for a year in or around the caldera of Askja with an average station spacing of ~1-2 km. The combination of the long-term recordings from the backbone network during deflation and the more recent short-term dense recordings will provide a unique dataset to examine how this switch from deflation to inflation may effect the seismic velocity structure beneath the volcano, thereby providing new insight into the underlying magmatic system. In this study, we present preliminary results from the application of ambient noise tomography to this dataset to try and image any changes in the magmatic system, which will involve stacking different periods of ambient noise cross-correlations to obtain two sets of dispersion curves that are sensitive to the subsurface velocity structure beneath Askja prior to and following the switch to reinflation in August 2021. This allows us to produce 3D models of shear wave velocity that can be compared to help elucidate changes in the plumbing system that occurred due to this switch. The dense deployments in the caldera have the advantage of allowing us to measure dispersion curves to high frequencies due to the short interstation distances, which is expected to yield more information on shallow subsurface structure where GPS and InSAR measurements appear to indicate that the source of the inflation is concentrated.

Poster # 5

Seismic methods for mapping hydrothermal fluids in volcanic systems

Sophie Shams[1], Mike Kendall[1], Jon Blundy[1], Thomas Hudson[1], Luca De Siena[2]

[1]*Department of Earth Sciences, University of Oxford, UK*
[2]*Department of Physics and Astronomy, University of Bologna, Italy*

Enhancing our ability to map hydrothermal fluids within volcanic systems via seismic methods would not only enhance our understanding of fluid migration within volcanoes; but would ultimately contribute to sourcing metals required for the net-zero transition. These metals can be found in hypersaline brines, which transport ore deep from the Earth's mantle to form as brine lenses near volcanoes. Current geophysical methods can identify large bodies of magma, however, smaller-scale methods to locate hydrothermal deposits are not yet developed. An attenuation tomography study using the Multi-Resolution seismic Attenuation Tomography (MuRAT) code has been used to analyse subsurface fluids around the Uturuncu Volcano, Bolivia. Uturuncu lies above the largest active magma body on Earth, the Altiplano-Puna Magma Body, and the migration of fluids from this body to the subsurface is incredibly important to understand. A seismic catalogue of 1356 events collated from the PLUTONS deployment is used to locate subsurface fluid structures. The attenuation tomography code uses a combination of peak-delay, direct wave attenuation and coda attenuation approaches to produce a 3D model via multiple inversions. Preliminary results indicate regions of high scattering and high absorption which could indicate a region of magma and/or hydrothermal brines at depths of up to 5 km. In addition, it is inferred that the Altiplano-Puna Magma Body lies at ~18-31 km depth, congruent with previous studies of the region. Future work requires an optimised model of both P and S waves from the MuRAT code. Seismic attenuation tomography studies could help to transform prospecting techniques to locate subsurface fluids enriched in the metals required for renewable technologies.

Anomalously thin lithosphere in the area of the Paleogene uplift and volcanism in Britain and Ireland: implications for the origin of the North Atlantic Igneous Province

Raffaele Bonadio[1], Sergei Lebedev[1,2], David Chew[3], Yihe Xu[1], Javier Fullea[4]

[1] *University of Cambridge, UK*
[2] *Dublin Institute for Advanced Studies, Ireland*
[3] *Trinity College Dublin, Ireland*
[4] *Universidad Complutense Madrid, Spain*

The extensive Paleocene magmatism of the British and Irish Tertiary Igneous Province (BITIP)—a part of the North Atlantic Igneous Province (NAIP)—was accompanied by significant uplift and exhumation, as evidenced by geothermochronological and other data. The enigmatic origins of the volcanism and uplift are debated. The Iceland Hotspot reached the North Atlantic at that time and could probably supply anomalously hot asthenospheric material to the volcanic areas of NAIP, but they were scattered over a broad area thousands of kilometres across. This motivates alternative, non-plume explanations.

Here, we obtain a map of the lithosphere-asthenosphere boundary (LAB) depth in the region using thermodynamic inversion of seismic surface-wave data. Love and Rayleigh phase velocity maps in broad period ranges were computed using optimal resolution tomography with direct model error estimation and supplied the data for the inversion.

Our results reveal a consistently thinner-than-average lithosphere beneath the Irish Sea and surroundings, encompassing northern Ireland and western Scotland and Wales. The Paleocene uplift, BITIP volcanism and crustal underplating are all located in the same regions, which are underlain, consistently, by anomalously thin lithosphere.

The previously unknown lithospheric anomalies we discover yield a new insight into how the Iceland Plume could cause volcanism scattered over the vast NAIP. Plume material is likely to have flowed into pre-existing areas of thin continental lithosphere, whose thickness was then reduced further by the erosion by the hot asthenosphere. The thinning of the lithosphere and the presence of hot asthenosphere beneath it can account for the uplift, volcanism and crustal underplating. The localisation of the plume material in scattered thin-lithosphere areas, such as the circum-Irish-Sea region, can explain the wide scatter of the volcanic fields of NAIP.

Surface wave mantle anisotropy tomography of the Azores-Madeira-Canaries region using UPFLOW data: initial results

Katrina Harris [1,2], Michael Witek[2], Ana M. G. Ferreira[1], Sung-Joon Chang[3], Miguel Miranda[4]

[1] *UCL, London, UK*
[2] *Los Alamos National Laboratory, Los Almos, USA*
[3] *Kangwon National University, Chuncheon 24341, South Korea*
[4] *IMPA, Lisbon, Portugal*

Upward mantle flow is key to understand global mantle geodynamics yet its imaging remains challenging due to potential associated low velocity contrasts and small lateral dimensions. In this study we use the UPFLOW ocean bottom seismometer (OBS) dataset to build images of radial anisotropy to constrain the patterns of mantle upwellings in the Azores-Madeira-Canary Islands region. We use the partitioned waveform inversion (PWI) method whereby non-linear waveform fitting of surface waves filtered between T~ 16 s and T~ 300 s is performed using a successive series of time-frequency windows in two stages. Firstly, the surface wave fundamental mode is extracted via phase match filtering and is used to obtain path average perturbations in shear radial anisotropy and isotropic shear wave velocity from a smoothed combination of the 1-D mantle model ak135 and the crustal model CRUST1.0. These perturbations establish a new initial model, which is subsequently used to estimate the path averaged radial anisotropy model that leads to the best fit between the observed trace and the synthetic waveform obtained by summing all overtones (up to n = 20). An iterative, regularized least squares inversion is used to invert for 3-D radially anisotropic mantle structure. Uncertainties are automatically quantified and used to interpret resolved seismic structures. Preliminary results are compared to previous tomographic models of the Atlantic region.

Crustal Structure and Mantle Deformation Across the Central African Plateau, Zambia: Evidence from Receiver Functions and Shear-Wave Splitting Analysis.

Rita Kounoudis[1], Christopher S. Ogden[2], Chaanza Chifwepa[3], Stewart Fishwick[2], John-Michael Kendall[1], Michael C. Daly[1]

[1] *University of Oxford, Oxford, UK*
[2] *University of Leicester, Leicester, UK*
[3] *Geological Survey Department, Ministry of Mines, Zambia*

The Central African Plateau comprises numerous Archean cratons sutured in Proterozoic to early Cambrian times — the Congo, Bangweulu and Kalahari cratons. In the heart of this region lies the copper-rich Neoproterozoic Katangan basin. Major deformation zones and complex craton margin fault zones reflect the region's tectonic history, which is further complicated by the Permo-Triassic and Pliocene development of the Southwestern Rift in southern Zambia. The extent to which surface deformation is mirrored to deeper crustal, and mantle lithospheric depths is uncertain but may also be key to ultimately understanding the Cu, Co and Ni mineralisation of the Katangan Basin. To investigate the tectonics and geodynamics that shaped the region, we utilise data from the Copper Basin Exploration Science (CuBES) seismic experiment — a NW-SE-trending, 750km-long profile of 35 broadband seismograph stations deployed across Zambia. Lithospheric deformation fabrics associated with past and present tectonic deformation are explored via an SKS splitting study of mantle seismic anisotropy. Crustal and lithospheric mantle seismic structure are also elucidated via receiver function and surface-wave analysis, the results of which are compared to bulk-crustal constraints derived from the modified H-K stacking method of Ogden et al., (2019). Results thus far reveal variable bulk crustal Vp/Vs ratios along the entire CuBES line, with crustal thickness contrasts across major tectonic boundaries, and clear evidence for short length-scale variations in upper-mantle seismic anisotropy.

Ogden C. S., I. D. Bastow, A. Gilligan, S. Rondenay, 2019. A reappraisal of the H–κ stacking technique: implications for global crustal structure, Geophysical Journal International, Volume 219, Issue 3, Pages 1491–1513, https://doi.org/10.1093/gji/ggz364

Shear-wave attenuation anisotropy: a fluid detection tool

Joseph P. R. Asplet[1], James Wookey[2], Mike Kendall[1], Mark Chapman[3]

[1]*University of Oxford, Oxford, UK*
[2] *University of Bristol, Bristol, UK*
[2] *University of Edinburgh, Edinburgh, UK*

Detecting fluids in aligned fractures have many important applications to improve our understanding of processes within the Earth. In the near-surface, understanding systems of fluid-filled fractures is important in various applications such as geothermal energy production, monitoring CO_2 storage site and exploring for metalliferous sub-volcanic brines (e.g., Blundy et al., 2021). In the mantle, melting is an important geodynamic process, exerting control over its composition and dynamic processes. Upper mantle melting weakens the lithosphere, facilitating rifting (Kendall et al., 2005) and other surface expressions of tectonic processes.

The presence of fluids has a significant effect on the overall elasticity of the medium. Models of aligned fluid-filled fractures, or inclusions with small aspect ratios, predict both velocity and attenuation anisotropy for shear-waves (e.g., Hudson, 1982, Chapman 2003). Forward modelling shows that attenuation anisotropy is highly sensitive to important fracture properties, such as fracture length and orientation. The rock physic models predict shear-wave attenuation anisotropy that is observable even for very low volume fractions of fluid (< 1%). Therefore, measurements of attenuation anisotropy offer an exciting new avenue to seismically detect fluids in the subsurface.

We show that attenuation anisotropy can be measured using shear-wave splitting, as the two separated shear-waves experience a different seismic quality factor as they propagate through the anisotropic medium. We use an instantaneous frequency matching method adapted from Mathenay and Nowack (1995). We explore the potential of this technique using synthetics and make measurements of attenuation anisotropy in SKS data collected at FURI, Ethiopia. Our synthetic experiments show the effect that attenuation anisotropy can have on shear-wave waveforms which has the potential to add systematic error to measurements of shear-wave splitting in certain scenarios. At FURI we measure attenuation anisotropy that requires poroelastic squirt flow of aligned melt inclusions oriented perpendicular to the Main Ethiopia Rift. These results highlight the potential for attenuation anisotropy as a tool to detect geofluids in the subsurface.

Seismic Methods for Detecting Geothermal Brines

Tesfahiwet Yemane[1], Mike Kendall[1], Jonathan Blundy[1], Thomas Hudson[1], Sacha Lapins[2], James Hammond[3]

[1] *Department of Earth Sciences, University of Oxford, Oxford, UK*
[2] *School of Earth Sciences, University of Bristol, Bristol, UK*
[3] *School of Natural Sciences, Birkbeck, University of London, London, UK*

Society's pursuit of net zero CO_2 emissions requires the utilization of subsurface reservoirs. Reservoirs beneath volcanic systems, offer a valuable source of geothermal energy through the injection and extraction of fluids from deep fracture systems. Moreover, recent studies have highlighted the potential of volcanic brines rich in critical minerals, such as lithium for batteries, to meet the growing demand for materials required in renewable energy technologies. The complex interaction of faults, fractures, and hydromagmatic systems within volcanoes gives rise to intricate stress patterns that exhibit spatial and temporal variability. My research aims to explore the application of seismic methods to gain insights into the stress state and its correlation with the migration of fluids from magmatic to hydrothermal systems, as well as the role of pre-existing faults and fractures. Additionally, it aims to utilize these seismic events to image geothermal systems, including potential brine reservoirs. As part of this study, deep learning models will be used for the detection of seismic events. Through the analysis of seismicity patterns, magnitudes, and source characteristics, areas of unrest and fluid migration can be identified. Furthermore, seismic events provide valuable information regarding the internal structure of volcanoes. Seismic velocities and their ratios offer insights into the presence of fluids and more deformable regions at depth, while directional variations in velocity, known as seismic anisotropy, enable the identification of fluid and fracture networks, providing valuable information on stress orientation. The seismic data for this research include datasets from a rift environment and their subsequent analysis will contribute to the understanding of geothermal systems and potential brine reservoirs. During the meeting, I will present the preliminary results, offering an initial glimpse into the findings.

3D surface-wave tomography with full resolution and robust model uncertainties using finite-frequency and SOLA-Backus-Gilbert inversion

Franck Latallerie[1], Christophe Zaroli[2], Sophie Lambotte[2], Alessia Maggi[2], Andrew Walker[1], Paula Koelemeijer[1]

[1] *University of Oxford, Oxford, UK*

[2] *University of Strasbourg, Strasbourg, France*

Surface-wave tomography models provide essential information about the structure of the upper mantle, especially in poorly sampled oceanic regions, where they help to understand geological features such as volcanic archipelagos, trenches or mid-oceanic ridges. Beyond their exploratory character, surface-wave tomography models can also be compared with other types of geophysical observations, or used to assess geodynamic predictions. However, surface-wave data are noisy and sparse, resulting in noisy tomographic models with complex resolution. Although challenging, accounting for the full 3D resolution and uncertainties of surface-wave tomography models is critical to make robust interpretations.

We propose a new tomographic scheme to build Vsv models in the upper mantle accompanied by 3D resolution and uncertainties information. Specifically, we measure vertical component Rayleigh-wave dispersion data and estimate data uncertainties including measurement and theoretical errors from a multi-taper technique and synthetic tests. To linearly relate data to the three-dimensional Vsv structure of the upper mantle we use a finite-frequency forward theory based on Born approximation. Finally, we use the SOLA (Backus-Gilbert-style) method to control and produce 3D model resolution and uncertainties together with the Vsv model.

We use this new tomographic scheme, firstly in synthetic tests to show the advantages of the method and subsequently on real data to obtain a new Vsv model of the Pacific upper mantle. In future, this tomography model together with its full 3D resolution and uncertainties may be used to quantitatively assess geodynamic simulations of mantle flow.

Towards constraining mantle flow through global radial anisotropy tomography with uncertainty quantification

William Sturgeon[1], Ana M.G. Ferreira[1]

[1] *University College London, UK*

In order to improve our understanding of mantle flow, we require a joint collaboration between all fields of Earth Sciences. Seismic tomography provides key information on the current state of the mantle and therefore can constrain geodynamic models. We image radial anisotropy in the Earth's mantle, which can be used as a proxy for mantle flow. Past studies have imaged radial anisotropy throughout the mantle and are starting to show some consistent features. However, the interpretation of existing models is hindered by the lack of uncertainties provided from the chosen inversion method. Uncertainties are also essential for multidisciplinary interpretations of geodynamic models. We aim to constrain global 3D geodynamic TERRA models of the mantle through high-resolution imaging of radial anisotropy with full uncertainty quantification.

In order to address this, we build a new global radially anisotropic model of the Earth's upper mantle which consists of two main stages. Firstly, we build global phase and group velocity maps using ~47 million Rayleigh and Love wave measurements and compute their associated uncertainties. This data set includes fundamental mode and up to 5th overtone measurements in the period in the period range of 16-375s. After careful data analysis and synthetic testing, we build 310 2D frequency-dependent maps, expanded up to spherical harmonic degree 60. We observe many relevant small-scale structures, such as e.g. the curvature of the Tibetan plateau at T~40s (fundamental mode). As expected, uncertainties are higher in regions of poor data coverage (e.g., southern hemisphere and oceans).

We then invert for 1D profiles of radial anisotropy using a Monte Carlo based inversion method, the Neighbourhood Algorithm (NA). The NA has been widely used for seismic inversion due to its relative simplicity and the ensemble of models can be used for an assessment of uncertainty. The interpolation of 1D profiles will lead to a new global 3D model of mantle radial anisotropy.

The Case of the Missing Diamonds: New global and regional thermo-compositional models of cratonic lithosphere

Felix Davison[1], Sergei Lebedev[1], Yihe Xu[1], Javier Fullea[2], and Sally Gibson[1]

[1] *University of Cambridge, Cambridge, UK*
[2] *Universidad Complutense de Madrid, Madrid, Spain*

Cratons are the ancient cores of continents, stable over billions of years. The thermochemical properties of their lithosphere are debated, with open questions regarding their composition, the presence of volatiles and the degree of metasomatism. Cratonic mantle lithosphere is thought to be dominated by depleted mantle peridotites, primarily harzburgites, which can provide chemical buoyancy and long-term stability. Some recently proposed models, however, featured substantially metasomatised shallow mantle lithosphere, modified by the addition of volatiles (Eeken et al. 2018) or significant proportions of eclogite and diamond within the lithosphere (Garber et al. 2018). The broad range of the compositions proposed highlights the persisting uncertainty over what cratons are made of.

Arguments for cratonic lithosphere complexity often follow from difficulties in fitting seismic velocity profiles (taken from tomographic models beneath cratons) using peridotitic compositions. Some Rayleigh-wave inversions have also found difficulty fitting phase velocity dispersion curves without significant metasomatism, including models with up to 5wt% CO_2.

Recently developed methods of petrological inversion can relate geophysical and geological observations directly to the thermochemical structure of the lithosphere and asthenosphere. We invert Rayleigh and Love surface wave phase velocities, elevation and heat flow data for temperature and composition at depth (Fullea et al. 2021) beneath a selection of cratons around the world and a global craton average. We aimed to assemble the most accurate surface-wave dispersion data, with broad period ranges and small errors. The models fit the data within 0.1-0.2% of the phase-velocity values. This accuracy is important to extract the information on the radial structure of the lithosphere from the dispersion data.

Our models use a harzburgitic (depleted peridotite) composition with major oxide weight percentages taken from prior global modelling (Fullea et al. 2021) and produce very close fits for the Rayleigh and Love dispersion curves averaged over cratons globally, as well as the Rayleigh and Love dispersion data measured in cratons around the world. The cratonic lithospheric thicknesses range from 180 km (Guyana) to almost 300 km (Congo). We demonstrate that these new models can also be produced by careful regularisation of purely seismic inversions of the same data.

We find that the features present in several major tomographic models of cratonic lithosphere, consistent with exotic compositions, are not required by the data, and can be produced as an artifact through norm damping. Ubiquitous presence of substantial quantities of eclogite and diamond in cratonic lithosphere is not required by the data.

Bounding filtered Earth models through Backus-Gilbert SOLA inferences

Adrian Mag[1], Paula Koelemijer[1], Christophe Zaroli[2]

[1] *University of Oxford, Oxford, UK*
[2] *Universite de Strasbourg, Strasbourg, UK*

Mathematical inversions are at the core of seismic tomography, leading to many of the models that exist today. However, inversions require a system to be invertible, which is generally not the case. In addition, seismic data coverage is poor, giving rise to non-uniqueness, which is normally addressed through regularizations. These regularizations place strong constraints on the model space based on prior information that is assumed to be true. The danger is that strong constraints that lack a physical basis may lead to systematically inaccurate models. Since we are not always interested in the model, but rather in some properties of the model, we could instead bypass the inversion of the system and aim to directly constrain the desired model property. This philosophy falls under the domain of mathematical inferences.

This contribution will present an application of deterministic linear inferences through a generalized version of the Backus-Gilbert SOLA method. The BG SOLA method has mostly been applied to estimate local averages of the Earth using seismic data, without the need for regularization. We will show how to expand the method to extract information on a wider range of observables, such as first and higher-order gradients. The only required prior information will be a norm bound on the model space, which is less restrictive than typical regularizations. We will use a parameter-free model space to avoid any implicit regularization from projecting the models on a finite subspace. The data space will be probabilistic to incorporate measurement errors and the data will be allowed to depend on multiple model parameters (v_s, v_p, ρ, etc) at once. The obtained properties will be accompanied by uncertainty quantification and resolution information. As an application, we will consider normal mode data and their ability to constrain average values, derivatives, and discontinuities in the Earth, and compare these to results obtained using regularized inversion methods.

Mantle Structure and Dynamics beneath NE China revealed by seismic imaging

Cunrui Han[1], James Hammond[1,2], Weiqian Yu[1,3]

[1]*Birkbeck, University of London, UK*
[2] *University College London, UK*
[3] *Institute of Geology, China Earthquake Administration, Beijing*

The westward subduction of the Pacific plate has led to widespread intraplate volcanism in NE China. In particular, the Changbaishan volcano (also known as Paektu/Baekdu in Korean), located on the border between China and the Democratic People's Republic of Korea (DPRK), has attracted much attention for its historical eruptions and recent unrest. However, the origin and mantle dynamics of these intraplate volcanoes in NE China have always been debated. In this study, we applied surface-wave eikonal tomography technique to measure the phase and group velocities of Rayleigh and Love waves, and invert for the shear wave velocity and radial anisotropy at different depths. The effect of overtones on the measurement of Love wave velocity is considered to ensure the accuracy of the inversion. Our seismic images reveal a remarkable low-velocity body in the uppermost mantle beneath the Changbaishan that exhibits large lateral differences from the peripheral blocks. Such feature is reconfirmed by the vertical cross-section of shear wave velocity obtained by receiver function adjoint tomography across the region. Moreover, the variation of radial anisotropy with depth then helps to constrain the magma alignments and clarify the boundary between the lithosphere and the asthenosphere (LAB) beneath the Changbaishan. Combined with our previously measured anisotropy parameters from three shear-wave phases (Local S, SKS and Pms), these new seismic images provide important clues to the dynamics of magma migration and storage in the region.

MOD3LTHERM – MODelling the 3D thermal and Lithospheric Structure of geoTHERMal regions

Emma L. Chambers[1], Javier Fullea[2], James Grannell[1], Patrick Smith[1], David Craig[1], Martin Möllhoff[1], Duygu Kiyan[1], Rob Raine[3], Sarah Blake[4] & Chris J. Bean[1]

[1] *Dublin Institute for Advanced Studies, Dublin, Ireland*
[2] *Universidad Complutense de Madrid, Madrid, Spain*
[3]*Geological Survey of Northern Ireland, British Geological Survey, Belfast, UK*
[4]*Geological Survey Ireland, Dublin, Ireland*

Whilst high-enthalpy geothermal systems (e.g. Krafla, Iceland) are already delivering significantly to decarbonisation, low-enthalpy regions with limited thermal property data (e.g. Ireland) still require significant risk reduction to understand the heat resource, before they can be fully exploited. The workflows for determining 'heat in place' in both scenarios are different in detail, but have some common characteristics.

In the MOD3LTHERM project we build on recent pilot work in geophysical estimation of deep sub-surface temperatures in a low enthalpy environment (Ireland, Chambers et al. 2023). Two core weaknesses in the previous approach were limited lithological constraints and no independent control on the results. We are developing a new joint geophysical-petrological-lithological inversion scheme by adapting two separate modelling codes, WINTERC and LitMod3D (Fullea et al., 2021 & 2009), and modify to full 3D models for all available datasets. This new workflow will relate newly available velocity and geophysical information to rock type and then predicts the geophysical-petrological-lithological response for different lithologies under variable thermal conditions and determines the geothermal gradients.

We will test the methodology for two case studies. 1. An all-Ireland low-enthalpy environment building on previous work of the DIG project by adding a newly acquired seismic dataset from Northern Ireland (GRANNUS DOI: 10.7914/c39w-b345) with new thermal conductivity measurements of Irish rocks. 2. A local (km) scale high-enthalpy study with known geothermal resources (Krafla), to test the methodology and integrate melt into the methodology. The main applications are to quantify Ireland's deep geothermal potential, and use the new workflows as a resource to investigate geothermal regions, worldwide.

Here we present the aims and initial results from the project including the new seismic data from the north of Ireland.

The MOD3LTHERM and GRANNUS projects are funded under the SFI-IRC Pathway Programme 22/PATHS/10676 and the Sustainable Energy Authority of Ireland under the SEAI Research and Development & Demonstration Funding Programme 2022, Grant number 2022/RDD/782.

Poster # 17

Using tomographic signatures to constrain lowermost mantle compositional and thermodynamic parameters

Justin Leung[1], Andrew M. Walker[1], Paula Koelemeijer[1], Federica Restelli[2], D. Rhodri Davies[3]

[1] *Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN, UK*
[2] *Department of Earth Sciences, Queen's Building, Royal Holloway University of London, Egham Hill, Egham, TW20 0EX, UK*
[3] *Research School of Earth Sciences, The Australian National University, Canberra, Australia*

Signatures of seismic tomographic models in the lowermost mantle feature increased ratios of shear-wave (V_S) velocity to compressional wave velocity (V_P) anomalies and negative correlations between shear-wave and bulk-sound velocity (V_C) anomalies. These signatures can be explained by either chemical heterogeneity in large low velocity provinces or the presence of the post-perovskite phase. Robustly constraining the origin of these seismic signals provides further insight on the geodynamics of the lowermost mantle, such as the stability of the core-mantle thermal boundary layer and the influence of subducting plates on lowermost mantle structure and composition.

Few studies have examined the combination of both chemical heterogeneity and phase transitions to explain lowermost mantle seismic signatures. Here, we use LEMA (Walker et al., 2018; AGU abstract) —a numerical toolkit developed for lower mantle modelling— to investigate the tomographic signatures expected from a range of scenarios for the stability of post-perovskite within models of different lowermost mantle temperatures and compositions. We calculate synthetic V_S and V_P fields from existing temperature, compositional fields as predicted by geodynamic simulations and recent thermodynamic data, which are then filtered to account for the limited resolution of seismic tomography. We reject synthetic velocity models that do not fit within the uncertainties of the seismic tomography model by Restelli et al. (2023; EPSL). This allows for a quantitative comparison between predicted and observed seismic tomography to obtain optimal compositional and thermodynamic parameters for the lowermost mantle.

4D Image Domain Wavefield Tomography for Cost-effective CCS Monitoring with Sparse Data Acquisition

Afsaneh Mohammadzaheri[1], Sjoerd de Ridder[1], Alexander Calvert[2], Mikael Lüthje[2]

[1] School of Earth and Environment, University of Leeds
[2] Danish Offshore Technology Centre, Technical University of Denmark

Seismic time-lapse (4D) imaging is recognized as a crucial approach for monitoring CO2 reservoirs. However, conventional implementation of this technology typically necessitates extensive data collection to generate high-resolution images. Given the prolonged monitoring periods, which may extend over several decades post-injection, the development of cost-effective imaging techniques becomes imperative.

This becomes increasingly crucial, given that Carbon Capture and Storage technology is likely to play a pivotal role in our transition to a low-carbon future, making the need for cost-effective technologies even more essential.

Leveraging historical knowledge of subsurface structures gained through years of exploration can potentially alleviate the data density requirements for 4D imaging. In this context, we conducted a CCS monitoring study at the Tyra gas field, a prospective CO2 repository in the Danish sector of the North Sea. We utilized field data and seismic images to construct a representative model and simulate scenarios involving CCS and potential leakage. Informed by our understanding of subsurface structures, we tailored seismic deployment scenarios to accommodate sparse data acquisition effectively.

Our approach involved pre-stack Image Domain Wavefield Tomography (IDWT), which utilizes short-offset data commonly employed in CCS monitoring to primarily capture kinematic changes rather than amplitude changes. The presence of CO2 in the reservoir and the impact of reservoir pressure on the overburden stress-state could alter the seismic velocity structure, leading to apparent depth (or time) shifts during data migration. IDWT mitigates these shifts between baseline and monitor migrations by optimizing the monitor velocity model. Unlike post-stack methods, pre-stack IDWT utilizes individual shot gathers to compute migration images, proving advantageous for sparse data acquisition and ensuring reliable measurement of shifts between monitor and baseline.

We have developed an open-access Fortran software package for time-lapse (4D) seismic imaging utilizing the IDWT technique. The pre-stack IDWT feature enhances its effectiveness as a tool for seismic monitoring in scenarios with sparse data acquisition, proving advantageous for CCS projects. The software is fast and easy to use. It incorporates a hybrid MPI and OpenMP parallelization approach to expedite computationally intensive tasks.

Poster # 19

Intricate 3-D post-subduction crust and upper mantle structure of northern Borneo (Sabah), SE Asia, from migrated teleseismic receiver functions

Cornwell, D.G.[1], Gilligan, A.[1], Rawlinson, N.[2], Tongkul, F.[3], Pilia, S.[2,4], Bacon, C. A.[2,5], Greenfield, T.[2], Baker, S.[1], Wehner, D.[2], Linang, H. T.[2], Fone, J.[1]

[1] *University School of Geosciences, University of Aberdeen, Aberdeen, UK*
[2] *Department of Earth Sciences, Bullard Laboratories, University of Cambridge, Cambridge, UK*
[3] *Faculty of Science and Natural Resources, Universiti Malaysia Sabah, Kota Kinabalu, Malaysia*
[4] *College of Petroleum Engineering and Geosciences, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia*
[5] *Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA*

Understanding the structure and tectonic evolution of Borneo is a key piece of the regional tectonic puzzle of southeast Asia and a unique location to study subduction termination. Sabah in northern Borneo has been formed and/or modified by at least two subduction events, with the Proto-South China Sea subducting southwards during the Late Eocene to Early Miocene (~40-20 Ma), probably terminated by continental collision, and northwest-directed Celebes Sea subduction (~17-9 Ma), both taking place while Borneo rotated ~45° anti-clockwise. Sulu Sea extension and seafloor spreading to the north during the Early-Late Miocene (~17-5 Ma) may also have modified the lithosphere beneath Sabah, and significant Neogene (23-5 Ma) uplift and subsidence events preceded rapid Late Miocene-Early Pliocene exhumation and the emplacement (at 7.8-7.2 Ma) of a granite pluton that formed the 4095 m high Mt. Kinabalu. We utilise the recently acquired nBOSS seismological array dataset to calculate multi-frequency receiver functions and constrain a strikingly complex crust and upper mantle structure beneath Sabah using common conversion point migration. A regional 3D velocity model derived from joint inversion of receiver function and surface waves with a two-plane wave tomography model is utilised to constrain mid-crustal and Moho discontinuities at 22-25 and 30-40 km, respectively, beneath most of Sabah. However, lateral variations in subsurface discontinuities delineate major boundaries in the crust and upper mantle, with clear evidence for a complex structure in northernmost Sabah that dips east in the upper crust to south at Moho depths, accompanied by a high velocity and density crust beneath surface ophiolite outcrops. We show clear evidence for an uppermost mantle slab remnant beneath onshore Sabah in the form of a WSW-dipping 75-100 km wide discontinuity at 45-55 km depth, which is probably linked to a later subduction event than the Proto-South China Sea and may have detached and/or delaminated. These new images present Sabah in unprecedented detail and show that: i) Mt. Kinabalu sits astride a major crustal lineament; ii) Proto-South China Sea subduction and collision varied in location and complexity onshore Sabah; and iii) crust and upper mantle structure changes likely contributed to differing uplift and subsidence rates across Sabah.

Estimating stress drops on crustal faults using inter-station phase coherence: comparison with the Ridgecrest stress drop validation study

I Made Kris Adi Astra[1], Jessica C. Hawthorne[1]

[1]*Department of Earth Science, University of Oxford, United Kingdom*

Earthquake stress drop estimation is a fundamental of many physical parameters in earthquake seismology. Yet the direct measurement of stress drop at depth is practically difficult; the estimations of stress drop resulting inconsistent values caused by different methods and dataset. Thus, over the past few years, researchers have used several approaches to estimate stress drops of a similar set of earthquakes: those in the 2019 Ridgecrest, CA sequence. Here we examine these events with a different method: inter-station phase coherence. The most common approaches to estimating stress drops examine the amount of energy at various frequencies.

Here, we instead estimate stress drops by examining the differences in the apparent source time functions (ASTFs) observed at a range of stations. We note that signals coming from different locations within the rupture area have different arrival time at the observing stations. The arrival time differences are proportional to the largest distance between generated seismic waves, which is proportional to the rupture diameter *D*. Thus longer-period inter-station differences can arise when the rupture diameter is larger, and we identify the periods where inter-station differences exist in order to identify the rupture diameter.

We examine the 2019 Ridgecrest earthquake sequence occurred between 4 July 2019 to 17 July 2019. The catalogue consists of well-relocated 55 earthquake in the range magnitude of 2.01 to 4.52. The hypocentre varies at the depth between 2 km to 10 km. By using a rather different approach to examine these well-studied earthquakes, we aim to validate the methodology and to learn more about which simplified models of earthquakes are plausible matches to the data.

ISC magnitudes based on automatic waveform measurements

Natalia Poiata[1], Domenico Di Giacomo[1]

[1] *International Seismological Centre, Thatcham, UK*

Magnitude is a fundamental source parameter facilitating the characterization of the size and amount of energy released by earthquakes and other types of seismic events. It provides an important input to a wide variety of seismological studies, from seismic hazard to statistical analysis of seismicity and nuclear explosion discrimination. Seismic network operators and observatories routinely estimate body- and surface-wave magnitudes, reporting the results that are often inconsistent due to the peculiarities of the waveform processing setup. With the scope to address this issue, the International Seismological Centre (ISC; www.isc.ac.uk) developed a procedure for routine estimation of the standard body- and surface-wave magnitudes using the global waveform data. We take the advantage of the comprehensive event-related information at ISC and the increasing amount of openly available waveform data to provide an automatic and reproducible estimation of standard magnitudes following the guidelines of the International Association of Seismology and Physics of the Earth's Interior (IASPEI) Working Group on Magnitude Measurements.

In this presentation we describe the details of the procedure and examine the results of the magnitude estimations for over 69,000 earthquakes (M > 4.0) reported in the ISC Bulletin for 2016-2020. We also present the workflow for the integration of the magnitude estimation procedure into the routine ISC Bulletin analysis at the level of the data-year 2022 (24 month behind the real-time) and discuss the preliminary impact of including such measurements.

Moment magnitudes from synthetic Green's functions

T. Dahm[1,2], D. Kühn[3,1], S. Cesca[1], S. Heimann[2], M. Isken[1]

[1] *GFZ German Research Centre for Geosciences, Germany,*
[2] *University of Potsdam, Germany,*
[3]*NORSAR, Germany,*

We suggest an approach employing full waveforms from synthetic seismograms to estimate moment magnitudes and their uncertainties from peak amplitudes. The new method does not change the established routines of traditional procedures for magnitude determination, while simultaneously overcoming some of the limitations as e.g., saturation, scattering and source complexity. Attenuation functions are derived on-the-fly for each source-station combination from synthetic seismograms using Green's function databases representing various velocity models if required. In a bootstrap approach, source depth, geometry, dynamic and kinematic parameters are randomly selected within a realistic range. After calibration with observations, attenuation functions can be extrapolated to distances, depths, regions and magnitudes for which no observations exist. Additionally, individual frequency filters and sensor types can be mixed independently of any definition of traditional magnitude scales. Uncertainties of attenuation functions are estimated for every source-station geometry including the sensor characteristics and its potential frequency saturation. Therefore, realistic uncertainties of mean magnitudes can be estimated even in case of only few measurements.

We provide software tools to compute attenuation curves either from pre-existing Green‘s function stores for standard velocity models, or alternatively from a user-defined velocity model. A cookbook example is provided of how the approach can potentially be integrated into the routine processing of a seismological survey as a complementary magnitude scale for local earthquakes. As a first test, we demonstrate the approach employing an example from a mining area in Germany and a gas field in the Netherlands. Further, we have combined the presented approach with a novel full-waveform detector considering machine learning-based phase picks of P- and S-phases.

Poster # 23

Moment Tensor Inversion of Microseismicity at the United Downs Deep Geothermal Project, Cornwall.

Callum Harrison[1], Brian Baptie[1], Richard Luckett[1]

[1] *British Geological Survey, Edinburgh, UK*

The United Downs Deep Geothermal Power (UDDGP) project aims to produce power and heat from the hot granite rocks beneath Cornwall, with production and injections wells, drilled to depths of 5275 m and 2393 m, targeting the Porthtowan Fault Zone. Flow testing between September 2020 and July 2021 resulted in microseismicity that was recorded by a dense network of broadband seismometers deployed as part of the NERC funded GWatt project. We find that the microseismicity is strongly aligned with the strike of the Porthtowan Fault with a total of 80 events with magnitudes of between 0 and 2 ML. We obtained full moment tensors for the largest events using waveform inversion to better understand the relationship between the microseismicity, the injected fluids and the natural fracture systems in the granite. Model uncertainties are derived using a Bayesian bootstrap-based probabilistic joint inversion scheme.

Synthetic tests were conducted using the range of realistic velocity models to explore the sensitivity of the results to the uncertainty in velocity. These models were based on both local geology and borehole information. These tests demonstrate that isotropic, CLVD and DC components may can be recovered accurately by considering the wider model space. Inversion results display minor isotropic components, deviatoric components are oriented approximately parallel to the strike of the Porthtowan Fault and show significant extension along the fault plane. Our results suggest that fluid injection has resulted in reactivation of faults and fractures in the Porthtowan Fault Zone with normal faulting and extension facilitated by reduced compressive stress within the injected region. Opening of tensile fractures appears to be relatively small components of the overall mechanism.

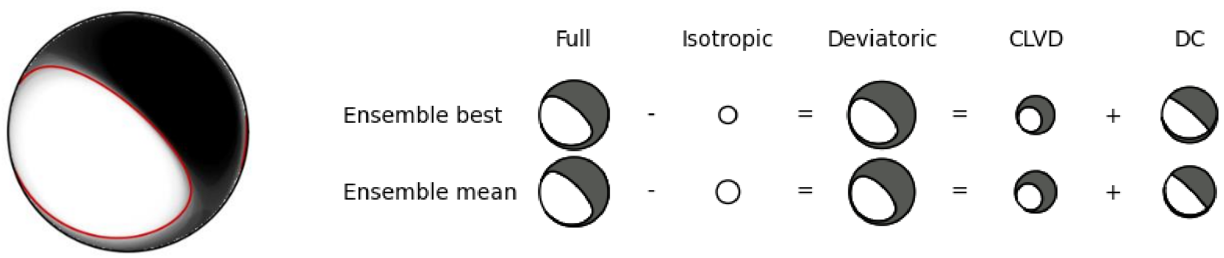


Fig. 1 (Left) Stacked ensemble of solutions for the largest event with the best fitting nodal lines in red. (Right) decomposition of mean and best fitting solutions.

Influence of modelling decisions on foreshock rates in Southern California

Russell Azad Khan[1], Maximilian Werner[1], Juliet Biggs[1], Ake Fagereng[2]

[1] *University of Bristol, UK*
[2] *Cardiff University, UK*

Some large earthquakes (mainshocks) are preceded by anomalously high seismicity rates ("foreshocks"). Foreshocks are important because a better understanding of how and why they occur when they do could lead to better forecasting. Recent studies, all using different foreshock definitions, estimated that between 19 and 72% of mainshocks in Southern California had foreshocks. The problem is that these studies varied more than just the foreshock definition. The studies also varied the earthquake catalogue, the mainshock selection method, completeness magnitudes, and more. Due to the range of modelling permutations used by each study, one cannot determine the influence of individual modelling choices on the foreshock rates (the proportion of mainshocks with foreshocks). We seek to: (1) quantify the individual impact of different modelling choices on foreshock rates; and (2) justify a preferred method for calculating foreshock rates in Southern California. To do this we run all method permutations for 3 earthquake catalogues for Southern California, 2 mainshock selection methods, and 4 foreshock definitions. We find that mainshock selection methods can just as strongly influence foreshock rates as foreshock definitions (~15% variation in rate). We also find that methods defining foreshocks as anomalously high seismicity rates do not agree with methods defining foreshocks as any detected magnitude 3+ earthquakes within 20 days of a mainshock. For our preferred foreshock definition, we find that the high resolution QTM catalogue only has a 2-6% higher foreshock rate than the lower resolution (monitoring room) SCSN (Southern California Seismic Network) catalogue, which is significantly lower than the previously reported 20% increase in foreshock rate. This suggests that high resolution catalogues may just contain more earthquakes, rather than proportionally more foreshocks that might improve predictability.

Poster # 25

Onshore background seismicity monitoring for CO_2 storage operations using array methods

Tom Kettlety[1], Joseph Asplet[1], Thomas Hudson[1], J. Michael Kendall[1]

[1] *University of Oxford, Oxford, UK*

To meet emissions reductions targets by mid-century, dozens of geological CO_2 storage projects are currently being developed in the offshore UK. Many of these are in the Southern North Sea, targeting the large saline aquifers in the Bunter sandstone. To design and operate these projects effectively, seismicity rates need to be accurately characterised. Measuring seismicity can provide insights into the stress state in the region, fault density and faulting style, as well as fracturing in the overburden. Understanding background seismicity is also key to discriminating and determining the risk of induced seismicity that could result from injection. To significantly improve the detection of smaller events in the Southern North Sea region, we have deployed a dense array of three-component broadband sensors on the North York Moors (Figure 1). Using this data and beamforming methods, we have more accurately characterised earthquake rates in the Southern North Sea, informing the development of CO_2 storage operations in the region. Telemetry systems have also been deployed, showing that onshore dense arrays could act as a cost-effective, real time, continuous monitoring method of the reservoir response to CO_2 injection.

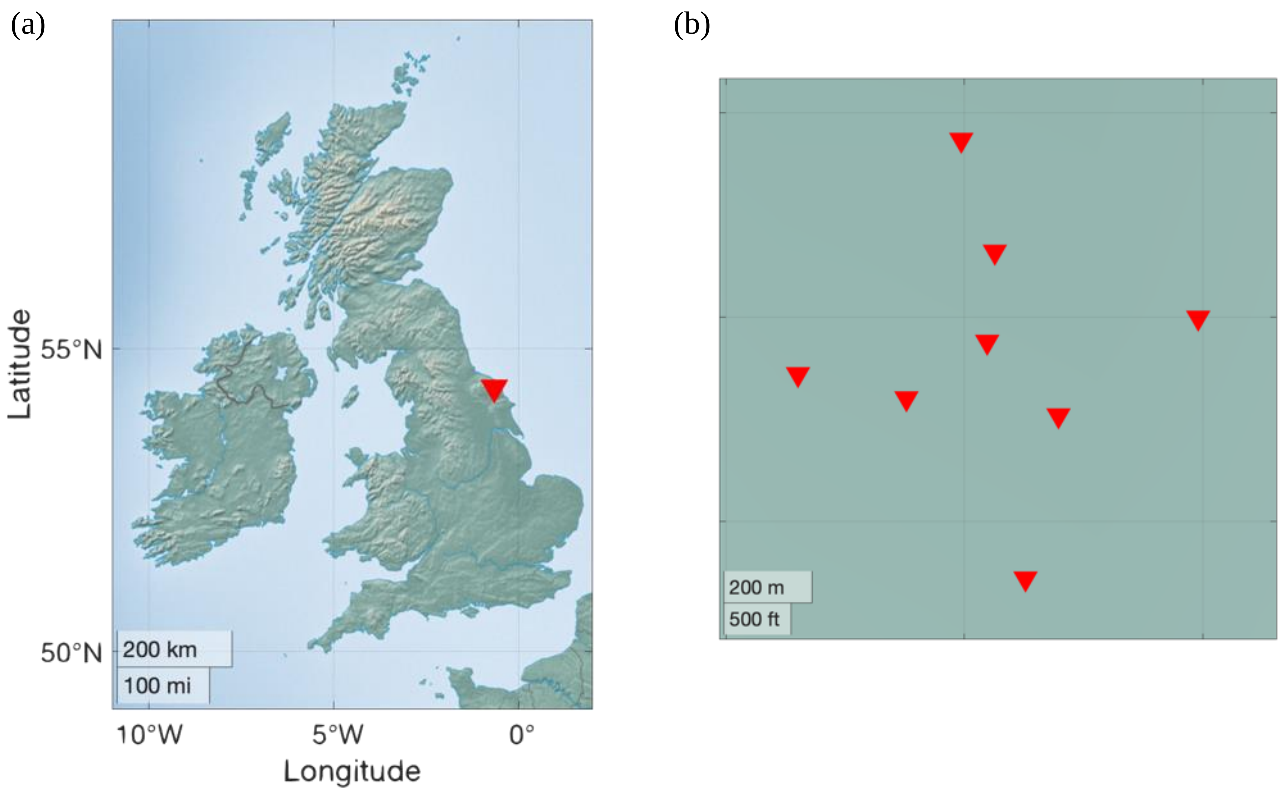


Figure 1: Location and array design of the North York Moors array (NYMAR). (a) shows the location of the array in the British Isles, and (b) shows the geometry of the 8-element array, each made up of 3-componet broadband seismometers.

Poster # 26

Insights from local earthquake analysis at the Hikurangi margin, Aotearoa New Zealand, with a high-density seismic network

Amy Woodward[1], Ian Bastow[1], Rebecca Bell[1], Bill Fry[2], Katie Jacobs[2], Victoria Lane[3], Thomas Merry[4], Laurene Ville[1], Luke Broadley[1]

[1]*Imperial College London, London, UK*
[2]*GNS Science, Wellington, Aotearoa New Zealand*
[3]*SEIS-UK, University of Leicester, Leicester, UK*
[4]*University of Cambridge, Cambridge, UK*

The Hikurangi subduction zone, where the Pacific Plate subducts beneath the Australian Plate, hosts a wide spectrum of slip modes, including earthquakes, tremor, and slow slip events (SSEs). This region experiences repeating SSEs, often accompanied by an increase in rates of seismicity. There are numerous mud volcanoes near Gisborne, which are regarded as the surface expression of fluid migration associated with SSEs. However, understanding of the architecture of the margin and which faults are active remains poor. We present a new catalogue of local earthquakes for the Gisborne and Raukūmara Peninsula region. We combine a very dense network of 49 land-based seismometers, deployed from December 2017 to October 2018, with 13 permanent broadband and short-period instruments and 8 ocean-bottom seismometers. We detect earthquakes with a combination of manual and automated phase picking, using EQTransformer and the GaMMA phase associator. We present initial shear-wave splitting results from local earthquakes, and discuss the links between fast directions, delay times, and fluid distributions.

Poster # 27

Downhole Insights into Induced and Tectonic Seismicity from Cornwall, UK

Antony Butcher[1], Joanna Holmgren[1,2], Sébastien Soulas[3], German Rodriguez[1], Will Wills[3]

[1] *School of Earth Sciences, University of Bristol, UK*
[2] *NORSAR, Kjeller, Norway*
[3] *Avalon Sciences Ltd, Somerton, Somerset, UK*

The geothermal resources of Cornwall, UK, have the potential of providing both power and heat through exploiting natural fracture zones. Understanding and monitoring induced seismicity resulting from stress state changes is important in successfully realizing deep geothermal energy. We explore the potential of repurposing legacy boreholes to provide cost-effective seismic monitoring using 3-component borehole geophones deployed at 1 km depth in a former geothermal well at Rosemanowes Quarry, Penryn, Cornwall. In particular, we examine two swarms of seismicity within 5-6 miles from the borehole: an induced sequence in August 2020 originating from the United Downs Deep Geothermal Power (UDDGP) project, and a tectonic sequence in February 2023 originating near Constantine, Cornwall.

We find that the lower noise and attenuation levels experienced by the borehole geophone array increased the detectability rates for both the induced UDDGP and the tectonic Constantine sequences. More than three times the number of seismic events were identified when compared with those reported in the BGS catalogue, which are based on surface measurements alone. This demonstrates the important contribution that deployments in legacy boreholes can make to the overall catalogue. Furthermore, we obtain very similar magnitude distributions for both sequences which are consistent with the BGS catalogued values, albeit with a much lower magnitude limit. This large dataset provides greater insight into induced and natural seismicity of the area, which is of significant value to future deep geothermal projects.

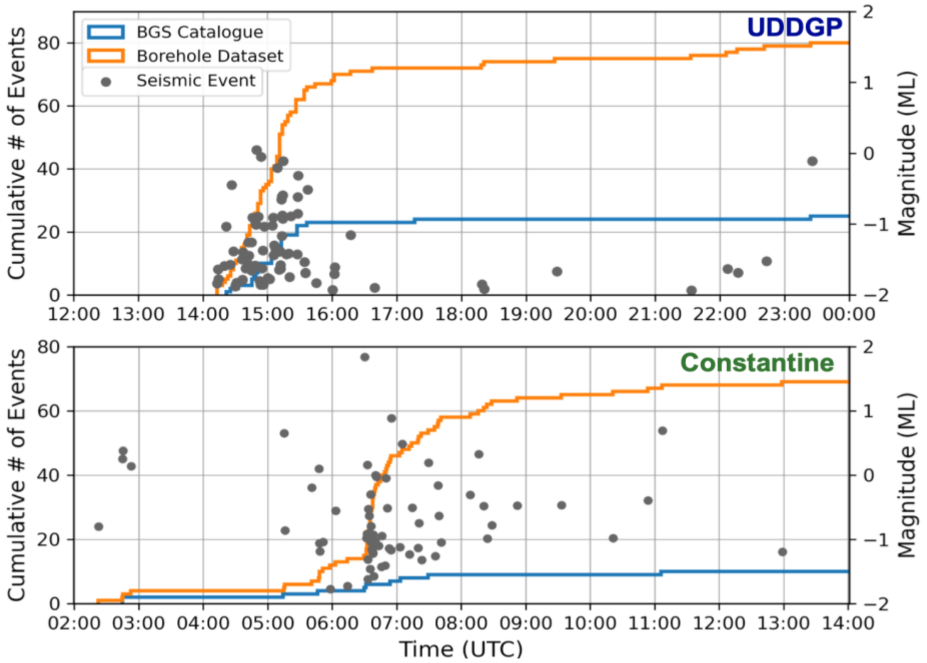


Figure: *Cumulative number and magnitude (ML) of events from UDDGP (top) and Constantine (bottom) sequences recorded on the 02/08/2020 and 24/02/2023 respectively. Significantly more events have been detected in the borehole dataset than identified using the surface networks.*

Poster # 28

The BELSHAKE database of earthquake ground motion in Belgium

Kris Vanneste[1], Mahsa Onvani[1,2]

[1] *Royal Observatory of Belgium (ROB), Brussels, Belgium*
[2] *UCLouvain, Louvain-La-Neuve, Belgium*

The BELSHAKE database is a new ground-motion database compiled in the frame of a project funded by the Belgian Science Policy Office. It currently contains ~7500 digital records from 333 natural and induced earthquakes with ML≥2 in and around Belgium since 1985 (Figure 1), and recorded with broadband, accelerometric, and short-period sensors operated by the ROB. For each event, the relevant source parameters and station metadata are extracted from the ROB database, event-station metadata are computed and waveforms capturing the complete event are downloaded. The waveform library is structured in folders corresponding to each event, containing one file for each station. All metadata, along with the ground-motion parameters, are collected in a relational database. All records have been visually inspected to identify, and if possible correct, problematic waveforms. We use a combination of two windowing procedures, the Goulet method to isolate P, S and coda windows, and the more sophisticated Perron method for the noise window. The latter was further refined to reduce the number of rejected records. We implemented a semi-automated workflow to process the waveform data in a uniform way, based on other databases like PEER NGA-East, RESIF, ITACA, and ESM. In this workflow, the corner frequencies of the bandpass filter are evaluated from plots of Fourier amplitude spectra and signal-to-noise ratio, and manually adjusted if necessary. Finally, a suite of intensity measures was computed from the processed data that were evaluated as reliable. These are computed for different windows (P, S, signal, full) and different components, including the geometric mean and orientation-independent (RotD) percentiles. Fitting a generic ground-motion model using mixed-effects regression shows that between-event, station-to-station and unexplained residuals are well behaved and have a similar range as the French RESIF database. Analysis of the evolution of unexplained residuals for each station allowed identifying additional issues (instrument response problems, stations that were moved to a different location or into boreholes), which were addressed. The BELSHAKE database is now ready for a first release. It will contribute to existing databases by increasing the coverage of low-seismicity zones. We will use it to re-evaluate local and moment magnitudes, as well as to evaluate existing ground-motion models and to develop or calibrate a ground-motion model specifically for Belgium.

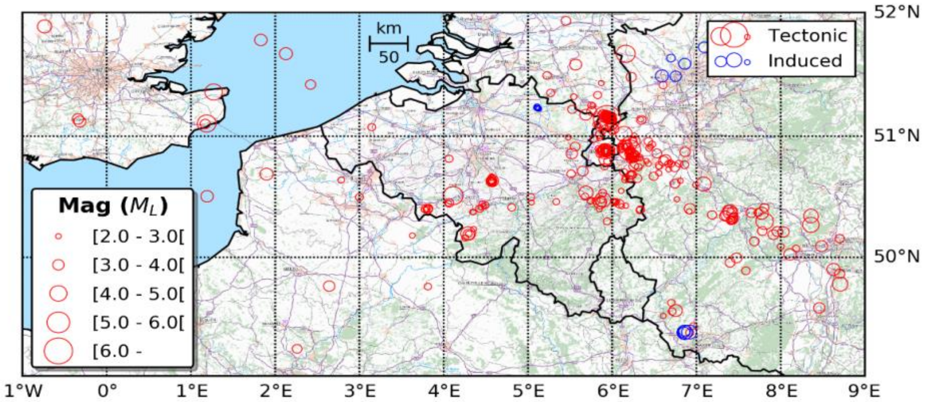


Figure 1 – Map of seismic events included in the BELSHAKE database

Irish National Seismic Network: An Enhanced Detection Capability

J. R. Grannell[1], M. Möllhoff[1], D. Craig[1], P. Smith[1], L. Collins[1], C. Horan[1], P. Grange[1], C. Hogg[1] and C.J. Bean[1]

[1] *Geophysics Section, School of Cosmic Physics, Dublin Institute for Advanced Studies, Dublin, Ireland*

The Irish National Seismic Network (INSN) is operated by the Dublin Institute for Advanced Studies (DIAS) and co-funded by the Geological Survey of Ireland (GSI). The goal of the INSN is to monitor seismic activity in Ireland and its near-offshore. Beginning with two stations in 1980, the INSN expanded its complement to six real-time seismic stations by 2014. From November 2018, the INSN received funding from the GSI with the aim of doubling the number of operational seismic stations to twelve.

We describe the methods used in planning the site locations for the new seismic stations, details on the deployment of test stations and the subsequent data quality analysis. In particular, we make use of power-spectral density plots, real-time seismic amplitude method (RSAM) and signal-to-noise ratios of local events. We also describe the layout of the structures housing the new seismic stations, which include traditional bunker-style designs, as well as shallow borehole and underground cave installations. We present results of the fully-operational new stations highlighting the enhanced detection capability of the network, as well as some examples of recent observations.

Possible warning times and expected ground motions for large magnitude earthquakes in Northeast India.

Brian Baptie[1], Richard Luckett[1]

[1] *British Geological Survey, Edinburgh, United Kingdom*

Earthquake early warning uses rapid detection to provide alerts of potentially damaging ground motions. This, in theory, could allow people to protect themselves or automated systems to trigger, thereby reducing loss of lives and damage. We use a simple method based on P- and S-wave velocities to model possible warning times for different distributions of monitoring stations for four different earthquake scenarios in NE India, where paleoseismological studies indicate that there is a seismic gap, where faults are assumed to be locked and large earthquakes can be expected in future. We combine this with population densities to estimate the number of people who would receive no or little warning. The scenarios are chosen based on both the historical seismicity of the region and the seismic gap on the Himalayan Frontal Thrust between Nepal and Northeast India. We also model ground motions using realistic fault ruptures for each scenario and compare these with calculated warning times. Finally, we examine the effect of the finite fault rupture process on both the warning time and the expected ground shaking.

Warning times calculated for the existing seismic network for a repeat of the 1897 Shillong earthquake, which had a magnitude of at least 8.5, suggest that approximately 8 million people would be in the blind zone, the area around the earthquake epicentre that cannot be alerted before strong shaking starts. This includes the cities of Guwahati and Shillong, at 74 km and 79 km from the epicentre, with populations of approximately 1,326,000 and 488,000 people. Both cities would be subjected to very strong ground shaking with estimated ground accelerations of 0.2 g or greater. A further 6 million would receive less than 10 seconds warning. Increasing the density of seismic monitoring stations reduces the radius of the blind zone and improves warning times. However, even for a dense network of 250 stations with an average spacing of 30-40 km, approximately 0.95 million people would still be in the blind zone for 1897 Shillong earthquake scenario, and 4 million people would receive less than 10 seconds warning. A further 7 million, including residents of Shillong and Guwahati, would receive between 10 and 20 seconds of warning.

Inversion of the internal and external current of the geomagnetic solar quiet daily field and study of its disturbance characteristics before strong earthquake

Yingyan Wu[1], Junsong Sun[2], Yalu Wang[1]

[1] *Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, 100036, China*
[2] *Jiangsu Earthquake Agency, Nanjing 210004, Jiangsu, China*

During earthquake preparation, processes of high temperature, high pressure and movement of the earth's crust are often accompanied in the seismogenic region, which may be closely related to the change of the electrical structure of the underground medium. The variation of the geomagnetic field at different periods may bring information of the electrical structure of the medium at different depths underground to the surface and be recorded. It is found that the Z component of the geomagnetic field has obvious large-scale regional anomaly disturbance before the strong earthquake. Geomagnetic solar quiet daily field is a normal diurnal variation around the world. It mainly originates from the ionospheric dynamo current driven by the tidal wind field in the middle and upper atmosphere and its underground induced current. Some results of previous studies suggest that the "abnormal" variation of ionospheric equivalent current before earthquake may be related to strong earthquake activity. In this paper, based on the global geomagnetic field observation data, the internal and external source fields of geomagnetic solar daily field are separated by the spherical harmonic analysis method, and the inversion algorithm of the internal and external source current of geomagnetic solar daily field is established according to the electromagnetic induction theory. The external field corresponds to the ionospheric equivalent current (representing the ionospheric dynamo current), and the internal field corresponds to the underground induced current. Focusing strong earthquake events and abnormal disturbance of geomagnetic field Z component, the spatial distribution and evolution characteristics of internal and external source currents before earthquakes are studied. The results show that the abnormal disturbance of Z component of geomagnetic field before earthquake may be closely related to the intensity and spatial structure evolution of external current in geomagnetic diurnal field.

Interseismic strain accumulation associated with the 2021 Mw 7.4 Maduo Earthquake from InSAR

Conor Rutland[1], Lidong Bie[1], Jessica Johnson[1]
[1] *University of East Anglia (UEA), Norwich, UK*

Seismic hazard assessment is challenging in remote regions such as the Tibetan Plateau where there are few available data due to a lack of near-field seismic stations. Interferometric synthetic aperture radar (InSAR) provides a remote method by which ground deformation can be monitored and crustal parameters constrained without the need for additional seismic data. By further processing InSAR results, we can map and monitor strain accumulation across faults, and use this information to assess local seismic hazard.

The Mw 7.4 Maduo earthquake occurred on 21st March 2021 within the Bayan Har Block in the Eastern Tibetan Plateau, and is the largest to occur within the block since the Mw 7.7 Dari earthquake in 1947. The seismogenic Jiangcuo fault is a secondary fault which runs roughly parallel to the large Kunlun Fault around 100 km to the North. Large earthquakes are commonplace on the Kunlun fault, where strain accumulates rapidly, but less so on slow moving faults in the region, such as Jiangcuo. This study aims to use InSAR to observe the temporal evolution of strain accumulation on the Jiangcuo fault in the interseismic period preceding the Maduo earthquake. Time-series processing will determine whether there is any observable change in strain rate before the earthquake and assess the utility of these results for seismic hazard assessment.

InSAR time-series processing is carried out on individual Sentinel-1 frames using LiCSBAS, an open-source processing package developed by Morishita et al. (2020) which integrates products from the COMET LiCSAR database. Frames are stitched and velocities are decomposed into Northward, Eastward and vertical components, using methods devised by Ou et al. (2022). These results are initially used to map strain rate for the ~5 year period preceding the Maduo earthquake. A strain time series is then produced by mapping strain using a moving window to observe the temporal evolution of the strain rate in small increments in the lead up to the fault rupture.

We compare our ~5 year interseismic velocities and strain rates across the Jiangcuo fault with those from Fang et al. (2022). Preliminary results of a strain accumulation timeseries display the temporal evolution of strain across the fault prior to the earthquake, which we use to assess uniformity of strain accumulation over time.

Fang, J., et al. (2022). *J. Geophys. Res. Solid Earth*, 127, e2022JB024268. https:// doi.org/10.1029/2022JB024268
Morishita, Y., et al. (2020). *Remote Sens.*, 12(3), 5–8. https://doi.org/10.3390/rs12030424
Ou, Q., et al. (2022). *J. Geophys. Res. Solid Earth*, 127, e2022JB024176. https://doi.org/10.1029/2022JB024176

Extensional failure at the tip of a weak slab under slab pull - the 2023 M_w 6.4 Zacualpa, Guatemala, earthquake

Timothy J. Craig[1]

[1] *COMET, School of Earth and Environment, University of Leeds, Leeds, UK*

The 2023 M_w 6.4 Zacualpa earthquake is the deepest recorded major earthquake to have occurred in the Cocos slab beneath Central America, at a depth of ~255 km. Here, we use teleseismic waveform inversion to refine the source parameters of both the Zacualpa earthquake, and the only other event at comparable depths (the 1997 M_w 5.5 Santa Catarina Mita earthquake), confirming both their exceptional depth within the downgoing slab, and their consistent down-dip extensional mechanism. That the Cocos slab remains capable of hosting major intraslab earthquakes, with mechanisms consistent with down-dip extension, near, or at, the tip of the contiguous slab, suggests that the slab itself is weak, such that the minimal stresses derived from supporting the short section of slab down-dip from this earthquake are still sufficient to lead to brittle failure of the slab.

Lithospheric Seismic Structure of the Anatolian Plate and its Implications for Plateau Uplift: Evidence from Joint Inversion of Receiver Functions and Surface Waves

Pengzhe Zhou[1], Ian D. Bastow[1], Rita Kounoudis[1,2], Christopher S. Ogden[1,3], Yanghua Wang[1]

[1]*Imperial College London, London, UK*
[2]*University of Oxford, Oxford, UK*
[3]*AWE Blacknest, Brimpton, UK*

A consensus has emerged in recent years that areas of high topography (>1km) on the Anatolian Plate are the result of buoyant mantle support, not the isostatic response of crustal shortening. Missing in this story, however, is the relative importance of asthenospheric versus mantle lithospheric contributions to the uplift. This is largely because of a lack of knowledge of plate thickness across the region. We calculate 46,584 teleseismic receiver functions across 576 seismograph stations from numerous seismic networks operating on the Anatolian Plate between 1994-2020. We then jointly inverted these receiver functions with Rayleigh wave group-velocity dispersion curves from Kaviani et al. (2020) to obtain 1D shear velocity profiles below the stations to a depth of 150km. Moho depths and lithosphere thicknesses are inferred via velocity proxies; conversion to temperature provides an additional strategy to constrain plate thickness. We also present Moho depths derived from a modified H-κ stacking approach (Ogden et al., 2019), which yields 582 independent measures of crustal thickness across the Anatolian Plate (Ogden & Bastow, 2022). Moho depth increases from ∼23km below western Anatolia to ∼45km below the Eastern Anatolian Plateau. The entire Anatolian Plate has a relatively thin lithospheric mantle, consistent with the numerous lithospheric dripping and/or delamination hypotheses that have been postulated for the region. Low velocities below the Anatolian lithosphere likely represent a warm, potentially melt-rich asthenosphere, which is supporting the plate's high topography.

Kaviani, A., et al (2020), Crustal and uppermost mantle shear wave velocity structure beneath the middle east from surface wave tomography, Geophys. J. Int., 221(2), 1349–1365.
Ogden, C., & I. Bastow (2022), The crustal structure of the Anatolian Plate from receiver functions and implications for the uplift of the Central and Eastern Anatolian Plateaus, Geophys. J. Int., 229(2), doi:10.1093/gji/ggab513.
Ogden, C., et al (2019), A Reappraisal of the H-κ Stacking Technique: Implications for Global Crustal Structure, Geophys. J. Int., 219(3), doi:10.1093/gji/ggz364.

Stress field Variation in the Western part of Africa-Eurasia plate boundary from the Azores to Tunisian Atlas derived from focal mechanisms inversion

Farida Ousadou[1], Abdelhakim Ayadi[1], Mourad Bezzeghoud[2]

[1] CRAAG, BP63 Bouzaréah, 16340, Algiers, Algeria
[2] Centro de Geofísica de Évora and Physics Department. University of Évora, Portugal

The Africa-Eurasia plate boundary displays, a transition from simple deformation at the Azores triple junction in the Atlantic Ocean to a complex and deformed zone in Atlas Mountains in Morocco, Algeria and Tunisia. Most of the studies concluded to a convergence movement between African and Eurasian plates in the NW-SE direction with anticlockwise rotation. Moreover, the general stress regime shows extension in the Azores region, right-lateral strike slip motion in the Gibraltar strait and Alboran Sea, and compression in the Maghreb Area. The aim of this work is to present a new insight of the tectonic stress regime along the plate boundary zone from the Azores triple junction to Tunisia, derived from the orientation of principal stress axes (Shmax and Shmin) and the shape factor calculated from focal mechanism inversion. Unlike the previous work (Ousadou et al., 2014) we inverted just the main shocks without the aftershock focal mechanism sequences that occurred in the study area. The present stress field obtained in this study switches progressively from extensional in the Mid Atlantic and Terceira Ridges-Azores Islands, to strike slip from Gloria Fault to the southern Spain crossing Gorringe Bank and Golf of Cadiz, progresses towards the Rif crossing the Alboran Sea. It turns to compressional regime in the western Algeria, and to Strike in the eastern and southern Tunisia, excluding the northern of Tunisia where the present stress is a reverse behavior. At the end, we present a kinematic model based on focal mechanism inversion compared with previous published models.

Probabilistic merging of seismic velocity datasets using deep learning: a case study on synthetic data

Sam A. Scivier[1], Tarje Nissen-Meyer[1, 2], Paula Koelemeijer[1]

[1] *University of Oxford, Oxford, UK*
[2] *University of Exeter, Exeter, UK*

Earthquakes can have devastating impacts on society. Reliable and actionable seismic hazard assessment is key to effective earthquake preparation and response, with the aim to save lives and limit damage. Estimates of seismic velocity (datasets) are typically used as input in earthquake simulations for modelling peak ground shaking for hazard assessment. However, in well-studied regions, there are often many spatially overlapping seismic velocity datasets at different scales and resolutions, stemming from different inversion, imaging, and direct extraction methods, as well as complementary observations (geology, magnetotellurics). Consequently, the choice of which seismic velocity dataset to use in a simulation is often arbitrary. Nevertheless, it has a significant impact on the simulation results as different velocity datasets have structures on different length scales with different amplitudes. In addition, limited methods exist for merging spatially overlapping velocity datasets and representing the collective multi-scale information they contain.

We propose a new method for merging seismic velocity datasets using a family of probabilistic deep learning models called neural processes (NPs). NPs are trained to learn a distribution of continuous functions that fit input (context) data. They have the ability to merge an arbitrary number of datasets at any resolution, predict an output at arbitrary coordinates, represent conflicting information between input datasets, and extend to 2D and 3D datasets. As a proof-of-concept experiment, we merge two synthetic seismic velocity datasets using conventional methods and NPs, comparing the results and highlighting the advantages of merging datasets in a probabilistic way. We then simulate ground shaking and perform seismic hazard assessments. We show that, given the same velocity dataset input, differences in the merged datasets have amplified impacts on measurements of peak ground shaking amplitudes. We thus demonstrate that having a flexible, robust, and probabilistic method for merging seismic velocity datasets is important for well-informed earthquake simulations and hazard assessment.

Building Data-Driven Short-Term Earthquake Forecasting Workflows Using Deep Neural Networks

Foteini Dervisi[1,2], Margarita Segou[1], Brian Baptie[1], Ian Main[2] and Andrew Curtis[2]

[1] *British Geological Survey, Edinburgh, UK*
[2] *The University of Edinburgh, Edinburgh, UK*

The emergence of deep learning-based earthquake monitoring workflows has increased the volume of earthquake catalogue data. These catalogues are now being generated by deep learning algorithms in significantly less time than those created by human analysts and contain at least ten times more earthquakes. The use of these extensive catalogues has been proven to enhance the predictive accuracy of statistical and physics-based forecasts of future earthquake rate in space and time. Coupled with the growing availability of computational power, which has enabled recent advancements in machine learning, the combination of rich datasets and machine learning workflows appears to be a promising approach for discovering new insights about earthquake sequences and identifying links between past and future patterns of earthquakes using earthquake catalogues as input. Here, our focus is on employing various deep learning architectures to generate high-quality earthquake forecasts. We hypothesise that deep neural networks can uncover underlying patterns within comprehensive earthquake catalogue datasets and produce accurate earthquake forecasts, given that a representative dataset that accurately reflects the properties of earthquake sequences is used for training. First, we use earthquake catalogue data from different geographical regions to construct time series of spatiotemporal maps depicting past seismic activity. Then, we divide this time series into training, validation, and test datasets, in order to investigate the capability of different types of deep neural networks to capture patterns within sequences of seismicity maps, and to generate short-term spatiotemporal earthquake forecasts. The performance of the trained deep learning-based forecasting models is evaluated by comparing against the persistence model, which assumes no change between consecutive time steps. This naïve approach, which is commonly used as a baseline in weather forecasting, serves as a null hypothesis and has been found to be a surprisingly effective model, as in cases where only background seismicity is observed, the change between consecutive time steps is minimal. Additionally, we assess the relative performance of different deep learning architectures and evaluate their suitability for addressing our specific problem. We find that deep learning techniques are an interesting alternative to traditional statistical and physics-based earthquake forecasting methods, as trained deep learning-based earthquake forecasting models have a potential to produce high-quality forecasts within seconds.

A Synthetically Trained Deep Learning Model for the Detection of Deep Focus Earthquakes

Zakary Asgher Hansen[1], Ana Ferreira[1], Maria Tsekhmistrenko[1], Alex Saoulis[1]

[1]*University College London, London, UK*

Improving our understanding of deep focus earthquakes (~300-700km source depth) is key to learning more about the conditions and dynamic processes which occur in subducted slabs as well as in earth's deep interior more generally. Deep Learning (DL) models have paved a new pathway towards expanding earthquake catalogues with varying network architectures reliably detecting significantly more events than has ever been done manually. This approach is however limited when investigating deep earthquakes as, in existing datasets, data on deep earthquakes is both underrepresented and heavily biased towards larger magnitude events when comparing with shallow events.

This study explores the application of DL network architectures trained on synthetic seismograms for the detection of deep earthquakes. Using synthetic data allows a series of augmentations to be applied to the data to expand existing datasets of deep earthquakes. Augmentations to the magnitude distribution of deep events, combining synthetic waveforms with randomly chosen sections of real noise data, and minor alterations to source location and depth (keeping within error range of the original source) allow the production of a vastly expanded database on which a neural network can be trained. We discuss initial results exploring the efficacy of using an expanded training dataset of synthetic waveforms for the detection of deep focus earthquakes using various DL architectures.

Statistical inference of locations and magnitudes of historical earthquake from archive data

Wenjin Lu[1], Ian Main[1], Mark Naylor[1], Finn Lindgren[1], Brian Baptie[2]

[1] *University of Edinburgh, Edinburgh, UK*
[2] *British Geological Survey, Edinburgh, UK*

To quantify the best estimate and uncertainties for epicentre location and felt area at different levels of Intensity for UK earthquakes using a consistent automated processing methodology. To use these to recalibrate the historical earthquake magnitude catalogue for the UK, for the first time routinely quoting uncertainties, ultimately for use in Probabilistic Seismic Hazard Analysis.

First, I describe and develop a method to estimate the felt area and it's uncertainty at a given level of intensity using the best fit elliptical shape for the contour. Then analyse the uncertainty for both centroid and felt areas for one historical and one recent event in the United Kingdom by determining the posterior density for relevant parameters from Markov-Chain Monte Carlo statistical sampling, and use it to define the median and credible limits as metrics of the optimal solutions and their uncertainties. The original dataset is based on historical data from British Geological Survey. I then compare my results for the felt area and centroid with those reported by the British Geological Survey (BGS), which form the basis for the current UK earthquake catalogue, and show the compatibility of my solutions with theirs within the stated uncertainty range. Later in the project I will use modern events in the BGS catalogue to correlate felt area at different intensities to earthquake magnitude and depth, and propagate the uncertainties estimated here through this correlation.

Defining an optimum frequency-band body-wave magnitude scale for noisy IMS stations

Bethany Grant[1] and Neil Selby[1]

[1] *AWE Blacknest, Aldermaston, UK*

Body wave magnitude (m_b) to surface wave magnitude ratios can be used to differentiate an underground explosion from an earthquake. The Comprehensive Nuclear-Test-Ban Treaty (CTBT) monitors for nuclear tests using the International Monitoring System (IMS). Signals are detected in different frequency passbands. However, the Reviewed Event Bulletin (REB) which is reviewed by analysts at the International Data Centre only reports m_b from the 0.8 to 4.5 Hz passband, with no signal-to-noise ratio test. Stations in the IMS with high amplitude noise at 1-2 Hz, but low amplitude noise above 2 Hz, could therefore be reporting a biased m_b relative to the network average. This is particularly likely if the station is close to the ocean. ARCES is a Norwegian primary seismic array that is part of the IMS. Teleseismic m_b measurements at this array are commonly higher than the network average m_b in the REB. We analysed a set of over 90 events recorded at ARCES from August to October 2022 to determine if the m_b measurements are dominated by noise. The m_b was calculated from the P wave amplitude for two passbands, 0.8 to 4.5 Hz and 2 to 4 Hz. The majority of signals in the 0.8 to 4.5 Hz passband are dominated by noise, but at higher frequencies (2 to 4 Hz) signals are clearly visible above the background noise. We investigate the use of these 2 to 4 Hz measurements to develop an optimum m_b scale for ARCES. Relative to network average m_b, we find no distance effect. Further study will consider the effect of depth on this proposed m_b scale.

Seismic Coupling from Near-Surface Explosions in Saturated Sediments: the Foulness Seismoacoustic Coupling Trials

David N. Green[1], Stuart E. J. Nippress[1], Andy Nowacki[2], Roger A. Clark[2], Nick Benson[3], Tugce Can[2,4], Evie Read[3], Sjoerd A. L. de Ridder[2], James Wookey[3], Nick A. Teanby[3]

[1] *AWE Blacknest, Brimpton Common, Reading, RG7 4RS, UK*
[2] *School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK*
[3] *School of Earth Sciences, University of Bristol, Wills Memorial Building, Bristol, BS8 1RJ, UK*
[4] *General Directorate of Mineral Research and Exploration, Department of Geophysical Studies, Ankara, Turkey*

Yield estimates for near-surface explosions can be made using seismic amplitude measurements; such assessments can, for example, contribute to investigations of industrial accidents. Explosively generated seismic displacements are a function of, amongst other factors: the source-to-receiver distance, the source yield (as an equivalent charge weight), the height of burst or depth of burial (HoBDoB) of the explosion and the geological material surrounding the detonation. Recent US experimental campaigns, focusing on ground motion recordings at distances of <15 km from explosive trials, have resulted in empirical models for explosively generated *P*-wave displacements in several geological settings. To extend these models to include sources within and above saturated sediments we conducted eight explosions at Foulness, Essex, where ∼150 m thicknesses of alluvium and clay overlie chalk. These shots, named the Foulness Seismoacoustic Coupling Trials (FSCT), had charge weights of 10 and 100 kg TNT equivalent and HoBDoB between -2.3 m (buried) and 1.4 m (above-ground). Initial *P*-wave displacements, recorded between 170 and 7000m from the explosions, exhibit amplitude variations as a function of distance that depart from a simple power-law decay relationship; this can be attributed in part to focusing of seismic energy from velocity gradients at depths between 100 and 300m. We extend the empirical model formulation to allow for such distance-dependent amplitude variations. Changes in explosive HoBDoB within the saturated sediments at Foulness result in large *P*-wave amplitude variations; FSCT surface explosions exhibit *P*-wave amplitudes that are a factor of 22 smaller than coupled explosions at depth. This factor is ten times larger than that observed in dry alluvium and three times larger than results in granite or limestone.

Surface waves generated by explosions in, and above, clay sediments: exploring the seismic coupling variability.

Evie Read[1], David Green[2], Stuart Nippress[2], James Wookey[1], Nick Teanby[1]

[1] *University of Bristol, Bristol, UK*
[2] *AWE Blacknest, Forensic Seismology, Reading, UK*

Chemical explosions close to the surface generate waves that travel through the atmosphere as blast waves and through the ground as seismic waves. The amount of energy converted into seismic energy is determined by the height-of-burst (or depth-of-burial) as well as the geological medium beneath (or surrounding) the explosion. Near surface explosions can be better characterised by understanding the wavefields produced and the corresponding variations in seismic coupling induced by different geological media. Forensic evaluations of unknown explosions depend on understanding this seismic coupling.

Particularly little is known about seismoacoustic coupling for near-surface explosions above and within saturated sediments, which are common environments in coastal and estuary settings. To fill in this knowledge gap, five 100kg charged TNT-equivalent explosions (between 1.39m above and 2.32m below) were carried out and recorded at four stations at 1.2–3.3km distance. Here, we analyse the surface wave portion of the resulting waveforms. We identify three distinct components: the expected Rayleigh wave, an inversely-dispersed wave and an air-to-ground coupled wave.

To understand the propagation pattern observed, and gain an insight into the velocity structure, we apply a range of forward modelling approaches to model different characteristics of the surface wave packet. We use the wavenumber integration method to generate synthetic seismograms, which we compare with analytically-predicted group velocity curves. This is supplemented with horizontal vertical spectral ratio (HVSR) modelling. Together, these approaches converge on a 1D velocity model which reproduces the features observed in the real data. Additional work has explored the ability to predict explosive charge weight (and/or yield) from surface wave amplitudes, and that the surface waves may be less influenced by multi-pathing when compared to the initial P-wave amplitudes that are commonly used in current procedures.

Estimating Full Moment Tensor Solutions for Nuclear Tests and Earthquakes near the DPRK Test Site

Christopher S. Ogden[1], Neil Selby[1], Ross Heyburn[1], Stuart Nippress[1]

[1] *AWE Blacknest, Brimpton Common, UK*

Event Screening is the rejection of the hypothesis that a seismoacoustic event is generated by a single explosion source and is essential in verifying compliance with the Comprehensive Nuclear-Test-Ban Treaty. Several methods are used to screen events, including using the ratio of body-wave to surface-wave amplitudes, the ratio of high frequency P-wave to S-wave energy, and source depth. However, these methods may not screen all relevant events and so forensic seismologists have looked for additional approaches. The full moment tensor solution (MTS) resolves the six independent components of the source moment tensor, and therefore fully characterises the source mechanism, including determining the proportion of deviatoric and isotropic energy released by a source. However, complications arise from sources at shallow depths where the moment tensor inversion is underdetermined. Furthermore, explosions can generate deviatoric energy which complicate the MTS.

Here, we use the mttime inversion scheme (e.g., Chiang et al., 2021), utilising data from IRIS, the International Data Centre (IDC) and recently published additional datasets, to calculate MTSs for: six announced DPRK nuclear tests, the collapse event after DPRK6, and for several nearby earthquakes in the IDC Reviewed Event Bulletin (REB). After tuning of station-specific time-shifts and velocity models, all six announced nuclear explosions have large positive isotropic components, with significant deviatoric components in the final MTS. The collapse event has a large negative isotropic component in comparison to double couple. In contrast, earthquakes have larger deviatoric components in comparison to isotropic. However, in all cases the compensated linear vector dipole component (volume expansion along a plane) is substantial, and solutions are not always stable; small adjustments in the time shifts, velocity model and station distribution can produce highly variable seismic source interpretations. Thus, care must be taken in determining the exact cause of a seismic source when using moment tensor analysis.

The Further Importance of The Historical Earthquake Pre-Digital Era Bulletins

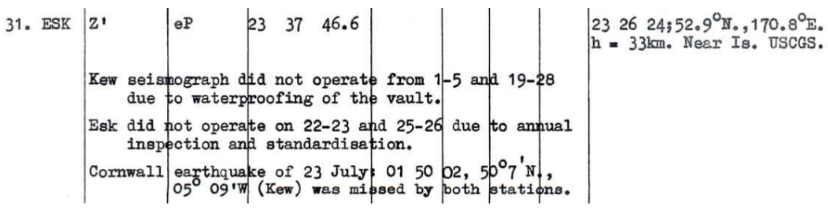
Susana Carvalho[1], Rian Harris[1], Domenico Di Giacomo[1]

[1] *International Seismological Centre, Thatcham, UK*

Digitization of pre-digital era bulletins has improved seismic data collection by standardizing the process, enhancing the precision and accuracy of data, enabling advanced processing techniques, and increasing the accessibility of data.

The historical importance of these side notes, beyond the seismic information such as seismograph instrument details, maintenance records in pre-digital era earthquake bulletins and even consequence recounts is profound. These bulletins, often the only source of records for when instruments were faulty or stations encountered specific malfunctions, have played a pivotal role in the evolution of seismic data collection.

The seismograph instruments of the pre-digital era were the primary tools for recording seismic activity. However, these instruments were not infallible and occasionally experienced faults and malfunctions. The bulletins served as a crucial record of these instances, providing invaluable insights into the reliability and accuracy of the recorded seismic data. Without the knowledge of these malfunctions, some correlated data could be misinterpreted as incorrect.


31. ESK Z' eP 23 37 46.6 23 26 24;52.9°N.,170.8°E.
h = 33km. Near Is. USCGS.

Kew seismograph did not operate from 1-5 and 19-28
due to waterproofing of the vault.

Esk did not operate on 22-23 and 25-26 due to annual
inspection and standardisation.

Cornwall earthquake of 23 July: 01 50 02, 50°7'N.,
05° 09'W (Kew) was missed by both stations.

Fig.1 Eskdalemuir 1966

The ISC-GEM Improvement Project has recognized the value of these bulletins and has undertaken significant efforts to digitize them. This initiative has not only preserved these invaluable sources of pre-digital knowledge but also made them more accessible for current and future research. The project has added thousands of earthquakes to the ISC-GEM Catalogue, complementing the catalogue with smaller earthquakes and fault plane solutions from the literature. It has also improved magnitude determinations by identifying and addressing some reporting gaps of quality long-term seismic stations. Scanning of these has now preserved all of these notes, for future generations.

In essence, the historical significance of these bulletins extends beyond their role as a record of seismic events. They represent an untold step in the journey to improve seismic data collection, serving as a testament to the challenges and triumphs of this endeavour. The scanning and digitization of these printed bulletins have ensured that this wealth of information continues to inform and guide the field of seismology, underscoring their enduring importance.

Poster # 45

The ISC Bulletin: Overview and Status

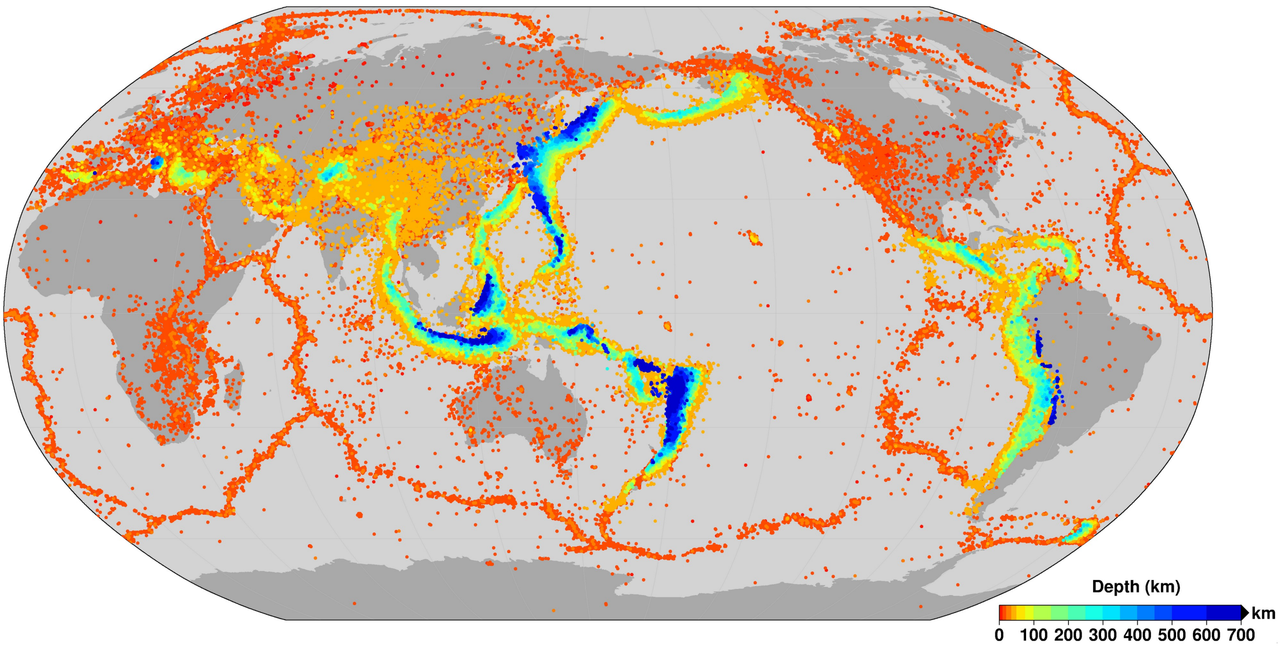
Kathrin Lieser[1], Blessing Shumba[1], Burak Sakarya[1], Lizzie Ayres[1], Rebecca Verney[1], Rose Hulin[1], James Harris[1], Domenico Di Giacomo[1], Tom Garth[1], Calum Clague[1], Dmitry Storchak[1]

[1] *International Seismological Centre, Thatcham, UK*

The Bulletin of the International Seismological Centre (ISC) is widely regarded as the most comprehensive record of the Earth's seismicity, and has been in production for 6 decades. With the support and cooperation of more than 150 agencies worldwide we are able to integrate and combine data from many sources, from global agencies with permanent networks to local temporary deployments. Our position as a not-for-profit and non-governmental entity allows us to create a unique product that is then freely provided to the global community. The ISC Bulletin is used by thousands of seismologists worldwide for seismic hazard estimation, for tectonic studies and for regional and global imaging of the Earth's structure. It served as a major source of data for such well known products as the ak135 global 1-D velocity model and the ISC-EHB Bulletin and presents an important quality-control benchmark for CTBTO.

This poster will give an overview of the ISC Bulletin and explain:

- How is the ISC Bulletin is created and reviewed?
- Who provides when, how much and what kind of data?
- What use does the ISC make of waveform data and contribute to the ISC Bulletin? (depth phases, focal mechanisms, source time functions, picking of under represented areas etc.)
- How many phase arrivals, amplitude data, seismic and anthropogenic events, seismic stations, ISC reviewed events can be found in the ISC Bulletin?



ISC Reviewed Bulletin

ISC-EHB Dataset for 1964 to 2020: Enhancing the Bulletin with In-house Depth Phase Picks

Burak Sakarya[1], Kathrin Lieser[1], E.R. Engdahl[2], Tom Garth[1], Blessing Shumba[1], James Harris[1], Domenico Di Giacomo[1] and Dmitry A. Storchak[1]

[1] *International Seismological Centre, Thatcham, UK*
[2] *University of Colorado, Boulder, USA*

In the past decade there has been a consistent decline in the number of depth phase picks reported to the ISC. The availability of depth phases is crucial for the ISC as they can be used to constrain the depth of remote earthquakes. To address this decline, analysts at the ISC began picking depth phases for global earthquakes with $mb^{NEIC} \geq 4.8$ recorded within 28° - 90° distance range, using SeisAn earthquake analysis software (Havskov and Ottemöller, 1999). These picks have been used in ISC products, including the Reviewed ISC Bulletin and ISC-EHB. In the period April 2016 to January 2022 there were 6485 events with depth phases picked at the ISC. Of these an additional 4414 events were improved with better constrained ISC depths.

In this contribution we also describe the procedures used to construct the newly refined ISC-EHB dataset covering earthquakes from 1964 to 2020. We illustrate noteworthy features in several regions, including some of those presented in Engdahl et al. (2020). The ISC-EHB now includes 199,578 earthquakes with a prime magnitude > 3.75. This advanced dataset of well-recorded seismic events can be used for regional and global seismicity and tomographic studies, especially in subduction zones where significant spatial and structural characteristics are observed. The ISC-EHB is now the most refined global seismicity catalogue and is freely available from the ISC website (isc.ac.uk/isc-ehb), where seismicity maps and cross sections along all subduction zones are shown. The ISC-EHB is updated annually in line with the completion of analysis of the data year in the Reviewed ISC Bulletin.

Poster # 47

An update on the ISC Seismic Event Bibliography

Domenico Di Giacomo[1]

[1] *International Seismological Centre, Thatcham, UK*

Since its launch in 2014 (Di Giacomo et al., 2014), the International Seismological Centre (ISC, www.isc.ac.uk) Seismic Event Bibliography service has been very popular with researchers worldwide. Indeed, this service differs from other literature search engines since it is based on the association between seismic events in the ISC Bulletin and bibliographic records. As such, web searches (www.isc.ac.uk/event_bibliography/bibsearch.php) are not only based on bibliographic parameters (e.g., author, journal title, year of publication) but also on event parameters (e.g., origin time, location). In addition, the literature considered is not limited to seismology but includes a broad range of disciplines (e.g., earthquake engineering, geodesy and remote sensing, tectonophysics and volcano-tectonics, monitoring research, tsunami, landslides, geology, geochemistry, hydrogeology, atmospheric sciences), a feature that makes the service useful also for multidisciplinary studies. Hence, the ISC Seismic Event Bibliography is an asset both to researchers studying specific events as well as editors and reviewers during every stage of the publication process.

The bibliographic record of this service has grown significantly in recent years, and new papers related to recent significant earthquakes (e.g., February 6, 2023, Kahramanmaraş earthquakes) as well as other types of seismic sources (e.g., the 15 January 2022 Hunga Tonga Hunga Haapai eruption) are published at increasing speed. In such a context, with this contribution we aim to showcase the usefulness of the ISC Seismic Event Bibliography, how the community can use it best and, at the same time, help improve it and facilitate its maintenance.

Updates on the ISC-GEM Global Instrumental Earthquake Catalogue (1904-2020)

International Seismological Centre, Thatcham, UK

The first version of the ISC-GEM Global Instrumental Earthquake Catalogue (www.isc.ac.uk/iscgem/index.php) was released in January 2013 (Storchak et al., 2013). The goal of the catalogue is to improve the homogeneity (to the largest extent possible, in time and space) of earthquake parameters (e.g., location and magnitude) and list them along with formal uncertainties to facilitate, among others, seismic hazard and Earth's seismicity studies.
Ten years on from the first release, we report on the latest developments of the catalogue following the completion of the Extension (Di Giacomo et al., 2018) and Advancement projects (Di Giacomo and Storchak, 2022). We expanded the catalogue with several thousands moderate earthquakes down to ~M5.5 between 1904 and 1959 and earthquakes down to ~M5.0 from 1976. Furthermore, we added over a thousand source mechanisms from the literature for earthquakes that occurred before GCMT began in 1976. Finally, we provide an overview of ongoing activities to further improve the catalogue. These include the use of station data recently digitized from the BCIS bulletins for 1950-1963 (Di Giacomo and Storchak, 2023), the reassessment of MS for hundreds of earthquakes for 1964-1970, the digitization of the Chinese network bulletins for 1971-1981, and the reassessment of error ellipses for early-instrumental earthquakes (i.e., pre-1964).

Probabilistic moment tensors and source time functions at the ISC

Tom Garth[1], Karin Sigloch[2], Dmitry A. Storchak[1]

[1] *International Seismological Centre, Thatcham, UK*
[2] *Geoazur, Université Côte d'Azur, CNRS, OCA, IRD, Valbonne, France*

The function of the ISC in collating earthquake locations and seismic phase arrival times, the latter of which can be combined into a revised ISC hypocentre is well established. As more agencies have moved to also reporting focal mechanism or moment tensor solutions, this data has also been collated at the ISC. In this instance however, the range of observation types and modelling and inversion techniques used make a combined moment tensor solution impractical, while the variety of moment tensor solutions reported draws attention to the significant uncertainties that remain in moment tensor analysis. We address this in three ways.

Firstly, and most simply, all moment tensors reported to the ISC are displayed in the ISC-bulletin. This allows researchers to make there own assessment of which solutions are reliable or representative. Secondly, we are pursuing combining polarity observations in the ISC Bulletin to build a first motion focal mechanisms (ISC-FM). Preliminary efforts in this direction have highlighted the huge variability in quality of reported polarities, making a stable first motion based solution difficult. By combining better quality control of polarity picks, with automated observations from openly accessible waveforms, we hope to improve the catalogue with more stable solutions.

Finally, we have introduced the ISC-PPSM (International Seismological Centre – Probabilistic Point Source Model). As well as adding new depth resolution to shallow depth, moderate magnitude earthquakes by solving jointly for the earthquake depth and source time function, this probabilistic parameter search approach allows the range of potential moment tensors to be constrained. The parameter search is based on teleseismically observed body wave (P and SH waves) observations, and therefore may have different biases to moment tensors based on surface wave or local body wave observations.

Seismic Phase Picking For Under-Reported FDSN Registered African Stations

Blessing T Shumba[1], James Harris[1] and Dmitry A. Storchak[1]

[1]*International Seismological Centre, Thatcham, UK*

The ISC Bulletin serves as a comprehensive repository for seismic phase data sourced globally; however, a notable gap exists in teleseismic data coverage, particularly from African stations. Since 2019, our project has been dedicated to narrowing this void by manually picking teleseismic phases mostly P, PcP, pP, sP, PKP, SKP and SP from about 20 freely available African stations. Focusing on earthquakes with mb NEIC ≥ 4.8 at distances exceeding 20 degrees. Our approach employs the SeisAn software (Havskov and Ottemöller, 1999), for precise phase picking. This effort aims to significantly improve the accuracy and comprehensiveness of the ISC bulletin, contributing vital information to the global understanding of earthquake locations. By incorporating these seismic stations, our refined dataset not only enhances the ISC Bulletin but also contributes to a broader understanding of teleseismic events, illustrating the impact of collaborative endeavours in seismic research.

Performance of SmartSolo Seismic Nodes in Seismological, Environmental and Geophysical research

Koen Van Noten[1], Martin Zeckra[2], Thomas Lecocq[1], Raphael De Plaen[1], Julien Govoorts[1,3]

[1] *Royal Observatory of Belgium, Brussels, Belgium*
[2] *Bensberg Seismic Station, University of Cologne, Germany, Thatcham, UK*
[3] *Université Libre de Bruxelles, Brussels, Belgium*

SmartSolo® seismic nodal sensors have been successfully introduced in the fields of seismology and geophysics. Their reduced costs, lightweight and modal setup, and user-friendly installation make them suitable for environmental and urban seismology, near-surface geophysics, and Quaternary geological research. Here we showcase the use of IGU-16 and IGU-BD3C-5 sensors during various research projects conducted by the Royal Observatory of Belgium. We used these sensors in:

- Urban seismological research, where H/V spectral ratio analyses (HVSR) of ambient noise records improve bedrock depth models in urban settings (Brussels, BE). We study characteristics of the Cambrian bedrock that is of interest for shallow geothermal energy usage in Brussels. We continuously monitor HVSR next to geothermal wells for improving bedrock depth prediction.
- Quaternary research, where thickness changes of Quaternary terrace layers of the Weser river (Hamelin, DE) was mapped by HVSR profiling using nodes installed in cross-profiles and arrays.
- Array seismology, where classic seismological array installations and active shots along linear arrays were used for the site characterization of the Belgian seismic network. Results are integrated in the Belgian station books in Orfeus (EPOS).
- Environmental seismology, where nodes installed on Icelandic glaciers allow calculating ice-thickness and bedrock topography or where nodes installed as gates on ski-slopes easily recorded moving skiers.
- Outreach, where seismic nodes installed in a linear array recorded an 800-people crowd jumping during a science festival, with a calculated magnitude of ML 1.5.
- Educational purposes, where we dress up nodes as minions to educate schoolchildren.

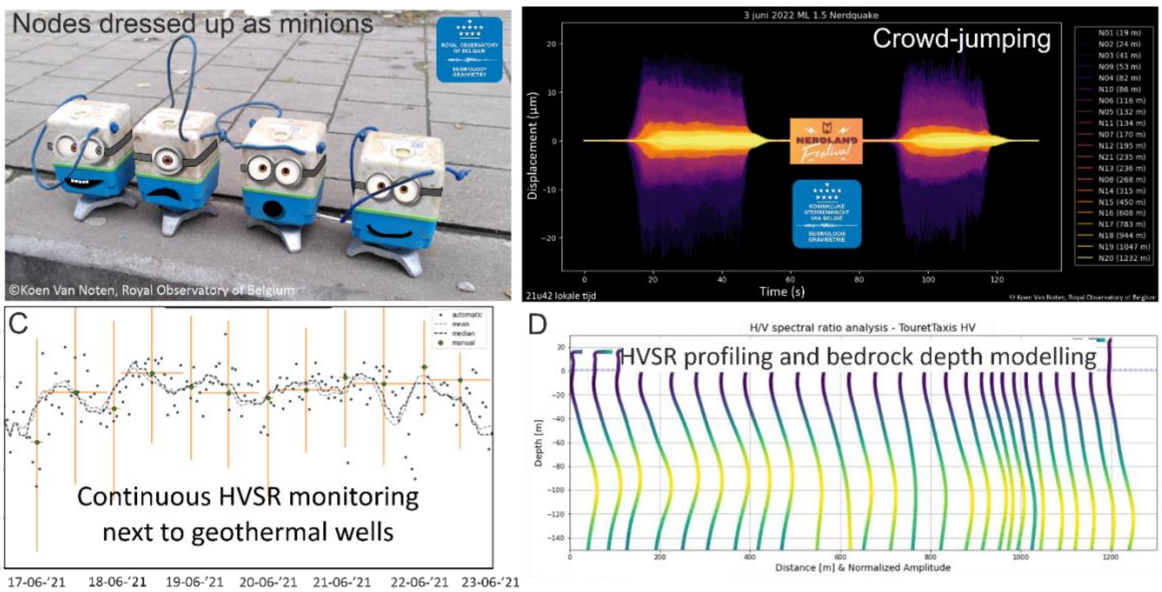


Figure 1: Output results of several applications of SmartSolo seismic nodes by the Royal Observatory of Belgium

Seismic velocity changes observed on a dense array of nodal seismometers reveal soil moisture changes in the Critical Zone

Kevin J. Davidson[1], James O. S. Hammond[1], Victoria S. Lane[2], Lucy E. Finch[2], J-. Mike Kendall[3], Chris S. Ogden[4], Cunrui Han[1], Jia-Cheng Wu[1], Dominic Ryan[1], Ken Doherty[5], Nick Tranter[5], Tom O'Toole[5]

[1] *Birkbeck, University of London, London, UK*
[2] *SEIS-UK, Leicester, UK*
[3]*University of Oxford, Oxford, UK*
[4]*University of Leicester, Leicester, UK*
[5]*Stryde, London, UK*

The Critical Zone (CZ) is the "living skin" of our planet, extending from the bottom of the water table to the top of the tree canopy. Processes occurring in the CZ are subject to a complex and dynamic interplay between soil structure, temperature, pressure, precipitation, and water content. Geophysical methods can be used to image the subsurface portion of the CZ but typically offer a point-in-time snapshot view which does not constrain changes over time.

The development of ambient noise seismology allows us to exploit continuous recordings of the seismic wavefield to detect small changes in seismic velocity over time, which may be indicative of changes in the subsurface. In December 2022, in partnership with Stryde, we deployed a "large-N" array consisting of ~1600 seismic nodes at spacings between 5m and 10m for one month at a site in Dumfries, southwest Scotland. The site was chosen as it hosts a Critical Zone observatory, recording real-time data on soil moisture and temperature along with other meteorological data.

Ambient noise recordings from this array are cross-correlated to retrieve the Green's function. We perform coda-wave interferometry to detect velocity changes across the array are able to observe relative seismic velocity changes of < 1% at a temporal resolution of 30 minutes. The time series of relative velocity variation are compared with measurements of soil moisture and temperature to establish relationships and correlations between changes in seismic velocity and environmental factors, and constrain the extent to which external hydrological factors influence seismic velocities.

Our study shows the strongest correlations are with soil moisture content (r ~ 0.6-0.7). Heavy rainfall events leading to soil saturation temporarily disrupt the correlation trend, which then recovers as water content returns to field capacity. The correlations between velocity and soil moisture are negative, with velocity decreasing as water content increases. We attribute this to a change in the properties of the soil, whereby the density increases with added water content but the bulk modulus remains the same. Other environmental factors such as soil temperature show a weaker correlation with soil moisture; however, the relationship between various factors is complex and cannot be considered in isolation.

This study shows the potential benefits of newly-developed nodal seismometer technology in the emerging field of Critical Zone seismology.

Poster # 53

Glimpse on Archaeoseismology from archaeological remains on Roman sites in the Eastern part of the Tel Atlas of Algeria

Roumane K.[1], A. Ayadi[2]

[1] *Institute of Archaeology, University of Algiers 2, Algiers, Algeria*
[2] *Center of Research in Astronomy, Astrophysics and Geophysics, CRAAG, Algiers, Algeria*

Archaeological Roman sites in Algeria are located in seismogenic areas where several strong earthquakes were reported by the available seismic catalogues. This seismicity, located in the Tell Atlas along the collision zone between the African and Eurasian plates, is well-documented for the period 1900 onwards. Unfortunately, the historical seismicity is considered poorly known until the beginning of the 19th century due to lack of data. To overcome this problem, the analysis of damage on archaeological structures is an important tool to recognize the possible effects of strong past earthquakes. The remains of the Roman sites (BC146-429) in eastern Algeria were selected in order to study the evidence of earthquakes that probably have occurred in their vicinity. Several cities in this region have preserved many archaeological remains of ancient Roman sites such those of *Lambaesis* (modern Lambèse), *Thamugadi* (modern Timgad) *Thibilis* (modern Salaoua Announa), *Thibursicum-Numidarum* (modern Khemissa), Madouros (modern Madaure) or *Thevest* (modern Tébessa). Epigraphic sources and other texts reported a series of damage during the antic period and the main reconstructions and rehabilitations of monuments following strong ancient earthquakes. This study focuses on damage, abrupt changes and disorders observed on several Roman sites and seeks to further advances in archaeoseismology in Algeria.

The effects of surface topography and basin layering on the earthquake ground motion intensities in intermontane-basin settings

Agrawal Himanshu[1], Naylor Mark[1]

[1] *University of Edinburgh, Edinburgh, UK*

Many densely populated intermontane sedimentary basins in collisional tectonic settings possess high seismic risk due to widely observed basin-specific ground motion amplifications. The documented observations show that ground motion predictions in these basins are often poorly constrained due to oversight of surrounding surface topography and the absence of sub-surface information about deeper basin layering, leading to inaccurate hazard assessment. In this study, we systematically evaluate the implications of these two factors on high frequency ground motion characteristics, which is crucial for earthquake engineering practices.

Using the Kathmandu sedimentary basin as our case-study area, we extract a 2D east-west cross-section of length 80km containing high relief surface topography on either side of the 20km-wide basin. We simulate the eastward travelling Rayleigh waves in a high-resolution domain allowing us to resolve frequencies up to 5Hz. Our results indicate that the topography reduces peak ground acceleration (PGA) in the basin by 40% as compared to scenarios when the topography is neglected, particularly shielding frequencies above 2 Hz. We also perform 3D simulations of a shallow thrust-faulting moment tensor source in the west of Kathmandu basin to confirm the high frequency attenuation of waves entering the basin area as a result of the surface topography. In a simultaneous analysis for basin specific properties, we find that the deeper Kathmandu basin layers control the spatial variability in the observed amplification that has an order of magnitude difference within the basin when compared to the scenarios excluding the deeper basin layers.

Hence, we conclude that neglecting topography in ground motion predictions may lead to an overestimation of ground motion amplification in the basin, particularly for higher frequencies. A strong emphasis must also be given to maximise the understanding of deeper basin layers to capture the spatial variability in the ground motions. This is particularly relevant to microzonation studies where high spatial resolution is needed for risk-mitigation measures.

PICO - a new Compact, Fully Tilt Tolerant, Feedback Broadband Seismometer

Cansun M. Güralp[1], Paul Minchinton[1] , Robert Kirrage[1] , Murray McGowan [1]

[1] *Gaiacode Ltd., Silchester, RG7 2LU, UK*

We present a newly designed, compact, three-component, broadband seismometer named PICO with capabilities exceeding those of many existing instruments available in much larger form factors. The three identical sensors inside this new instrument are arranged orthogonally and are designed so that the instrument can be deployed and operated under any tilt angle.
Other new design features include:

- a completely new feedback transducer with a constant magnetic flux, which significantly increases linearity and reduces intrinsic noise,
- - the sensors inertial frame of reference is designed the basis of a balanced and truly symmetrical suspension system with extremely high cross axis rejection,
- - an integrated three-component MEMS sensor provides information about the sensors tilt angle, and
- - the standard frequency response of each sensor is flat between 120 sec and 200 Hz with less than 0.1 dB variation. Seven other response curves with lower 3 dB-points in the range between 120 sec and 1 sec can be remotely selected.

The PICO seismometer itself is one of the smallest broadband instruments currently on the market with a diameter of just 10 cm and a height of 14.5 cm. With its standard housing made of anodized aluminium, it weighs 2.4 kg. A Titanium-PEEK housing is also available for deployment in wet boreholes of up to 100 meters of depth.
The response characteristics, each sensor's calibration information, its production parameters, as well as the tilt information are stored within the seismometer's memory, which is accessible via a serial connection. PICO’s power consumption at 12V is less than 450 mW and is reduced to 350 mW when the processor is in sleep mode.
All PICO instruments are equipped with a new type of connector which can be rotated 270 degrees around its base even while the cable is attached. This rotating connector is absolutely water tight and provides a reliable electric connection without introducing significant extra weight or bulk to the whole set-up.

Comparing seismic wave sensitivity of armoured seabed fibre optic telecommunications cable with collocated seismic and acoustic instruments

David M. Fairweather[1,2], Giuseppe Marra[2], Max Tamussino[2], Ali Masoudi[3], Richard Barham[4], Andrew Curtis[1]

[1] *University of Edinburgh, Edinburgh, UK*
[2] *National Physical Laboratory, Teddington, UK*
[3] *University of Southampton, Southampton, UK*
[4] *Acoustic Sensor Networks, UK*

Fibre-based seismic monitoring is increasingly deployed in Earth scientific studies. This has been achieved through methods such as integrated interferometric measurement, distributed acoustic sensing (DAS), and state-of-polarisation (SOP) monitoring. A key challenge in understanding recordings made from fibre networks is incomplete knowledge of the transfer function between deformation in the surrounding media and the fibre, and how the latter affects recorded signals. The cable coupling efficiency, geometry, armouring, and fibre structure within the cable, all contribute to this transfer function and numerous studies have sought to understand the effects of each. Current theory proposes that there should only be certain points of a line receiver that are sensitive to an incoming wavefield (e.g., Fichtner et al., 2022) depending on the geometry and curvature of the fibre sensor. Indeed, observations and experiments with DAS arrays appear to confirm this (Kennet, 2022).

We present early results from a controlled testbed which contradicts this theory. Upon a sand layer, we situated two differently armoured cables and one bare fibre, each ~26m long, parallel to each other and with no curved sections. We interrogated each fibre with a DAS interrogator. We placed vertical-component geophones and three-component SmartSolo seismic nodes at evenly spaced intervals along the cable array and included microphones to record airborne acoustic signals. Our source was a hammer on a baseplate.

We clearly record the active incident wavefield from a perpendicular source geometry on the seismic sensors, and a simultaneous interferometric signal from a straight section of the cable fibres. We also observe comparable waveforms between the interferometer data obtained from the integrated cable measurements and the summed seismic instruments. This suggests that a different model of fibre optic transfer functions is required.

Fichtner, A., Bogris, A., Nikas, T., Bowden, D., Lentas, K., Melis, N. S., Simos, C., Simos, I. & Smolinski, K. (2022), 'Theory of phase transmission fibre-optic deformation sensing', Geophysical Journal International 231(2), 1031–1039.

Kennett, B. L. N. (2022), 'The seismic wavefield as seen by distributed acoustic sensing arrays: local, regional and teleseismic sources', Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 478(2258), 20210812.

Sedimentary thickness across Australia from passive seismic methods

Augustin Marignier[1], Caroline M. Eakin[1], Babak Hejrani[2], Shubham Agrawal[3]

[1] *Australian National University, Canberra, Australia*
[2] *Geoscience Australia, Canberra, Australia*
[3] *University of South Carolina, Columbia, SC, USA*

Finding new mineral deposits hidden beneath the sedimentary cover of Australia has become a national priority, given the country's economic dependence on natural resources and urgent demand for critical minerals for a sustainable future. A fundamental first step in finding new deposits is to characterise the depth of sedimentary cover. Excellent constraints on the sedimentary thickness can be obtained from borehole drilling or active seismic surveys. However, these approaches are expensive and impractical in the remote regions of Australia. With over three quarters of the continent being covered in sedimentary and unconsolidated material, this poses a significant challenge to exploration.

Recently, a method for estimating the sedimentary thickness using passive seismic data, the collection of which is relatively simple and low-cost, was developed and applied to seismic stations in South Australia. The method uses receiver functions, specifically the delay time of the P-to-S converted phase generated at the interface of the sedimentary basement, relative to the direct-P arrival, to generate a first order estimate of the thickness of sedimentary cover. In this work we apply the same method to the vast array of seismic stations across Australia, using data from broadband stations in both permanent and temporary networks. We also investigate using the two-way traveltime of shear waves, obtained from the autocorrelation of radial receiver functions, as a related yet separate estimate of sedimentary thickness.

From the new receiver function delay time and autocorrelation results we identify many features, such as the relatively young Cenozoic Eucla and Murray Basins. Older Proterozoic regions show little signal, likely due to the strong compaction of sediments. A comparison with measurements of sedimentary thickness from local boreholes gives a straightforward predictive relationship between the delay time and the cover thickness, offering a simple and cheap way to characterise the sedimentary thickness in unexplored areas from passive seismic data. This study and some of the data used are funded and supported by the Australian Government's Exploring for the Future program led by Geoscience Australia.

Upper-mantle velocity and anisotropy under the Mongol-Baikal region

Hanting Wu[1], Zhouchuan Huang[1]

[1] *School of Earth Sciences and Engineering, Nanjing University, Nanjing, China*

The Mongol-Baikal region is located in the western segment of the Central Asian Orogenic Belt. This area had experienced multiple periods of extensive compression since the Proterozoic. In the Cenozoic, the study region was modified by neotectonics, featured by large extensional rifting (the Baikal rift zone) and plateau uplift (the Hangai Dome). However, the deep mechanisms of the onset of rifting and doming are still debated. We performed high-resolution 3-D P-wave tomography under the southwestern Baikal and western Mongolia. The images show distinct low-velocity anomalies under the Baikal Rift at ~60 km depth, the Hangai Dome at ~200 km depth, and beneath the Siberian craton. This may indicate that potential mantle flows ascended from the deep Siberian MTZ to shallower levels, influencing the rifting of the Baikal rift zone and lithospheric process of the Hangai Dome. We then further determined the seismic anisotropy of the upper mantle under western Mongolia using SKS splitting measurements. The study region is dominated by NW-SE trending fast polarization directions (FPD), which indicates consistent compressional and transitional stress among the whole study area. Small delay times in the Hangai Dome spatially coincides with the low-velocity anomalies, supporting remarkable asthenosphere upwelling. However, the local Hangai upwelling did not affect the general anisotropic structures significantly, indicating that the lithospheric process only occurred in a limited area.

Wu, H., Huang, Z., 2022. Upper mantle anisotropy and deformation beneath the western Mongolian Plateau revealed by SKS splitting. Tectonophysics 835, 229376.
https://doi.org/10.1016/j.tecto.2022.229376
Wu, H., Huang, Z., Zhao, D., 2021. Deep structure beneath the southwestern flank of the Baikal rift zone and adjacent areas. Physics of the Earth and Planetary Interiors 310, 106616.
https://doi.org/10.1016/j.pepi.2020.106616

BSM2024

British Seismology Meeting
25th-27th March, Reading, UK

International
Seismological
Centre

Organized by the ISC with support and sponsorship from:

BGA British Geophysical Association

AWE

Royal Astronomical Society

GaiaCode

nanometrics

STRYDE

Raspberry Shake
Watch the Earth Move

SMARTSOLO SCIENTIFIC

güralp