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SESSION 1

AG Machine Learning

1.1 Deep learning prediction of measured earthquake waveforms from synthetic data

Alexander Bauer[1], Jan Walda[1], Conny Hammer[1]

[1]*University of Hamburg*

Waveforms of teleseismic earthquakes are highly complex since they are a superposition of numerous phases that correspond to different wave types and propagation paths. In addition, waveforms measured at seismological stations are contaminated by noise from the surroundings of the station, which can be problematic particularly in urban environments. The regional distribution of seismological stations is often relatively sparse, in particular in regions with low seismic hazard such as Northern Germany. However, a detailed knowledge of the seismic wavefield generated by large earthquakes is crucial for highly precise measurements or experiments that are carried out for instance in the field of particle physics, where these wavefields are considered noise. While synthetic waveforms for cataloged earthquakes can be computed for any point on the Earth's surface, they are based on a highly simplified Earth model. As a first step towards a better-resolved prediction of earthquake wavefields in a region with sparsely distributed stations, we propose to train a convolutional neural network (CNN) to predict measured waveforms of large earthquakes from their synthetic counterparts. For that purpose, we gather data from a seismological station in Bad Segeberg (Northern Germany) for all earthquakes with magnitudes larger than 6.0 between 1996 and the end of 2023 and compute the corresponding synthetic waveforms with the IRIS synthetics engine (Syngine). We test the performance of the trained neural network for events not part of the training data and subsequently also apply it to synthetic waveforms generated at the coordinates of more noisy seismological stations within the city of Hamburg. The results suggest that the neural network largely seems to be able to provide a good first estimate of complex measured waveforms despite the simple Earth model underlying the synthetic input waveforms. This is a first step to pave the way for a large-scale prediction of the seismic wavefield generated by earthquakes also in noisy urban environments.

1.2 Neural network approach on seismic array processing

Benjamin Banaskiewicz[1], Matthias Ohrnberger[1]

[1]*University of Potsdam, Institute of Geoscience, Potsdam, Germany*

Standard seismic array processing methods (e.g. f-k techniques) are normally based on time- consuming grid searches in the wavenumber or slowness domain to detect and analyze the wave propagation properties of the seismic wave field. The application to long time continuous data recordings requires powerful computational resources. To improve the processing speed, we have been testing to shortcut the slowness domain search by using a neural network model trained on purely synthetic data and thus treating the array analysis as a regression problem. For the moment being, we employed a simple plane wave model (as inherent to standard f-k techniques) to demonstrate the feasibility of such an approach. Other wave models such as cylindrical, spherical or arbitrary curved wave fronts based on modeling the local wave front propagation for more realistic earth models can be potential extensions to the simple scheme presented here. The training data set is built from randomly selected horizontal slowness vectors in the range of interest and then computing the corresponding upper triangular complex cross spectral matrix for a small number of discrete frequencies given the fixed array geometry for each of the input slowness vectors. We then trained a simple MLP-type neural network using the real and imaginary parts of the cross spectral matrix as input and the slowness vector as output. In the training procedure we varied the number of hidden layers as well as other hyperparameters (optimizer choice, learning rate and decay type, batch sizes, normalization and dropout ratios, ...) on the same training data sets and finally selected the best performing models based on the model loss. We chose two array geometries for our exercise: the Gräfenberg array GRF and the Svalbard array SPITS. For GRF we designed the neural network-based array processor for teleseismic body wave arrivals whereas for SPITS we targeted regional body wave arrivals. We show the results from applying the neural network approach to sample waveforms in comparison to the results from a standard array analysis implemented in Obspy and discuss the performance gain (roughly a 70-590 times speed-up), the robustness, and accuracy of the approach.

1.3 HR-GNSS Data Monitoring for Earthquakes Analysis using Deep Learning Algorithms

Claudia Quinteros-Cartaya[1], Javier Quintero-Arenas[2], Andrea Padilla-Lafarga[3], Carlos Moraila[3], Johanes Faber [1,2], Wei Li [1]], Jonas Köhler [1,2], Nishtha Srivastava [1,2]

[1]*Frankfurt Institute for Advanced Studies, Germany,*[2]*Goethe University Frankfurt, Germany,* [3] *Autonomous University of Sinaloa, Mexico*

The High-Rate Global Navigation Satellite System (HR-GNSS) is an effective tool for capturing ground displacements caused by high magnitude seismic events, providing crucial information for improving seismic analysis and early warning systems. In this study, we present a Python-based monitoring tool for HR-GNSS data that integrates into the SAIPy API a platform dedicated to large earthquakes analysis.

This tool operates as a pipeline involving two sequential deep learning algorithms: the first detects the onset of ground displacements from 1Hz HR-GNSS data and the second estimates the magnitude of these detected displacements. Because the effects of noise on GNSS data quality, both algorithms are trained to work on data from earthquakes $M_w \geq 6.9$.

The detection algorithm is trained using time series from observation windows without seismic activity in the signal and is tested with both real and synthetic data that include large earthquakes. Once an event is detected, the magnitude estimation process begins 15 seconds later, updating every second for up to 6.5 minutes. The pipeline has been validated using HR-GNSS data from seismic events occurred in diverse regions.

Although this pipeline is still in the development stage, it is designed to be adapted to real-time analysis of seismic data and, particularly improve the early warning systems. Further work is needed to address challenges related to data quality, real-time data preprocessing, computational efficiency, and adaptability to different seismogenic scenarios.

1.4 DeepDAS: Earthquake Phase Picker from Submarine Distributed Acoustic Sensing Data

Han Xiao[1], Frederik Tilmann[1], Martijn van den Ende[2] Diane Rivet[2], Afonso Loureiro[3], Takeshi Tsuji[4]

[1]*Helmholtz Center Potsdam, German GeoResearch Center GFZ, Potsdam, Germany,* [2]*Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, IRD, Géoazur, Sophia Antipolis,* [3]*University of Lisbon, Institute D. Luiz, Lisbon, Portugal,* [4]*School of Engineering, The University of Tokyo, Tokyo, Japan*

The EU-INFRATECH funded SUBMERSE project will establish continuous monitoring of several oceanic telecom cables for landing sites in Portugal, Greece, and Svalbard. We develop tools for the automated analysis of these upcoming data sets as well as other submarine DAS data. Employing DeepLab v3, a cutting-edge deep neural network architecture renowned for its exemplary performance in semantic segmentation, this project aims to develop a specialized machine learning model for the detection of earthquakes and the identification of P and S waves using submarine DAS data. The inherently two-dimensional nature of our input data mandates the adoption of DeepLab v3.

Confronted with the distinctive challenges posed by submarine DAS data, which encompass varied oceanic noise environments and a spectrum of operational parameters including cable length, configuration, channel spacing, deployment conditions, and geographic diversity, we have chosen to implement a more expansive model to enhance detection capabilities. This project exclusively utilizes submarine DAS seismic records, now encompassing nearly three million earthquake records from multiple international locales. This approach ensures that our model is more effective to the unique characteristics of the submarine environment.

Our findings corroborate the model's good capacity to detect seismic events and accurately categorize P and S waves using single-component DAS data—a notable feature considering the absence of the multi-component architecture typically essential for wave discrimination in conventional seismology. The model proficiently differentiates between P and S waves, even in scenarios where the order of these waves is reversed or their amplitudes are markedly altered, indicating that the model discerns complex patterns and features inherent in seismic data beyond mere amplitude analysis.

1.5 Predictive modeling of seismic wave fields: Learning the transfer function using encoder-decoder networks

Jana Klinge[1], Sven Schippkus[1], Jan Walda[1,2] Celine Hadziioannou[1], Dirk Gajewski[1]

[1] *Institute of Geophysics, Centre for Earth System Research and Sustainability (CEN), Universität Hamburg, Hamburg, Germany;* [2]*Currently: Emetriq GmbH, Hamburg, Germany*

Wouldn't it be beneficial if we could predict the time series at a seismic station even if the station no longer exists? In geophysical data analysis, this capability would enhance our ability to study and monitor seismic events and seismic noise, particularly in regions with incomplete station coverage or where stations are temporarily offline. This study introduces a novel adaption of encoder-decoder networks from the subfield of Deep Learning, modified to predict the development of seismic wave fields between two seismic stations. Using one-dimensional time series measurements, our algorithm aims to learn and predict signal transformations between the two stations by approximating the transfer function. Initially, we evaluate this proof of concept in a simplified controlled setting using synthetic data, before we incorporate field data gathered at a seismic exploration site in an area containing several roads, wind turbines, oil pump jacks and railway traffic. Across diverse scenarios, the model demonstrates proficiency in learning the transfer function among various seismic station configurations. Particularly, it achieves high accuracy in predicting a majority of seismic wave phases across different datasets. Diverging significantly from encoder-decoder networks that estimate time series forecasts by analysing historical trends, our approach places greater emphasis on the wave propagation between nearby locations. Thereby, the analysis incorporates both phase and amplitude information and provides a new approach to approximate the transfer function relying on Machine Learning techniques. The gained knowledge enables to reconstruct data from missing, offline, or defunct stations in the context of temporary seismic arrays or exclude non-relevant data for denoising.

1.6 Towards the Clustering of Large Distributed Acoustic Sensing Datasets

Oliver Bölt[1], Conny Hammer[1], Céline Hadziioannou[1]

[1]*Institute of Geophysics, University of Hamburg*

Distributed Acoustic Sensing (DAS) measures strain or strain rate along an optical fiber with a high spatial and temporal resolution. The typical channel distance is in the order of a few meters while the sampling frequency can reach 1 kHz or higher, which makes it possible to record a wide range of seismic signals. The optical fibers used for DAS can be several kilometers long and measurements take place over days, weeks or months, resulting in very large datasets of up to several tens of TB per day. However, due to this large amount of data, it is challenging to get a good impression of the different types of seismic signals present in the data, since a manual inspection can become immensely time-consuming. In this study we aim to automatize this process by clustering the data to detect and categorize different types of seismic signals. A 2D continuous wavelet transform (CWT) is used to automatically extract features from the data. In contrast to many other approaches, this allows to not only use temporal information, but to also include the spatial dimension to further distinguish between different seismic sources and wave types. The clustering is performed in two steps. First, a Gaussian Mixture Model (GMM) is used to cluster the features. Then, the final clusters are obtained by merging similar components of the GMM. A first application to several days of DAS data shows very promising results, with the clusters exhibiting potentially insightful temporal and spatial patterns.

1.7 Machine learning for labquake forecasting using catalog-driven features

Sadegh Karimpouli [1], Grzegorz Kwiatek[1], Patricia Martínez-Garzón[1], Georg Dresen[1,2], Marco Bohnhoff[1,3]

[1]*Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam; Germany,* [2]*Institute of Earth and Environmental Sciences, Universität Potsdam, Potsdam, Germany,* [3]*Department of Earth Sciences, Free University Berlin, Berlin, Germany*

Earthquake forecasting is crucial for enhancing disaster preparedness and mitigating the devastating impact of seismic events. However, it is a highly challenging task due to the complexity of deformation processes, evolving fault structure and the varying mechanical behavior of geomaterials. Recent advances in machine learning (ML) have provided new avenues to the seismology community. As a laboratory-scale experiment for labquakes, we use acoustic emission (AE) records from three stick-slip tests performed on Westerly granite samples with rough faults, extracting 47 seismo-mechanical and statistical features (e.g., AE event rate, b-value, correlation integral, to name a few). These features are then subjected to an unsupervised K-means clustering, revealing three distinct stages with a proper agreement with the temporal evolution of stress. The identified stages characterize the mechanical behavior of the rock, including an initial stable (elastic) deformation, followed by a transitional stage leading to unstable deformation prior to failure. This indicates that these features include high-dimensional data points that inform about stress evolution and time to failure (TTF). Therefore, an ensemble of Long-Short Term Memory (LSTM) networks is employed to predict the TTF of large and small stick-slip events. The TTF prediction on test data yields a coefficient of determination (R2) of 70%. Through a feature importance analysis, we find that AE rate, correlation integral, event proximity, and AE-derived focal mechanism-based features are the most important features in TTF prediction. The network incorporates all available information for forecasting failure, encompassing either general trends or small multi-scale details of the preparatory process from both high- and low-correlated features. Overall, these findings hold promise for advancing earthquake forecasting methodologies based on laboratory experiments and catalog-driven features.

1.8 Testing AI-based denoising and picking techniques for microearthquake detection in an urban area in the Lower Rhein Embayment, Germany

Sebastian Carrasco[1], Marco P. Roth[1], Rebecca M. Harrington[1], Kasper D. Fischer[1]

[1] *Ruhr University Bochum, Germany*

The Lower Rhine Embayment (LRE) is one of Germany's most seismically active regions, where historical records provide evidence for a total of nine Ms > 5 earthquakes in the region near Aachen. The extensional faulting system hosts a moderate seismicity rate with regional mean slip rates of approximately 0.1 mm/yr on a set of normal faults that offer many possible conduits for fluid circulation along the general NNW strike direction. The combination of comparatively high permeability near the fault zone and a profitable geotherm also makes the LRE an ideal potential target for geothermal energy production. In the context of the SIEGFRIED project (see poster by Dietl et al.), creating a high-resolution earthquake catalog to quantify background seismicity and study the active structures in the region is necessary to ensure safe and economical energy production. Nevertheless, the comparatively high average noise level above 1 Hz in the LRE study area (primarily of anthropogenic origin) hinders classical automated earthquake detection routines, particularly for low-magnitude events (M<0.5).

In this study, we test the performance of different state-of-the-art AI-based denoising and picking techniques with the aim of developing a workflow that automates earthquake catalog building in a high-noise environment. We start by creating a waveform database of local seismic-event recordings and add random noise recordings from a local station to generate customized signal-to-noise ratios (SNR) that range between -15 and 7 dB. We then implement different AI-based pickers via SeisBench (Woollam et al., 2022), by applying them to raw, filtered, and denoised waveforms from the waveform database. We test four denoised datasets by implementing different denoising models, including the untrained DeepDenoiser (Zhu et al., 2018), and three area-, station-, and channel-wise trained denoising models using an autoencoder approach (Heuel & Friederich, 2022) that allows evaluating how specific the denoising model should be. The results show that DeepDenoiser provides a higher denoised SNR for high input-SNR signal, while the trained denoising models provide similar results in terms of waveform retrieval parameters. Specifically, the trained denoising models provide higher denoised SNR for low input-signal SNR, more similar waveforms, and preserve waveform amplitudes better than DeepDenoiser. We apply the final combination of picker and denoiser to the ZB seismological network (Finger et al., 2022), deployed during the time period between 2021 and 2022 near Weisweiler. We perform event association with PyOcto (Münchmeyer, 2024) to generate a catalog that is compared to the manual solutions from the Bensberg Earthquake Observatory, University of Cologne.

1.9 Transformer-Based Prediction of 3-Component Seismic Waveforms and Phase Arrival Times

Waleed Esmail[1], Alexander Kappes[1], Stuart Russell[2], Christine Thomas[2]

[1]*Institut für Kernphysik, Universität Münster,* [2]*Institut für Geophysik, Universität Münster*

This study aims to improve the precision of predicting seismic waveforms and phase arrival times, which are essential for diverse applications such as earthquake monitoring and gravitational waves detection. We utilized the Patch Time Series Transformer (PatchTST), a transformer-based model specifically designed for multivariate Long Time Series Forecasting (LTSF). The model employs data patching techniques to manage the complexities of seismic data effectively, thereby significantly reducing computational demands.

Our approach involved training the PatchTST model on noise-free synthetic seismograms calculated using realistic source parameters and Green's function databases derived from a 1D Earth model. This model was developed using AxiSEM, a spectral element code for simulating global seismic wave propagation. The objective was to predict future seismic phases and their arrival times from recorded seismograms. The model employed a windowed prediction technique, beginning with an input window at the P-wave arrival and iteratively forecasting subsequent seismic phases.

The findings indicate that the model can accurately predict various seismic phases, including S-waves and surface waves, demonstrating its robustness and reliability. This capability positions the PatchTST as a valuable tool for early warning systems and seismic risk management. Moreover, the model's strong performance suggests it could enhance the sensitivity and detection capabilities of next-generation seismic observatories, such as the Einstein Telescope.

SESSION 2

AG Seismology

2.1 A refined shear velocity model beneath the Iranian plateau using adjoint noise tomography

Abolfazl Komeazi[1], Ayoub Kaviani[1], Farzam Yaminifard[2], Mohammad Tatar[2], Georg Rümpker[1,3]

[1]*Institute of Geosciences, Goethe-University Frankfurt, Frankfurt, Germany;* [2]*nternational Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran;* [3]*Frankfurt Institute for Advanced Studies, Frankfurt, Germany*

We perform an adjoint waveform tomography using Rayleigh wave Empirical Green's Functions (EGFs) at 10-50 s periods to improve a prior 3-D velocity model of the crust and uppermost mantle beneath the Iranian Plateau. EGFs were derived from cross-correlations of 8 years of continuous vertical component seismic noise recorded by 128 broadband stations within the region. Adjoint tomography refines the initial model by iteratively minimizing the frequency-dependent traveltime misfits between the synthetic Green's Functions (SGFs) and EGFs measured in different period bands. The total misfit is dropped by 85 percent after 16 iterations. The use of a numerical spectral-element solver in adjoint tomography provides highly precise structural sensitivity kernels, resulting in more robust images compared to those generated by ray-theory tomography. Our study also demonstrates improvement in lateral resolution and depth sensitivity. The final model adjusts the shapes of velocity anomalies at crustal and uppermost mantle depths especially in the Zagros convergence zone. The refined model reveals a more pronounced and regionally variable underthrusting of the Arabian plate beneath Central Iran, with distinct differences in crustal and mantle configurations between the NW, Central, and SE Zagros. Additionally, the model provides new insights into the thermal and mechanical processes at play within the upper mantle, indicating that the uppermost mantle beneath Central Iran and the Zagros are in a more comparable state than previously understood.

2.2 The cascade of events triggering a teleseismic week-long monochromatic signal

A. Carrillo-Ponce[1,2], S. Heimann[2], G. Petersen[1], T. R. Walter[1,2], S. Cesca[1], T. Dahm[1,2]

[1]*GFZ German Research Centre for Geosciences, Potsdam, Germany;* [2]*Institute for Geosciences, Universität Potsdam, Potsdam, Germany*

A cascade of events took place in a remote area of East Greenland on 16 September 2023. Using seismological data on regional and global scales we can reconstruct the series of events, which is also validated with high-resolution satellite images. The seismic signals generated in the Dickson fjord are dominated by two distinct frequency ranges: a long-period (LP) signal (0.02-0.06 Hz) immediately followed by a very-long period (VLP) monochromatic signal (0.0109 Hz). While the LP signal is clearly visible at regional distances, the latter VLP signal was recorded as far as at 5000 km distance and lasted over a week. To characterize their seismogenic processes we perform single force (SF) inversions to both signals and obtain that the LP waveform is well reproduced by a downward SF, whose orientation is consistent with the rockslide geometry reconstructed by the satellite imagery. The VLP signal, on the other hand, is characterized by a oscillating horizontal force that is oriented perpendicular to the fjord, which is consistent with water seiching back and forth in the fjord. To understand the long duration of the VLP oscillation, we analyse the stacks of three teleseismic arrays signals, where the best fit of the amplitude decay is explained with a damped oscillator model. A simple analytical model is also considered to explain the force direction and frequency of water seiching in a narrow fjord.

Angela Carrillo-Ponce, Sebastian Heimann, Gesa M. Petersen, Thomas R. Walter, Simone Cesca, Torsten Dahm; The 16 September 2023 Greenland Megatsunami: Analysis and Modeling of the Source and a Week-Long, Monochromatic Seismic Signal. The Seismic Record 2024;; 4 (3): 172–183. doi: https://doi.org/10.1785/0320240013

2.3 Recent developments at GEOFON

Angelo Strollo[1] and the GEOFON team

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

The GEOFON program consists of a global seismic network, a seismological data centre and a global earthquake monitoring system (https://geofon.gfz-potsdam.de). These three pillars are part of the Modular Earth Science Infrastructure (MESI) of the GFZ. GEOFON provides real-time seismic data, access to its own and third-party data from its archive facilities, and global and rapid earthquake information. The GEOFON seismological software, together with the related technology and knowledge transfer activities, can be considered as the fourth module of the GEOFON program promoting open science policies. Data, services, products and software openly distributed by GEOFON are used by hundreds of users and data centres worldwide. In this presentation, we highlight the latest developments and provide an update on ongoing and planned activities of interest to the German seismological community.

2.4 Rotational Seismology: ground motion simulations to structural health monitoring

Anjali Dhabu[1], Céline Hadziioannou[1]

[1]*nstitute of Geophysics, University of Hamburg, Germany*;

Seismic ground motions have continued to provide crucial information regarding the Earth's interior and identifying the sources. Understanding earthquake ground motions is also crucial to designing earthquake-resistant infrastructure. In the absence of recorded ground motions, analytical or numerical simulation techniques are often employed to obtain synthetic ground motions. Conventionally, translational ground motions have been used to carry out waveform tomography, moment tensor inversion, and earthquake-resistant design of civil engineering structures and simulations.

The development of seismic instruments over the last two decades has shown that earthquakes generate translational ground motions and rotational ground motions. Therefore, there is a need to cross-verify whether the existing methodologies to understand Earth's interior, simulation techniques, and ways of structural health monitoring apply to rotational ground motions. The current work focuses on these aspects of rotational ground motions. A novel attempt is made to develop analytical solutions for the response of Earth when subjected to earthquake sources when the medium is modeled as a homogeneous and layered Reduced Micropolar medium. It is observed that the rotational ground motions are higher in the reduced micropolar medium and closer to recorded data than those obtained from the classical elastic medium. However, as the additional material properties required to model a medium as reduced micropolar are unknown for the Earth medium, there is a need to explore numerical simulation techniques. In order to achieve this objective, our work currently focuses on incorporating heterogeneities in the Earth medium to simulate realistic rotational ground motions. An important aspect of analyzing earthquake ground motions is ensuring the safety of infrastructure in the advent of an earthquake. The present work also makes a unique attempt to carry out operational and experimental modal analyses using six component ground motions.

2.5 Does rotational data change our understanding of Modal Analysis?

Anjali Dhabu[1], Céline Hadziioannou[1]

[1]*Institute of Geophysics, University of Hamburg, Germany*;

Earthquakes cause catastrophic damage to buildings and loss of human life. Civil engineers across the globe design earthquake-resistant buildings to minimize this damage. Conventionally, the structures are designed to resist the translational mo- tions caused by an earthquake. However, with the increasing evidence of rotational ground motions in addition to the translational ground motions due to earthquakes, there is a crucial need to identify if these additional components have an impact on the existing structural design strategies. In this regard, the present study uses a novel approach to obtain the dynamic properties of a large-scale prototype prestressed re- inforced concrete bridge structure using six component (6C) ground motions. The structure is instrumented with conventional translational seismic sensors, rotational sensors and newly developed six-component sensors under operating and exter- nally excited conditions. The recorded data is used to carry out Operational Modal Analysis and Experimental Modal Analysis of the bridge. Modal analysis using the rotational measurements shows that the expected location of maximum rotations on the bridge differs from the maximum translations. Therefore, further understanding the behavior of rotational motions is necessary for developing earthquake-resistant structural design strategies.

2.6 Whispers in the WAVEs: Decoding Campus Vibrations with Distributed Acoustic Sensing

C. Hadziioannou[1], L. Bogner[1], O. Bölt[1], S. Croatto[2], D. Gajewski[1], E. Genthe[2], O. Gerberding[3], M. Hoffmann[2], K.-S. Isleif[2,4], A. Kiel[1], C. Krawczyk[5], R. Maaß[1,6], I. Malucelli Barbosa[1], N. Meyners[2], R. Rading[4], H. Schlarb[2], W. Vossius[4], V. Wodtke[1], C. Wollin[5]

[1]*University of Hamburg, Institute of Geophysics, Hamburg, Germany;* [2]*DESY, Hamburg, Germany;* [3]*University of Hamburg, Institute for Experimental Physics, Hamburg, Germany;* [4]*Helmut-Schmidt-Universität, Hamburg, Germany;* [5]*GFZ, Potsdam, Germany;* [6]*DIAS, Dublin, Ireland*

Dense seismic sensor networks, especially distributed acoustic sensing, and methods of big-data processing, such as artificial intelligence, are revolutionizing our capabilities to monitor, understand and predict seismic and seismo-acoustic processes and disturbances. In May 2021, we started developing a seismic network, consisting of seismometers, geophones and a 19 km DAS fiber loop. The network was deployed on a scientific campus in Hamburg, Germany, which comprises the Deutsches Elektronen-Synchrotron (DESY), the European XFEL, PETRA III and Physics institutes of the University of Hamburg and further institutes and infrastructures. Our measurements provide insight into the sources of anthropogenic and natural vibrations and how they couple into large-scale and ultra-precise measurement research facilities that are otherwise limited by such disturbances. Here, we will present a selection of initial observations, along with a summary of the lessons learned while deploying fiber inside existing infrastructure.

2.7 Mantle Scattering of Seismic Energy into the Core Shadow

Tuo Zhang(1, 2), **Christoph Sens-Schönfelder**[1], Marcelo Bianchi[3], Klaus Bataille[4]

[1]*GeoForschungsZentrum GFZ, Potsdam, Germany;* [2] *College of Geophysics, Chengdu University of Technology, Chengdu, China;* [3] *Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Brazil* [4] *Earth Sciences Department, University of Concepción, Chile*

In the ray theoretical limit of high frequency waves, core phases are the first arrivals in the core shadow beyond about 100 deg epicentral distance. Waves diffracted at the core-mantle boundary decay rapidly above 1Hz and the PKP precursor between 120 and 145 deg that results from scattering of core phases in the mantle precedes the PKP wave by up to 20 second, only. Yet, one can observe high frequency energy arriving dozens of seconds prior to the core phases throughout the core shadow up to 150 deg. This energy has previously been observed up to a distance of 130 deg and it has been associated to the diffracted P-diff phase and hence termed P-diff coda. We present new observations that show a transition of the energy in the core shadow from a decaying shape the could be interpreted a coda of P-diff energy at short distances via a flat portion between 120 and 130 deg to an emergent shape beyond 140 deg. Especially the emergent shape at large distances defies an origin as scattered coda of diffracted energy. Modelling the propagation of scattered high frequency energy in established models of mantle heterogeneity explains the shape of the envelopes. It confirms the origin of the energy as waves scattered in the mantle with a minor influence of core diffraction. Due to the weak heterogeneity in the mantle scattering is dominantly single-scattering which results in a particular sensitivity of the wave path to the depth of scattering. Different depths contribute to different time windows between the P-diff and PKP arrivals, providing new opportunities to infer the depth distribution of mantle heterogeneity.

2.8 Impact of ocean-generated microseism on the European X-ray - Free Electron Laser

Erik Genthe[1]

[1]*Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*

The bunch arrival time stability at European XFEL has noise between 0.05 Hz and 0.5 Hz, sometimes stronger than 25 fs peak-to-peak. By correlating European XFEL bunch arrival time data with seismic Distributed Acoustic Sensing (DAS) measurements, it is shown that the noise is of seismic origin. The seismic noise in this frequency band is known to be ocean-generated microseism, low-frequency seismic noise caused by ocean waves. Next, both primary and secondary ocean-generated microseism were identified using seismometers and a numerical ocean wave model. Whereas secondary microseism has a strong impact on the bunch arrival time, primary microseism has no notable effect. It is shown, that effect on the bunch arrival time is caused by Rayleigh waves, while Love waves have a negligible influence on the bunch arrival time. In the presented cases, the noise originates from the North Atlantic and/or the North Sea. The amplitude of the noise depends on the weather conditions in the North Sea and the North Atlantic and is generally much stronger in winter. In conclusion, this work shows that ocean-generated microseism is a significant bottleneck that must be addressed to achieve femtosecond bunch arrival time stability.

2.9 Predicting earthquake-induced wavefield and stress dynamics in high-alpine mountains using full waveform modeling

Fabian Limberger[1], Georg Rümpker[1], Jan Philipp Kruse[1], Thibault Duretz[1]

[1]*Institute of Geosciences, Goethe-University Frankfurt, 60438 Frankfurt am Main, Germany*

Landslides and rockfalls in mountain regions have become a growing concern due to various factors such as increasing permafrost melting and heavy rainfalls. However, the characteristics and potential criteria of earthquake-induced slope instabilities remain poorly understood. This study investigates earthquake-induced wave dynamics at mountain summits, particularly at the Matterhorn (Switzerland) and Tre Cime di Lavaredo (Italy). Full wavefield modeling is utilized to simulate the induced resonant oscillations and amplification of seismic signals at the summits compared to adjacent valleys. The simulated amplification (up to 10 times) in the summit depends on the characteristics of motion direction, topography, and presence of permafrost. Major resonance modes are identified at Matterhorn at frequencies of 0.4 Hz and 1.4 Hz. Higher resonance frequencies above 2 Hz are obtained at the smaller rock formation Tre Cime di Lavaredo, indicating the existence of mountain-specific resonances. Furthermore, we demonstrate that the presence of a permafrost body inside the mountain tends to mitigate seismic amplification by up to 30this effect is dependent on the amount of permafrost and the wavelength of the seismic waves. To identify locations of potential slope instabilities on the mountain's surface, the dynamic stress changes during the simulated earthquake are calculated. We find that locations of stress amplification are mainly at the mountain flanks and are influenced by azimuthal characteristics of the incoming wave. The approach and findings presented in our study have the potential to improve hazard assessments, specifically for earthquake-induced slope instabilities at mountains caused by external seismic waves.

2.10 Uncertainty estimations of manual shear wave splitting measurements by comparing multiple analyses of the same dataset

Dorn Fiona[1], Dillah Muhammad I. F.[1], Fröhlich Yvonne.[1], Ritter Joachim R. R.[1]

[1]*Karlsruhe Institute of Technology (KIT), Geophysical Institute (GPI), Karlsruhe, Germany*

The observation of shear wave splitting (SWS) is an important indication of seismic anisotropy in the Earth's interior and, thus, of deep geodynamic deformation processes. We measure the SWS of SKS, SKKS, and PKS (jointly referred to as XKS) phases and determine the splitting parameters, the fast polarization direction and the delay time t, using both the energy minimization and the rotation-correlation methods. Especially, we search for phase pair SWS discrepancies, i.e., between SKS and SKKS phases, as they are a clear indication for a lowermost mantle (LMM) contribution to the splitting signal. Here, we present SWS measurements (SWSMs) of XKS phases recorded at the station KEF (network HE) in Finland, which sample the LMM underneath Siberia and the North Atlantic. By comparing phase pairs and splitting parameters obtained by different analysts, we study both subjective and objective aspects that are crucial to consider when performing SWSMs. These include the selection of the filter parameters (corner frequencies, bandwidth) and the time window (length relatively to the dominant period), phase interferences (direct S wave, depth phases), as well as the systematic deviation of the initial polarization direction from the theoretical backazimuth (e.g. to detect a potential misorientation of the seismic sensor or other disturbing seismic phases including noise). Repeated measurements, in combination with analytical criteria for the quality classification of the SWSMs, allow us to estimate the reproducibility and the uncertainties of the splitting parameters. This can be used as a basis for future analyses and the interpretation of modeling results. This study is embedded in the DFG priority program 2404 "Reconstructing the Deep Dynamics of Planet Earth over Geologic Time" (DeepDyn, https://www.geo.lmu.de/deepdyn/en/).

2.11 "Verlorene" seismologische Archive

Frank Krüger [1], Galina Kulikova[2], Johannes Schweitzer[3]

[1]*Institut für Geowissenschaften, Universität Potsdam;* [2]*UP Transfer GmbH an der Universität Potsdam;* [3]*NORSAR*

Im Rahmen unserer Pilotstudie zur Digitalisierung von seismischen Aufzeichnungen in Deutschland haben wir 12 seismische Datenarchive gefunden. Die Einzelheiten dieser Studie finden Sie in unserem anderen Abstract. Hier möchten wir ein weiteres Problem diskutieren, dem wir bei der Suche nach analogen seismischen Datenarchiven begegnet sind. Durch unsere Recherche wissen wir, dass die gefundenen 12 seismischen Datenarchive analoge seismischen Aufzeichnungen von 16 Stationen enthalten. Den damaligen Literatur- und Erdbebenberichten zufolge gab es jedoch auf dem Gebiet des Deutschen Reiches mehr aktive seismische Stationen. Wir haben eine Liste der Stationen erstellt, die zwar teils mehrere Jahrzehnte aufgezeichnet haben, deren Daten jedoch bisher nicht gefunden wurden. Wir haben nur in wenigen Fällen Beweise (in der Regel nur Hinweise aus zweiter Hand) dafür gefunden, dass diese Daten endgültig vernichtet wurden. Ein interessantes Beispiel ist der Seismograph des Astrophysikalis-Seismic full-waveform inversion (FWI) is widely used for subsurface imaging across a broad range of scales. To this end, it is essential to model the wavefield as accurately as possible to avoid becoming trapped in a local minimum. In addition to a suitable initial model, knowledge about the source mechanism and the radiated source wavelet is required. While we usually know the source mechanism in active seismic experiments and the wavelets can be derived from near-offset traces, seismological sources are frequently unknown. Therefore, seismologists perform moment tensor inversion to reconstruct the source mechanism and use standard wavelets for modeling. Similarly, one could approach the determination of the source signature of an active source prototype.

Here, we discuss the case of a prototype borehole SV-source, which produces predominantly vertically polarized S-waves. The source is clamped to the borehole wall with an inflatable bladder. According to the manufacturer, the source pulse is generated electromagnetically. The source does not require a predefined orientation, but allows the user to choose between an upward or downward shot direction. The latter was used in our field data acquisition in the glacial sediments of the overdeepened Tannwald Basin north of Lake Constance.

In order to gain insight into the source mechanism, we forward model synthetics in our crosshole geometry, based on a 2D tomography model. We choose a bandpass-filtered spike as source wavelet, as this allows modeling all frequencies in the defined frequency range equally well. As potential source mechanism we use a vertical force and moment tensors that have zeros on the components which are related to the transverse direction. A comparison of the synthetics with the field data indicates that a simple vertical force assumption produces a signal that is most closely aligned with the observed waveforms with regard to the relative amplitude changes with offset and the P-to-S-amplitude ratio. chen Instituts Heidelberg. Er registrierte mindestens bis 1915. Für die Station liegen Bulletins (beim ISC) von 1909 bis 1916 vor. In der Literatur fanden wir: „... ein alter mechanischer Seismograph war seit etwa 1900 in Betrieb, die Aufzeichnungen sind nicht mehr verfügbar". Durch Kontakt zur Sternwarte Königsstuhl, haben wir aber vielleicht doch eine Spur bezüglich der Aufzeichnungen gefunden. Ein weiteres interessantes Beispiel ist die ehemalige seismische Station in Clausthal. Hier existieren analoge seismische Aufzeichnungen im Kieler Archiv (Institut für Geowissenschaften, Universitätsarchiv Kiel), aber Details zur Station (Standort, Betriebszeit, Instrumentenparameter) fehlten bis vor kurzem völlig und sind immer noch bruckstückhaft. Insgesamt gibt es mindestens 8 seismische Stationen aus dem frühen 20. Jahrhundert, bei denen Erklärungsbedarf über den Verbleib der Daten besteht. Bisher haben wir eine kurze Veröffentlichung in GMIT (Juni 2024) erstellt, in der wir um Hinweise zu diesen Daten gebeten haben. Darüber hinaus haben wir diesbezüglich auch mit Staatlichen Geologischen Diensten, Bergämtern, Landes- und Universitätarchiven Kontakt aufgenommen, mit der Bitte zu prüfen, ob in deren Archiven oder Bibliotheken noch weitere analoge seismische Daten vorhanden sind. Hier möchten wir vorstellen, was unsere Recherche bisher ergeben hat. Wir hoffen, durch diese Präsentation auch noch mehr Input, Tipps und Ratschläge von der AG-Seismologie zu bekommen.

2.12 Towards continuous sub-oceanic monitoring with SUBMERSE and SAFATOR

Frederik Tilmann[1,4], Chris Atherton[6], Carmela Asero[7], Fabrice Cotton[1,2], Charlotte Krawczyk[1,3], Laura Wallace[5], Maik Thomas[1,4], Wolfgang zu Castell[1] and the SUBMERSE[8] and SAFATOR teams[1,5]

[1]*GFZ German Research Center for Geociences, Potsdam (tilmann@gfz-potsdam.de);* [2]*University of Potsdam;* [3]*Technical University Berlin;* [4]*Freie Universität Berlin;* [5]*GEOMAR, Kiel, Germany;* [8]*GÉANT Vereniging, Amsterdam;* [7]*European Future Innovation System Centre, Bruxelles;* [7]*24 partners, see https://submerse.eu/partners/*

In the last years, fibre optic sensing methods, among them Distributed Acoustic Sensing (DAS) and State-of-Polarisation (SoP) have been demonstrated to be suitable for monitoring Earth System parameters in submarine cables through several pilot experiments, but full integration with telecommunication infrastructure has not yet been achieved. A new development concerns sensor pods containing classical sensors placed along telecom Cables (making them SMART-cables). Here, we introduce the EU HORIZON funded SUBMERSE project (SUBMarinE cables for ReSearch and Exploration) and the Helmholtz Large Infrastructure proposal SAFAtor (SMART Cables And Fiber-optic Sensing Amphibious Demonstrator). The SUBMERSE project links Research and Education Networks (RENs), universities, research institutes and industry to establish multi-method monitoring along submarine optical telecommunication cables at several key oceanic cable routes branching off from Sines in Portugal, Madeira, Svalbard and in the Ionian Sea. Those pilot sites should serve as a blueprint for establishing continuous monitoring services along many more cables. The project comprises technical developments for integrating DAS and SoP measurements, for establishing differential SoP measurements and for operating DAS in in fibres carrying telecom traffic. A range of geoscientific and marine biology use cases are included, which seek to establish code/services for monitoring earthquakes and tsunamis, tracking whales, etc. It is planned to distribute the data collected by SUBMERSE through EIDA but one of the lessons from this project is that striking a balance between national and cable security concerns and data openness can be challenging, and suitable protocols are still being worked on. SAFAtor aims at closing the observational gap in the continental shelf, slope, and deep oceans, with three main objectives 1) establish DAS permanent offshore monitoring at three existing Plate Boundary Observatories in coastal areas (N Chile, Marmara Sea and Sicily; 2) drive innovation in SMART sensor technologies by equipping a submarine telecom cable with robust sensor packages to measure temperature, absolute pressure and ground acceleration on the sea floor. 3) develop a FAIR data infrastructure to process, archive and distribute these new DAS and cable data, and enable the global user community to select and process the data services in a user-friendly and interoperable way.

2.13 Sustainable preservation of analogue seismic data in Germany – Digitization test.

Galina Kulikova[1], Frank Krüger[2], Celine Hadziioannou[3]

[1]*UP Transfer GmbH at the University of Potsdam;* [2]*Institute of Geosciences, University of Potsdam;* [3]*Institute of Geophysics, University of Hamburg*

Last year the beginning of our feasibility study aiming to estimate the possibility to digitize all analogue seismic data in Germany was announced. This study is funded by the Federal Institute for Geosciences and Natural Resources (BGR) and is carried out by a small working group of researchers from the University of Potsdam and the University of Hamburg. Here we would like to present and discuss the first results of the study. A rough inventory of the contents of the analogue seismic data archives has now been completed. A total of 12 German institutions that stored seismic records in analogue form and the corresponding metadata in their archives participated in it. The information was collected from all 12 institutions and combined into a single database. The database is to be published together with a report describing the contents of all analogue seismic data archives existing in Germany, with detailed information on their contents. Furthermore the digitisation test has started in order to estimate the workload for continuous scanning and digitizing of seismic records. The appropriate time period for scanning and digitizing has been intensively discussed. It was then decided to select 3 different time periods of 1 month (continuously). Each of this time period covers very important stage in the development of seismic instrumentation, and thus in the quality of seismic data. So far we have scanned the data from two stations and two more are in planning. Corresponding metadata information was collected accordingly. Different techniques and equipment have been and will be tested for scanning the paper records. Different scanning parameters such as resolution, color depth, brightness, contrast, file formats, have been tested as well. Additionally the scanned seismic records are to be vectorised with two different tools and compared. The Albstadt earthquake on 16.11.1911 was selected for testing the methods of determining an earthquakes source parameters (e.g.Im Rahmen unserer Pilotstudie zur Digitalisierung von seismischen Aufzeichnungen in Deutschland haben wir 12 seismische Datenarchive gefunden. Die Einzelheiten dieser Studie finden Sie in unserem anderen Abstract. Hier möchten wir ein weiteres Problem diskutieren, dem wir bei der Suche nach analogen seismischen Datenarchiven begegnet sind. Durch unsere Recherche wissen wir, dass die gefundenen 12 seismischen Datenarchive analoge seismischen Aufzeichnungen von 16 Stationen enthalten. Den damaligen Literatur- und Erdbebenberichten zufolge gab es jedoch auf dem Gebiet des Deutschen Reiches mehr aktive seismische Stationen. Wir haben eine Liste der Stationen erstellt, die zwar teils mehrere Jahrzehnte aufgezeichnet haben, deren Daten jedoch bisher nicht gefunden wurden. Wir haben nur in wenigen Fällen Beweise (in der Regel nur Hinweise aus zweiter Hand) dafür gefunden, dass diese Daten endgültig vernichtet wurden. Ein interessantes Beispiel ist der Seismograph des Astrophysikalischen Instituts Heidelberg. Er registrierte mindestens bis 1915. Für die Station liegen Bulletins (beim ISC) von 1909 bis 1916 vor. In der Literatur fanden wir: „... ein alter mechanischer Seismograph war seit etwa 1900 in Betrieb, die Aufzeichnungen sind nicht mehr verfügbar“. Durch Kontakt zur Sternwarte Königsstuhl, haben wir aber vielleicht doch eine Spur bezüglich der Aufzeichnungen gefunden. Ein weiteres interessantes Beispiel ist die ehemalige seismische Station in Clausthal. Hier existieren analoge seismische Aufzeichnungen im Kieler Archiv (Institut für Geowissenschaften, Universitätsarchiv Kiel), aber Details zur Station (Standort, Betriebszeit, Instrumentenparameter) fehlten bis vor kurzem völlig und sind immer noch bruckstückhaft. Insgesamt gibt es mindestens 8 seismische Stationen aus dem frühen 20. Jahrhundert, bei denen Erklärungsbedarf über den Verbleib der Daten besteht. Bisher haben wir eine kurze Veröffentlichung in GMIT (Juni 2024) erstellt, in der wir um Hinweise zu diesen Daten gebeten haben. Darüber hinaus haben wir diesbezüglich auch mit Staatlichen Geologischen Diensten, Bergämtern, Landes- und Universitätarchiven Kontakt aufgenommen, mit der Bitte zu prüfen, ob in deren Archiven oder Bibliotheken noch weitere analoge seismische Daten vorhanden sind. Hier möchten wir vorstellen, was unsere Recherche bisher ergeben hat. Wir hoffen, durch diese Präsentation auch noch mehr Input, Tipps und Ratschläge von der AG-Seismologie zu bekommen. epicentre location, magnitude and focal mechanism determination) based on digitized analogue data. All digitization steps will be documented in detail with the corresponding recommendations for data collection, data digitization and further processing of the digitized data. These recommendations will be recorded in a manual, which will serve as the basis for development of long-term concept for preservation und digitization of all analogue seismic records and corresponding metadata available in Germany.

2.14 Onshore Seismic Monitoring of Submarine Kavachi Volcano Reveals Vigorous Eruptive Activity

Georg Rümpker[1], Ludwig Bitzan[1], Patrick Laumann [1], Clinton Roga[2], Ayoub Kaviani[1], Carlos Tatapu[2], Jack B. Gwali[2], Fabian Limberger[1], Tina Manker[1], Christopher S. Vehe[2]

[1]*Institute of Geosciences, Goethe University Frankfurt, Frankfurt, Germany;* [2]*Geological Survey Division, Ministry of Mines, Energy and Rural Electrification, Honiara, Solomon Islands*

Submarine volcanoes pose considerable challenges in monitoring their activity. Kavachi, situated in the Western Province of the Solomon Islands, is a highly active submarine volcano that presents potential risks to nearby communities, as well as to air and marine traffic in the region. In this study, we employ onshore seismic stations to observe Kavachi's eruptive activity by analyzing seismo-volcanic signals. Based on recordings from seismic array stations situated on Nggatokae Island, approximately 28 km and 36 km away from the volcanic edifice, we detected and quantified the eruptive activity of Kavachi between February and August 2023. We first discuss a dual-station approach that employs station-specific band-limited amplitude ratios to quantify the occurrence of characteristic seismo-volcanic signals. This methodology is inspired by techniques previously applied in bioacoustics for detecting whale sounds within seismograms. Using this method, we compiled an event catalog and demonstrate that it can be effectively used to monitor volcanic activity. Additionally, the method shows potential for long-term monitoring and early warning applications. We further conducted a detailed analysis using data from nine closely spaced seismic stations, focusing on determining the back-azimuth and apparent velocity of volcanic events through automated array analysis in the time domain. Our approach utilizes cross-correlation techniques to solve the inversion problem. The method was tested on synthetic data, followed by calibration with earthquakes from the USGS catalog. We examined the influence of the number of active stations and thresholds for cross-correlation and RMSE. The array analysis identified over 30,000 events, predominantly originating from the direction of Kavachi volcano. Two main phases of activity were observed, characterized by slight variations in back-azimuth and apparent velocities, suggesting shifts in the locations of eruptive centers. The results indicate that onshore seismic arrays can provide crucial data on submarine volcanic eruptions, revealing eruption patterns and associated hazards. This methodology not only offers insights into the eruptive activity of Kavachi volcano but presents potential applications for monitoring other submarine volcanoes globally.

2.15 First results of local earthquake travel-time tomography in the Eifel region based on the large-N seismic dataset

Hao Zhang[1], Christian Haberland[1], Torsten Dahm [1], Marius Paul Isken[2], Patrick Laumann[1]

[1]*GFZ German Research Center for Geosciences, Potsdam, Germany*

The Eifel volcanic fields are located in central Europe and represent a world-class example of distributed volcanism away from plate boundaries, with a large number of volcanoes distributed in two separate fields, and eruption types ranging from monogenic cinder cones to maars and explosive centres. A better understanding of the 3D crustal velocities and anomalous regions is needed to unravel the magma plumbing system, fluid transfer and ultimately the volcanic hazard in the region. From September 2022 to August 2023, more than 350 seismic stations were deployed around the Eifel volcanic fields. The station density in the Laacher See region and along a

140 km long, EW-NS trending profile was only 1 km or less. In addition, a 70 km long fibre- optic cable was used for Distributed Acoustic Sensing (DAS) monitoring for a period of 5

months. Moreover, permanent monitoring stations from seismological services and universities were integrated. The Eifel large-N experiment provides a unique dataset with unprecedented station density, allowing us to resolve and characterize P- and S-wave velocity anomalies in the upper crust beneath the phonolitic centres of the East Eifel Volcanic Field. In this study, a catalog of local earthquake arrival times was automatically generated using a rapid machine learning detection and localization technique. We selected 58000 P picks and 36000 S picks of more than 700 events from the preliminary catalog and then applied the SIMULPS program to invert for both Vp and Vp/Vs models. Here we present our preliminary 3-D tomographic models. Beneath the Laacher See we find low P-wave velocities together with a distinct anomaly of high Vp/Vs ratios reaching values of 1.9 or more down to 6 km depth. In other volcanic regions, such patterns and combinations of Vp and Vp/Vs ratios have been interpreted to indicate the presence of partial melts. Future work could include more catalogs and other dataset (e.g. DAS profiles) to obtain more constrained models.

2.16 Testing the consistency of D'' reflected waves beneath Siberia for different crossing paths

Harini Thiyagarajan,[1],Christine Thomas[1]

[1]*Universität Münster, Institute of Geophysics, Germany*

In recent geomagnetic field models , patches of intense magnetic flux can be identified. The north magnetic field is characterized by two such flux lobes, one underneath Canada and one underneath Siberia, known as High Latitude Flux Lobes (HLFL). A third HLFL is postulated underneath the Norther Atlantic but has not been observed. Studies show that the lower mantle influences the magnetic field through the control of the geodynamo . The aim of this study is to investigate how the underlying lower mantle structure and mineralogy may influence these regions of high magnetic signature.

Using array methods, we search for D'' reflected PdP and SdS waves which arrive as precursors to the core-reflected PcP and ScS waves and that sample the lowermost mantle beneath Siberia with a number of intersecting paths. Especially the new Alaskan station (TA) deployment allows for a better number of crossing paths that are needed to establish whether anisotropy is present. Vespagram and slowness-backazimuth analysis are carried out to detect the presence of lower mantle reflectors at the top of the D'' and establish the wave's travel direction (in plane versus out- of-plane). A comparison with synthetic seismograms establishes whether the observations can be explained by a previously suggested 300km thick D'' layer. We present a number of observations in this region and a wider coverage than previously possible by showing the results for PdP and SdS waves, their travel time and polarity measurements for different crossing paths and focus on the consistency of the observations.

2.17 First analysis from two BlueSeis rotational seismometers in Vogtland, Germany: Indications for strong site-effects?

Johanna Lehr[1], Stefanie Donner[1], Frank Krüger[2], Mathias Hoffmann[1]

[1]*Bundesanstalt für Geowissenschaften und Rohstoffe;* [2]*Universität Potsdam*

We present results from two BlueSeis rotational sensors, operating in the Vogtland region for two years and discuss their usefulness in seismological analysis. The instruments were installed within around 10 km of the Novy Kostel focal zone, which is the source of frequent earthquake swarms. Between June 2022 and June 2024, 313 events with Ml > 1.0 and 10 events with Ml > 2.5 occurred. The most striking result is a strong difference in sensitivity between the two sites Landwüst and Wernitzgrün. At Landwüst, the magnitude of completeness for events detected on the rotational sensor is 1.0 with events down to ML=-0.6 being sometimes well observed. The other site in Wernitzgrün rather shows a magnitude of completeness of 1.5 with the lowest observed magnitude being Ml=+0.7. We attribute this discrepancy to local site conditions. In addition, when determining the backazimuths for individual events from the combined rotational and translational data, we rarely obtained the expected backazimuths between source and receiver coordinates. We believe that this is a consequence of anisotropy, which is known to cause significant S-wave splitting in the region. Overall, our results show that rotational sensors are capable of recording local seismicity at satisfying quality. However, they seem to be much more sensitive to site effects than traditional translational sensors

2.18 Investigation of the D” reflector with short epicentral distances

Julia Pahlings[1] and Christine Thomas[1]

[1]*Institut für Geophysik, Universität Münster*

The Earth’s lowermost mantle is a region that shows many different structures, such as large low velocity anomalies, possibly caused by MORB or primordial material, small-scale scatters and ultra-low velocity zones and ancient slabs that rest at the core-mantle boundary. Another interesting feature is the D" reflector, which has been found in many studies but is not always visible. The reflector lays at a depth of around 2605 km but shows strong topography in places. However, it is still unknown whether the reflector is a global or a local feature, and neither is its origin, as it could be caused by a phase transition, scattering layer, or due to deformed material causing seismic anisotropy. To study the reflector, we analysed earthquakes from Japan, Kuriles, and the eastern Russian coast recorded at the seismic array KNET. We searched for PdP arrivals between P and PcP, SdS arrivals between S and ScS, but we also searched for reflections SdP and PdS, as the short epicentral distance range allows for the detection of these waves. We generate vespagrams and slowness-backazimuth analysis to identify the arrivals and confirm their travelling along the great circle path. Several of the events showed a seismic arrival that could indicate a reflection from the top of the D" layer. The depth range shows a strong scatter, possibly due to out-of-plane propagation that we find in our dataset, but we only find a polarity of the reflections that agree with the main phases, indicating an increase in velocity across the reflector. Our results agree with tomographic images in the area that show a high-velocity zone and our observations suggest that the reflector, mapped in the regions around our study area, continues. But using the directional parameters, we will back-project the reflections in a follow-up study, determining the topography of the D" reflector in this area.

2.19 High frequency 3D array analysis of April 2021 earthquake swarm and search for tremor-like source processes in Westbohemia/ Vogtland

Katrin Hannemann[1], Nikolaus Rein, Matthias Ohrnberger, Frank Krüger

[1]*Universität Münster*

The ICDP Project “Drilling the Eger rift” investigates the geodynamic processes in the czech- german border region in Westbohemia and the Vogtland. It especially focuses on the relationship between the frequently occurring earthquake swarms and the CO2 degassing in the region. For this purpose, several boreholes were drilled to install seismic sensors and gas probing devices to gain new knowledge of this relation. One aim is to improve the high-frequency observations of the frequently occurring earthquake swarms by using 3D arrays as novel observational instruments recording at high sampling frequencies (1000 Hz). One of the sub-projects focuses on the analysis and localization of the continuous wave field trying to image the hypothesized fluid movements in the area. The pilot 3D array in the West of the swarm area at the ICDP site 1.5 km south of Landwüst (Vogtland, Germany) is recording since December 2020. The installation consists of a 12 surface three component (3C) station array and and a 10 level almost vertical 3C borehole array. This new instrument recorded the 2020 December activity as well as the earthquake swarm in April 2021. A first analysis using differential power spectral density (PSD) levels at stations in the area revealed a slight increase in the continuous wave field energy levels before the main phase of the swarm took place. There has been speculations whether this observations could be interpreted as an indication for fluid movements within the crust. In order to confirm or reject this hypothesis we used the 3D-3C array to separate body and surface wave components in the continuous wave field both for this special time period of enhanced energy levels as well as for the period of the swarm itself. Our analysis reveals that the 3D-3C array is capable of clearly identifing the distinct arrivals of body waves form the swarm earthquakes even for very low SNR ratios. However, in the pre- swarm period which showed increased differential PSD (dPSD) levels we rather observe a diffuse mixture of surface waves originating from different directions without any clear body wave content. Moreover, the horizontal components show a loss of waveform coherence within the period of the elevated dPSD levels by a drop in the semblance of about 50recorded wave field. Therefore it seems unlikely that the elevated dPSD levels are caused by deeper crustal sources such as the suspected fluid migration paths which are expected to be located in spatial proximity to the swarm earthquakes.

2.20 Deutsches Stationsnetz und BGR Datenzentrum

Klaus Stammler, Arbeitsbereich “Seismologische und Infraschallstationen, Datenzentrum”: Markus Dohmann, Björn Goebel, Torsten Grasse, Holger Hauswirth, Mark Hanneken, Mathias Hoffmann, Christian Müller, Jonas Schneefeld, Ralf Schönfelder, Uwe Stelling

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover

Der EIDA[1] -Knoten BGR[2] betreibt in Zusammenarbeit mit Universitäten und anderen Einrichtungen der Länder das Deutsche Regionalnetz (GRSN)[3] . Dieses und inzwischen fast alle Netze der Bundesländer sowie einige permanente Netze von Universitäten sind über standardisierte EIDA/FDSN-Webdienste[4] über das Datenzentrum der BGR verfügbar (Permanentnetze BQ, GR, GQ, HS, KQ, LE, RN, SX, TH, siehe dazu FDSN Netzliste[5]). Um die Datenqualität zu sichern, werden verschiedene Algorithmen auf die Wellenformdaten angewendet. Zum einen durch EIDA-Standards[6] zum andern ergänzt durch BGR eigene Analysen[7] . Um die angebotenen Dienste des Datenzentrums langfristig zu sichern, muss die über viele Jahre gewachsene Software-Infrastruktur zukunftsfähig, d.h. zum großen Teil erneuert werden. Mit diesen Arbeiten wurde begonnen, der Abschluss dieser Umstellung soll bis 2029 erfolgen.

[1] *https://www.orfeus-eu.org/data/eida/*
[2] *https://www.bgr.bund.de*
[3] *https://doi.org/10.25928/mbx6-hr74*
[4] *https://www.fdsn.org/webservices/*
[5] *https://www.fdsn.org/networks/*
[6] *https://www.orfeus-eu.org/data/eida/quality/*
[7] *https://www.szgrf.bgr.de/quality_summary_pages/*

2.21 Investigating the D structure beneath the Indian Ocean with source- and receiver arrays

Cristine Thomas[1], **Lena Tölle**(1, 2)

[1]*Institute for Geophysics, University of Münster;* [2]*Institute for Mineralogy, University of Münster*

The lowermost mantle beneath the Indian Ocean has not been extensively studied with P- and S-reflected waves from the D" region but the region is thought to be adjacent to the

large-low velocity province beneath Africa and it may contain ancient slab material. Mapping the D structure will help to understand processes and mineralogy in this area. To investigate seismic structure and mineralogy in this region, we collect a large number of events from Indonesia recorded at arrays in East Africa and the Middle East. We are looking for seismic waves reflected at the D" discontinuity, that lies about 300 km above the CMB. These reflected waves are mainly PdP and SdS waves, but later we also want to use also PdS and SdP waves. We analyze the events using array methods (vespagram, slowness-backazimuth analysis). We find a good number of PdP waves from this area, where the PdP waves can be easily distinguished from the P and PcP waves based on different slowness. The traveltime, amplitude, polarity and slowness of the waves are then recorded. The traveltime is used to estimate the depth, and we detect differences between the observed traveltime and the expected traveltime for reflections at a depth of about 2600 km. The amplitude and polarity are used to analyze changes in velocity and density between the mantle and the D region and our data show variable polarity of the PdP waves, which may indicate anisotropy in D". For a larger coverage of the Indian Ocean, a comparison with source vespagrams (several events recorded at one station) for stations in the western Indian Ocean. These data, which we process with migration methods also show a presence of a D" reflector.

2.22 Real Time 3D-Earthquake visualization of Earthquakes

Lutz Sonnabend[1], Sascha Gröne[1]

[1] *SAXON STATE OFFICE FOR ENVIRONMENT, AGRICULTURE AND GEOLOGY Referat 102 | Geological Survey and Geophysics*

The visualisation of earthquakes, especially large earthquake clusters, is a major challenge. Due to the 3D nature of fault zones and the associated distribution of earthquakes, maps are often very difficult to interpret. Even seismologists with years of experience often struggle to make sense of all the information, which is often decoded in a variety of marker colours, shapes, shading and sizes. The problem gets worse as the dataset grows. Our area of responsibility includes the Vogtland/Northwestern Bohemia earthquake swarm, with tens of thousands of earthquakes in a small region. As a public institution with an obligation to inform the majority of the population about our environment, we have developed a new approach to this problem. Over the past few years, we have been working with GiGa infosystems GmbH to develop a viewer for our geological 3D models. In its latest update, we have added the ability to harvest the live earthquake data we provide on our 2D platform and other FDSN web services. The data can be displayed alongside our 3D structural models and is updated hourly. It's completely open and universally accessible via a convenient web service. It provides an easy way to customise the visual appearance (e.g. size and colour) of the markers, along with a free choice of earthquake parameters (e.g. time-depth magnitude) that control said markers. The service is highly performant and we have tested it with datasets of up to 50,000 data points with no signs of stuttering or lag. Navigation in the 3D dataset is very intuitive and fluid. Each data point has its full parameter set attached, which can be examined in real time using the query tool provided. Originally intended as a public outreach tool, it has proven to be very useful in our daily work in seismology.

2.23 Monitoring seismic velocity changes at Campi Flegrei (Italy) using seismic noise interferometry

Marcel van Laaten[1], Jozef Müller[1,2], Ulrich Wegler[1]

[1]*Friedrich Schiller University Jena;* [2]*Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung Bremerhaven*

Campi Flegrei is a volcanic field located west of the densely populated area of Naples (Italy). Since 2005, its ground has been rising steadily due to the accumulation of fluids at shallow depths. The inflation of volcanic edifices is a possible precursor of an impending eruption. The uplift is accompanied by increasing seismic activity. This raises concerns about the possibility that the volcano may be on the verge of an eruption. To track the fluid movement, it is possible to monitor subtle changes of velocities of seismic waves by exploring ambient seismic noise. By examining different frequency bands, we can observe velocity changes at different depths. We interpret these changes as a monitoring of depth-dependent deformation in addition to the standard monitoring of surface deformation. We observe a velocity decrease in the long-term trend, presumably due to the extension of the hydrothermal system at shallow depths. To explain the long-term changes, we model a spherical pressure source to simulate volumetric strain changes induced by recent fluid activity. The model explains both, surface and subsurface deformation which leads to the opening of microcracks and pores, resulting in the observed velocity decrease. The short-term velocity changes are mainly driven by temperature or groundwater level changes. Once velocity changes are corrected for seasonal effects, remaining short term velocity changes can be associated with volcanic activity and earthquake swarms.

2.24 Time- and stress-dependent elastic properties in a concrete structure; spotting internal damage footprints

Marco Dominguez-Bureos[1], Christoph Sens-Schönfelder[2], Ernst Niederleithinger[3], Celine Hadziioannou[1]

[1]*Institute of Geophysics, University of Hamburg, Germany;* [2]*German Research Centre for Geosciences, GFZ Potsdam, Potsdam, Germany;* [3]*Bundesanstalt für Materialforschung und -prüfung (BAM), Division 8.2 „Non-Destructive Testing*

Time- and stress-dependency of elastic properties are features mainly observed in a variety of complex solids, ranging from steel, polymers, and cracked structures to rocks and concrete. Recently, considerable effort has been made to understand the underlying physics of these phenomena, commonly regarded as Nonlinear Mesoscopic Elasticity (NME) in laboratory setups. As a result, various models have been suggested to explain a range of NME phenomena like hysteresis, dynamic softening, and slow dynamics, among others. Due to the high sensitivity of NME to imperfections or internal damage on solids, there is a growing interest in taking the current models and applying them to construction materials for damage assessment. Intending to observe and incorporate these models into real-condition structures, we carried out a 1-day multifrequency vibration experiment in a 24-meter-long reinforced concrete test bridge equipped with a pretension system to investigate the possible presence of internal damage with vibration-based methodologies. We used the pretension system to subject the specimen to eight compression states in its longitudinal direction (forces of 400kN at the highest and 280kN at the lowest). At every compression state, we struck the structure in the vertical direction three times on the north and south sides of the bridge with an impulse drop weight. Throughout the whole experiment, we recorded ambient seismic noise at different frequency bands with a 14-six-component sensor array to measure the acceleration in the conventional translational components and the angular velocity (rotation rate), a 14-geophone array of 4.5 Hz of natural frequency, and four pairs of embedded ultrasound transducers were used to estimate relative velocity changes (dv/v) by applying the Coda Wave Interferometry (CWI) stretching technique. The internal temperature of the concrete was also recorded to correct our measurements by first-order thermal effects. At the material scale (ultrasound regime) we observe stress-dependent dv/v at four different locations in the specimen and describe them by using the acoustoelastic effect concept regarded as a classical nonlinear phenomenon. The experimental setup allows us to investigate differences in the consecutive-struck recovery for increasing and decreasing loadings in the structure. Our findings reveal that the north side of the bridge exhibits larger magnitudes in both classical and non-classical nonlinear elastic effects. It is important to mention that, according to a visual inspection, there is evidence of external cracking in this span of the bridge.

2.25 FRAME – a Fast Response Aftershock network for the Moroccan Earthquake 2023

Martin Zeckra[1], Lahcen El Moudnib[2], Abderrahime Nouyati[2], Sebastian Carrasco Morales[1,3]

[1]*Seismological Station Bensberg, University of Cologne, Germany;* [2]*Geophysics and Natural Risks Laboratory, Scientific Institute; Geophysics, Natural Patrimony and Green Chemistry Research Center "GEOPAC", Mohammed V University in Rabat, Morocco;* [3]*Ruhr-University Bochum, Germany*

The 2023 Mw 6.9 Moroccan earthquake (September 8th, 2023 at 22:11 UTC) has been the most damaging in this region, in terms of costs (7 billion US-$) and fatalities (2,946) for over 60 years. Located in the slowly deforming Western High Atlas mountain range, this event occurred in an area that showed historically a seismic quiescence. Under the absence of open-access stations in Morocco and little station coverage in the High Atlas, most seismological analyses relied on teleseismic waveforms and satellite remote sensing techniques. From this, an exceptional hypocentral depth of 30 km could be identified, while open questions remained about the source mechanisms and fault geometries driving the mountain building process in general.

Here, we present the first results of a rapid-response effort installing an aftershock network in the source region. As a novelty, we only relied on 5 Hz geophone sensors, enabling fast access to remote locations in and around the heavily affected epicentral region. The performance of these sensors has exceeded our expectations and delivered reliable data over a broad frequency range, way below their natural frequency. Applying an AI-based, ready-to-use event picking and phase associator - as implemented in the SeisBench suite - identified and located around 3000 aftershocks. Despite its preliminary data quality, this catalog already reduces location uncertainties and greatly increases the event density. Here, the events clearly outline the steeply dipping fault plane estimated in the teleseismic and geodetic source inversion, shedding light on the remaining open questions.

In this study we show, that combining easy to deploy, self-reliant geophone sensors with pre-trained Machine Learning software suites largely reduces reaction times in rapid response initiatives. The high flexibility allows us to set-up aftershock networks within hours to days after the main shock, while it becomes possible to present a full aftershock catalog within a few days after data collection.

2.26 Secondary microseisms in ice-covered areas - two examples from Antarctica

Mechita C. Schmidt-Aursch[1], Javier Almendros[2], Won Sang Lee[3], BRAVOSEIS Working Group, EWARS Working Group

[1]*Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany;* [2]*University of Granada, Granada, Spain;* [3]*Korea Polar Research Institute, Incheon, Korea*

Oceanic microseisms are the most prominent noise peaks in seismograms. Especially the secondary microseisms dominate the recordings over a broad period range. In some areas, they split up into a high frequency (HF, approx. 1-5 s) and a low frequency (LF, approx. 5-10 s) band. Two main mechanisms lead to the excitation of secondary microseisms, coastal reflected waves in shallow waters and ocean standing waves in deep water. Sea ice coverage affects the generation and spreading of these waves. Data recorded by ocean-bottom seismometers (OBS), which are situated directly in the propagation medium, are not only strongly affected by secondary microseisms, but also can help to study these effects. In this contribution, we show two examples from intermittent ice-covered areas in Antarctica. Within the EWARS project, three broadband OBS were deployed in the Ross Sea for one year, the fourth station recorded data for 17 months. Recordings from (semi-)permanent onshore stations complete this data set. During the BRAVOSEIS project, several broadband onshore stations and eight broadband OBS were deployed for one year in the Bransfield Strait. High-resolution probabilistic power spectral densities were calculated for all broadband stations to study the noise-generating processes. Noise cross-correlations between stations within one area were computed to determine the source directions of the secondary microseisms. All stations show seasonal amplitude variations of the secondary microseisms, which can be linked to the local sea ice coverage. Nevertheless, there are major differences between the study areas. In the Ross Sea a clear splitting into HF and LF microseisms is visible. The HF noise disappears during the austral winter, while the Ross Sea is completely frozen. The LF noise amplitude decreases during this time, but is still abundant. Separate noise sources most probably account for this. In contrast, the secondary microseisms in the Bransfield Strait show no distinct frequency bands. A moderate decrease of amplitudes during the austral winter, a high signal coherence of all stations, and consistent asymmetries of noise cross-correlations give evidence for noise sources outside the basin. In summary, secondary microseisms are affected by sea ice coverage; the extent of interaction depends not only on the amount of sea ice, but also on type and location of the noise sources.

2.27 Geophysical/Geological survey for underground laboratories in the Lausitz granodiorite massif

Mike Lindner[1*], Andreas Rietbrock[2], Christian Haberland[3], Stefan Buske[4], Oguzhan Guenaydin[4], Felik Hlousek[4], Christoph Butscher[5], Sandro Körschner[5], Frank Fischer[6], Sebastian Weber[6], Olaf Kleditzsch[1*], Peter Achtziger-Zupančič[7], Katharina Henjes-Kunst[1*]

[1]*Deutsches Elektronen-Synchrotron, Zeuthen;* [2]*Geophysikalisches Institut, Karlsruhe Institut für Technologie, Karlsruhe;* [3]*Geoforschungszentrum Potsdam, Potsdam;* [4]*Institut für Geophysik und Geoinformatik, TU Bergakademie Freiberg, Freiberg;* [5]*Lehrstuhl für Ingenieurgeologie und Umweltgeotechnik, TU Bergakademie Freiberg, Freiberg;* [6]*Landesamt für Umwelt, Landschaft und Geologie, Freiberg;* [7]*Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems, Aachen;* [*]*also part of Deutsche Zentrum für Astrophysik (founding phase)*

An environment with zero seismic noise is highly desirable for the Deutsche Zentrum für Astrophysik (DZA) to operate susceptible detectors and to conduct pioneering experiments in astrophysical research. The DZA is still in its founding phase and will reside in Görlitz, Saxony, with planned research facilities in the Lausitz region. The basement of this region is formed by the Lausitz granodiorite massif. The DZA aims to take advantage of it to host the Low Seismic Lab (LSL), an underground laboratory that will be built at 200 m depth. However, the regional extent of the granodiorite is not known for certain, and recent observations contradict the historic geological maps in some locations. To test whether the granodiorite is a suitable host with properties benefiting the LSL, the DZA commissioned a large geophysical/geological survey. This survey aims to produce a high- resolution 3D model of the massif and to study the regional seismic noise conditions. Since 2021, two seismometers in a borehole doublet and one surface broadband seismometer record the seismic activity within the center of the target area near the town of Cunnewitz. We examine and compare the seasonal variations and spectral footprint at the surface with those measured in the subsurface. In the spring and summer of 2024, two perpendicular 2 km long seismic lines (N-S and W-E) were acquired, crossing nearby said doublet borehole. At the same time, a 15 x 15 km large seismic array consisting of 191 short-period and 8 broadband stations was deployed within the target region. Acquired data offer a general insight into the local noise conditions and allow for identifying low activity areas. The deployment will be renewed with 100 short-period stations for a one-year-long measurement at previous locations with an especially quiet noise footprint and new locations. Additional boreholes are planned in the north and south of the target area to further study the noise footprint at depth and to gain insights into the variability of the granodiorite. In this talk, I will give an overview of the current status of the project, ongoing measurements, and planned work in the near future. I will present results on a local ambient noise study, active seismic lines, borehole core analysis, and borehole seismometer/DAS recordings.

2.28 Short distance observations of mantle transition zone discontinuities

Morvarid Saki[1], Christine Thomas[1]

[1] *Institute of Geophysics, University of Münster, Münster, Germany*

Mantle transition zone discontinuities have previously been investigated using PP and SS precursors for the epicentral distances above 90 ° in most cases. In a recent study (Saki et al., 2018), we showed that anisotropy in the mantle transition zone influences reflection coefficients of PP and SS precursors for some epicentral distances, such that even polarities are reversed. This, happens, however, only for short distances, i.e. at distances of 30 to 70 degrees, where these waves are usually not detected or used. Here we searched a number of different datasets for the presence of these short-distance PP and SS precursor arrivals. Synthetic modelling confirms that the waves should be visible (Saki et al., 2018) and we search for the reflections from the 410 km discontinuity at short epicentral distance of 60 to 90 degrees for PP and SS precursors and using different source-receiver combinations. Our initial results indicate that the observations of underside reflections from 410 km boundary at the short epicentral distance range of 60 to 90 degrees are indeed possible but the examples where these waves are found are few, mostly due to interfering waves with large amplitudes at the same time. However, up to now, we also found examples where the reflections from 410 km discontinuity shows an opposite polarity compared to that of the main PP phase, which agrees with the results of the reflection coefficient modelling in the presence of anisotropy reported by Saki et al. (2018). These first results show that there may be a possibility to test the mantle transition and confirm the slip systems, deformation and style of anisotropy.

Saki, M., Thomas, C., Merkel, S., Wookey, J., 2018. Detecting seismic anisotropy above the 410 km discontinuity using reflection coefficients of underside reflections, Phys. Earth Planet. Int., 274, 170-183.

2.29 Attenuation tomography in North Rhine-Westphalia

Nasim Karamzadeh[1], Lina Schumacher[1], Katrin Hannemann[1], Luca De Siena[2], Christine Thomas[1], Rafael Abreu[3]

[1]*Institut für Geophysik, Universität Münster, Münster, Germany;* [2]*Dipartimento di Fisica e Astronomia (DIFA), Alma Mater Studiorum Università di Bologna, Bologna 40129, Italy;* [3]*Institut de Physique du Globe de Paris, CNRS, Université de Paris, 75005 Paris, France*

Wind turbines are becoming more popular as a reliable alternative energy source, praised for their ability to generate clean and renewable energy. This growing use meets the urgent global needs for sustainable energy solutions. Nevertheless, there are ongoing concerns regarding their environmental impact, particularly related to acoustic emissions and the generation of seismic noise.

The dbMISS project focuses on understanding the seismic emissions generated by wind turbines and their impact on the overall seismic noise environment, which is particularly relevant in areas with seismic networks for earthquake detection. Wind turbines emissions, can interfere with seismic data analysis, especially in regions with a high density of turbines. A key element of this research is examining the attenuation factor, which measures how seismic wave amplitudes decrease with distance, influenced by the local geology. To address these challenges, we are conducting attenuation tomography studies in North Rhine-Westphalia (NRW).

We utilize a diverse set of data, including recordings from local earthquakes, explosions, and background noise, primarily sourced from the Geological Service (Geologischer Dienst – GD), Ruhr-University Bochum, and the DMT group. These institutions provide a comprehensive catalog of seismic events and waveform data from the GD and RN (RuhrNet) networks, along with additional active seismic data contributed by the DMT group. We discuss how the uneven distribution of this data affects our analysis and results. To ensure consistent attenuation tomography across North Rhine-Westphalia (NRW), we utilize the MuRAT code, a robust method that effectively processes data from explosions, earthquakes, and surface waves derived through background noise cross-correlation. MuRAT calculates the frequency-dependent ratios of P-to-coda and S-to-coda energy, employing a velocity model to estimate the attenuation factor. We present preliminary results of attenuation tomography obtained using earthquake data.

2.30 Investigation of seismicity in the Eifel region, using data from the Eifel Large-N Network

Patrick Laumann[1], Marius Isken[1], Hao Zhang[1], Torsten Dahm[1], Bernd Schmidt[2]

[1]*GFZ German Research Centre for Geosciences; University of Potsdam,* [2]*Geological Survey of Rhineland-Palatinate, State Seismological Service, Mainz, Germany*

The Laacher See volcano is with a VEI 6 Plinean eruption just 13,000 years ago the second youngest silicic-carbonatitic magma system in the world. Currently, although the volcano is classified as dormant, phenomena such as CO2 degassing, ground uplift, subsidence, and seismic activity persist as indicators of potential magmatic processes occurring at depth. A comprehensive analysis of this seismic activity may yield valuable insights into both magmatic and tectonic dynamics in the region. Such knowledge can subsequently be employed, for instance, to enhance the planning and implementation of geothermal energy projects within the locality. To enhance the understanding of the magmatic system under investigation, a seismic network comprising over 350 seismic stations was established in the East Eifel region, specifically surrounding the Laacher See, from September 2022 to August 2023. Furthermore a 60 km long dark fiber DAS cable was utilized for data collection over a period of three months. We are using both datasets to study seismicity, characterize active fault zones in the region, and investigate the possible relationship with magmatic processes and fluids at depth.

Given the large amount of data collected by the Large-N network and the DAS cable, we are using rapid machine learning techniques to identify and localize events. Therefor a Stacking and Migration Approach combined with Neural Network Phase Characterization was used. To optimize the detection of the events, tests were conducted to ascertain the appropriate parameters and configurations for event identification. This knowledge was then used to process the whole dataset. Preliminary findings indicate, that many of the events recorded by the network originate in the Ochtendung fault zone. However additional clusters are also visible, for example north-east of the Ulmener Maar.

2.31 Fluid-induced earthquake swarms: The 2024 Klingenthal-Kraslice Seismic Activity and Fluid Dynamics in NW Bohemia/Vogtland

Pınar Büyükakpınar[1], Torsten Dahm[1,2], Marius Isken[1], Sebastian Hainzl[1], Matthias Ohrnberger[2], Jana Doubravová[3], Siegfried Wendt[4], Sigward Funke[5]

[1]*German Research Centre for Geosciences (GFZ), Potsdam, Germany;* [2]*Institute of Geosciences, University of Potsdam, Potsdam, Germany;* [3]*Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic;* [4]*Geophysical Observatory Collm, University of Leipzig, Wermsdorf, Germany;* [5]*Institute of Earth System Science and Remote Sensing, University of Leipzig, Leipzig, Germany*

The region of Northwestern Bohemia/Vogtland is subject to persistent mid-crustal earthquake swarms, which are documented in regions mainly active at Luby and Nový Kostel, including Plauen, North and South Oelsnitz, Františkovy Lázně and Mariánské Lázně. Therefore, the region of North Bohemia/Vogtland is well monitored today by a dense seismological network including surface stations, borehole stations and a modern 3D high-frequency array with more than 60 stations located only a few kilometers from the most active swarm zone. In March 2024, after decades of quiescence, a massive earthquake swarm started beneath Klingenthal. We combined and exploited the large dataset and generated an earthquake catalog with a magnitude of completeness of Mc - 0.5 by applying Qseek, an automated machine learning-based stacking method for detecting and locating seismicity. Furthermore, moment tensor analysis was applied to 64 events Mw>1.2 to retrieve the source mechanisms using a Bayesian bootstrap-based probabilistic method in a joint inversion scheme with body waveform modeling and first motions. We propose that the Klingenthal swarm was generated by the subsequent ascent of fluid batches from depth, which were silent and undetected in the ductile lower crust below 10 km depth, but induced seismicity after entering the brittle part of the crust and interacting with a pre-existing fault zone. The first charge to contact the fault may have contained a large proportion of low-density CO_2, which has a smaller volume, while the second charge consisted of heavier fluids, which are slower and have a larger volume. We show, that the first phase propagated vertically and bilaterally from the high-pressure injection point in the fault, while the second phase generated radial growth of 900 m of seismicity within the fault plane. The inverted source mechanisms are consistent with shear faulting, with the orientation of the 57° dipping nodal plane in perfect agreement with the fault defined from the earthquake hypocenter. The normal faulting events and the orientation of the fault plane are unusual for the swarm region and its stress field, as most earthquake swarms to date have activated NS-oriented vertical faults.

2.32 Optimizing Seismic Noise Mitigation in Sensitive Research Environments: The Role of Distributed Acoustic Fiber Sensing

Reinhardt Rading[1], Katharina Sophie Isleif[1]

[1]*Helmut Schmidt Universität- Universität der Bundeswehr Hamburg*

The sensitivity of facilities such as particle colliders, synchrotrons and gravitational wave detectors are impacted by seismic,vibration, and environmental noises. Enhancing their sensitivity can involve various methods. For instance, in gravitational wave detectors, one approach is to build narrow moats near test masses or to excavate recess structures around them. However, implementing such measures would require modifications to the infrastructure of the facility. One approach that doesn't require structural modifications is coherent noise cancellation (CNC). In CNC, an array ofwitness sensors are deployed to record these perturbations, and the sensor data is utilized for coherent subtraction of the noises. The precision of the cancellation is dependent on the number of witness sensors, sensor sensitivity, sensor placements, signal-to-noise ratio (SNR), and the statistical error correlation of the filter used. Traditionally, seismometers and geophones have been used as witness sensors in many facilities and recently, distributed optical fiber sensors have garnered increased interest in their application in seismic measurement and environmental monitoring. Unlike seismometers and geophones which suffer from spatial coverage, optical fibers provide multiple sensor points along their length, allowing for better localization of noise sources and enhancing the SNR of the recorded signal . The sensitivity of a distributed optical fiber sensor is influenced by both the sensor and the local noise. A sensor noise is a fluctuations introduced by the measuring instrument itself while local noise is the unwanted, spatial dependent noise that is correlated between the neighboring sensors. In sensitive applications like the upcoming lunar mission and gravitational wave detection, the instrument noise can overshadow the signal of interest therefore stressing the need to estimate the self-noise of the witness sensors. In this talk we will present results from the WAVE seismic network, starting with a demonstration of how DAS can effectively cancel both coherent and incoherent noise. We will also compare the performance of DAS with traditional seismic sensors such as seismometers and geophones. Next, we will highlight the sensitivity of DAS in monitoring research facilities, showing its ability to detect temperature variations caused by fans in research rooms, detect earthquakes up to 6,000 km from the epicentre, and monitor environmental conditions within these facilities. Finally, we will outline our plans to develop advanced fibre-optic seismic sensors using digitally enhanced interferometry to meet the stringent requirements of the Einstein telescope.

2.33 Lifting the veil on enigmatic low-frequency signals from Greenland

Rudolf Widmer-Schnidrig[1,2], Thomas Forbriger[1,3], Walter Zürn[1], Sven Schippkus[4] and the 68 member international Greenland VLP team

[1]*Black Forest Observatory;* [2]*University of Stuttgart;* [3]*Karlsruhe Institute of Technology KIT;* [4]*Universität Hamburg*

On September 16, 2023 a rock and ice avalanche into a NE Greenland fjord excited a seiche. The slushing of the water perpendicular to the fjord axis exerted an oscillatory force on the walls of the fjord that in turn radiated seismic waves which could be observed with broad-band seismometers and gravimeters world wide. This signal lasted for up to nine days. In this talk I will discuss the different source models that we considered and eventually discarded during the last 12 months before arriving at the above interpretation for the source of the almost mono-chromatic, 92 s period seismic signal. Particular attention is given to how the different aspects of the radiated seismic signal could be used to rule out certain hypothetical source models.

2.34 The known unkown source

Sarah Beraus[1,2], Daniel Köhn[3], Thomas Bohlen[4], Gerald Gabriel [1,2]

[1]*LIAG Institute for Applied Geophyics, Geophysical Exploration;* [2]*Leibniz University Hannover, Institute for Earth System Sciences;* [3]*Christian-Albrechts-University Kiel, Institute for Geosciences;* [4]*Karlsruhe Institute of Technology, Geophysical Institute*

Seismic full-waveform inversion (FWI) is widely used for subsurface imaging across a broad range of scales. To this end, it is essential to model the wavefield as accurately as possible to avoid becoming trapped in a local minimum. In addition to a suitable initial model, knowledge about the source mechanism and the radiated source wavelet is required. While we usually know the source mechanism in active seismic experiments and the wavelets can be derived from near-offset traces, seismological sources are frequently unknown. Therefore, seismologists perform moment tensor inversion to reconstruct the source mechanism and use standard wavelets for modeling. Similarly, one could approach the determination of the source signature of an active source prototype.

Here, we discuss the case of a prototype borehole SV-source, which produces predominantly vertically polarized S-waves. The source is clamped to the borehole wall with an inflatable bladder. According to the manufacturer, the source pulse is generated electromagnetically. The source does not require a predefined orientation, but allows the user to choose between an upward or downward shot direction. The latter was used in our field data acquisition in the glacial sediments of the overdeepened Tannwald Basin north of Lake Constance.

In order to gain insight into the source mechanism, we forward model synthetics in our crosshole geometry, based on a 2D tomography model. We choose a bandpass-filtered spike as source wavelet, as this allows modeling all frequencies in the defined frequency range equally well. As potential source mechanism we use a vertical force and moment tensors that have zeros on the components which are related to the transverse direction. A comparison of the synthetics with the field data indicates that a simple vertical force assumption produces a signal that is most closely aligned with the observed waveforms with regard to the relative amplitude changes with offset and the P-to-S-amplitude ratio.

2.35 The onset of aftershocks: Testing predictions of seismicity models

Sebastian Hainzl[1,2], Morgan T. Page[3], Nicholas J. van der Elst[3]

[1]*GFZ German Research Centre for Geosciences, Potsdam, Germany;* [2]*Institute of Geosciences, University of Potsdam, Germany;* [3]*U.S. Geological Survey, Pasadena CA, USA*

The two most important relationships in statistical seismology are the Gutenberg-Richter law for the frequency-magnitude distribution and the Omori law for the aftershock decay. Initially, the Omori law was simply introduced as a 1/t decay of the aftershock rate with time t after the mainshock. Later, it was extended to include an exponent p, which may be different from one, and a value c, which represents a delayed onset of the power-law decay, resulting in the so-called Omori-Utsu law, R(t) = K (c+t) -p with parameters K, c and p. This empirical relationship has been found to fit most aftershock sequences very well and is therefore an essential constraint for seismicity models. The rate-and-state (RS) model is currently the most popular physics-based seismicity model, which is based on friction laws derived from laboratory experiments. One of its successes is that it predicts an Omori-Utsu decay with p=1 for a coseismic stress change. However, the c-value is predicted to depend on the size of the coseismic stress change, and since the mainshock- induced stresses strongly vary in space, the c-value should vary accordingly. Short-time aftershock incompleteness (STAI) in earthquake catalogs has prevented a detailed test of this prediction so far, but the newly developed a-positive method for reconstructing the true earthquake rate now allows its testing. Using previously published slip models, we calculate the coseismic stress changes for the six largest mainshocks in Southern California in recent decades and estimate the maximum shear as a scalar proxy of the coseismic stress tensor. Aftershock rates reconstructed for events in different stress ranges show that the rates follow a power-law with p=1 independent of stress, which is in agreement with the model prediction. However, we do not observe a clear sign of a c- value. The onset of the power-law decay is abrupt and more delayed in areas with smaller stress changes. The latter observations are not necessarily inconsistent with the RS model since STAI limits the resolution for early aftershocks, and the RS model can reproduce the observations for certain values of the model parameter $A\sigma$. However, the observations lead to strong constraints, namely $A\sigma$ < 10 kPa and a power-law decay of the background rate with distance to the fault, with exponent 2.7.

References: *1. Hainzl, S., M. T. Page, and N. J. van der Elst, Onset of aftershocks: Constraints on the rate-and- state model, Seism. Res. Lett., in press 2. Page, M. T., N. J. van der Elst and S. Hainzl, Testing rate-and-state predictions of aftershock decay with distance, Seism. Res. Lett., in press*

2.36 Pyrocko Squirrel - Prompt seismological data access with a fluffy tail

Sebastian Heimann [1]

[1] *University of Potsdam*

Squirrel is a new software framework to handle and manage massive seismological datasets with continuous waveforms, meta-data, and events. It is primarily designed for seismologists who want to program their own processing software. It frees software authors from the burden of writing large amounts of data management code and from writing documentation for these. Additionally, tools for data analysts are provided, to drastically simplify management of large datasets. Squirrel-powered apps share a common look and feel, making them more versatile in complex workflows, as well as easier to adapt.

Squirrel is part of the Pyrocko Toolbox since release v2022.04.28.
`https://https://pyrocko.org/docs/current/topics/squirrel.html`

2.37 From Fiber Optics to Public Fascination: The WAVE Initiative's Seismic Outreach

Spiridon Beis[1]

[1]*HSU Hamburg*

In this poster, we demonstrate how we utilize Distributed Acoustic Sensing (DAS) to engage the public and raise awareness about seismic measurement efforts conducted by the interdisciplinary research initiative "WAVE " on the science campus Hamburg Bahrenfeld. A highlight of our outreach efforts was our open campus day, where visitors were invited to walk over the DAS fiber laid beneath rubber mats. The data was shown on a screen in the form of a waterfall plot, allowing participants to experience the measurements firsthand. Additionally, some part of the fiber was suspended in the air, functioning as a microphone to capture sounds in real-time. During this event, attendees could see airplanes flying overhead, demonstrating the technology's sensitivity to various vibrations. This event generated significant interest, where attendees tested different ways to interact with the fiber. For other events, we live-streamed seismic data from our 19 km fiber network, measuring seismic waves from activities such as football games and concerts at the Volksparkstadion which is 2 km away from campus. One of these events was the Taylor Swift concert, where we measured the famous "swift-quakes" This poster will detail how we conducted and planned these outreach activities, including a live stream of seismic DAS data and how the public responded to this offer. Furthermore, we will show results from different events and compare different events, such as concerts and football games.

2.38 Modelling the Effect of Source-side Subduction on PKP Differential Time Measurements

Stuart Russell[1], John Keith Magali[1], Kimberly Vallenton[1], Christine Thomas[1]

[1]*Institut für Geophysik, Universität Münster, Correnstraße 24, 48149, Münster, Germany*

When making measurements of the seismic properties of the deep Earth, seismologists use earthquakes and seismometers from many different geographic areas. Due to the high rates of seismicity and large magnitude earthquakes, many teleseismic studies utilise earthquakes from subducted slabs, the seismic waves from which will interact with the slab itself and potentially cause artefacts in any subsequent measurements. Constraining inner core anisotropy by comparing polar and equatorial PKP paths inherently involves comparing data from different source regions, and therefore source structure must be adequately accounted for. Despite this, to date there have been no studies on the effect of source-side subduction on these measurements.

We use AxiSEM3D, a 3D spectral element seismic forward modelling code, to model the effect of source-side subduction on the differential time measurements used to constrain inner-core anisotropy. We build semi-realistic synthetic subduction zones from a simple thermal model and convert temperature to velocity and density using PerpleX. We optimise the AxiSEM3D inputs for our problem, allowing us to run global simulations at 3 s period with modest computational resources. We run simulations for a wide range of realistic slab properties, finding that source-side subduction can lead to artefacts of several seconds, which is significant, however there are also a wide range of slab geometries that do not produce notable artefacts.

We also examine an existing dataset of over 5000 PKP differential time measurements to search for the signal of source-side subduction, finding that it may be visible but is not more significant than the scatter in the data caused by other seismic velocity variations in the mantle. Interestingly, we find that the well-studied South-Sandwich Islands (SSI) anomaly is not strongly influenced by the SSI slab, and that the anomaly must have some other causal mechanism. While this study is inner core specific, the results have implications for a wide range of deep Earth seismology studies that utilise earthquakes from subduction zones.

2.39 On the undesired behaviour of higher-order correlations

Sven Schippkus[1], Gregor Hillers[2], Céline Hadziioannou[1]

[1]*Institute of Geophysics, Centre for Earth System Research and Sustainability (CEN), University of Hamburg, Hamburg, Germany;* [2]*Institute of Seismology, Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland*

Seismic interferometry yields a correlation wavefield that is closely related to the Green's function of the medium under the condition of homogeneously distributed sources. In cases where this condition is not met, iteratively computing the correlations of correlation wavefields ("higher-order correlations") has been argued to improve Green's function retrieval and thus be a useful processing step for imaging applications. Higher-order correlations can also retrieve correlation wavefields between stations that were not installed simultaneously, which can help to homogenize the imaging conditions for asynchronous deployments. We show that higher-order correlations do not improve correlation wavefields for inhomogeneous source distributions, which are common in seismic field data. Instead, higher-order correlations enhance the impact such non-ideal source distributions have on the correlation wavefield. We observe this effect on a large-N deployment with thousands of sensors and confirm it with numerical simulations. This work exposes the need for a reliable strategy to assess the correlation wavefield properties before applying advanced processing, such as higher-order correlations.

2.40 A rockslide-generated tsunami in a Greenland fjord rang the Earth for 9 days

Kristian Svennevig[1], Stephen P. Hicks[2], Thomas Forbriger[3], Thomas Lecocq[4], Rudolf Widmer-Schnidrig[5], Anne Mangeney[6], Clément Hibert[7], Niels J. Korsgaard[1], Antoine Lucas[6], Claudio Satriano[6], Robert E. Anthony[8], Aurélien Mordret[9,1], **Sven Schippkus**[10], Søren Rysgaard[11], Wieter Boone[12], *et al.*

[1]*Geological Survey of Denmark and Greenland, Denmark;* [2]*Department of Earth Sciences, University College London, UK;* [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;* [8]*U.S. Geological Survey, Albuquerque, New Mexico, USA;* [9]*Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, Univ. Gustave Eiffel, ISTerre, 38000 Grenoble, France;* [10]*Institute of Geophysics, Centre for Earth System Research and Sustainability (CEN), Universität Hamburg, Hamburg, Germany;* [11]*Department of Biology, Arctic Research Centre, Aarhus University, Denmark;* [12]*Flanders Marine Institute, Belgium*

Climate change is increasingly predisposing polar regions to large landslides. Tsunamigenic landslides have occurred recently in Greenland, but none have been reported from the eastern fjords. In September 2023, we detected the start of a 9-day-long global 10.88 mHz (92 s) monochromatic very-long period (VLP) seismic signal, originating from East Greenland. We demonstrate how this event started with a 25 M m 3 glacial thinning-induced rockslide plunging into Dickson Fjord, triggering a 200 m high tsunami. Simulations show the tsunami stabilized into a 7 m-high long-duration seiche with a near- identical frequency (11.45 mHz) and slow amplitude decay as the seismic signal. An oscillating, fjord-transverse single-force with a maximum amplitude of $5 \times 10^{11} N$ reproduces the seismic amplitudes and their radiation pattern relative to the fjord, demonstrating how a seiche directly caused the 9-day long seismic signal. Our findings highlight how climate change is causing cascading, hazardous feedbacks between the cryosphere, hydrosphere and lithosphere.

2.41 Cemented fibers as a test-bed for distributed acoustic sensing (DAS)

Thomas Forbriger[1,3], Rudolf Widmer-Schnidrig[2,3], Laura Hillmann[4], Han Xiao[4], Andreas Rietbrock[1], Veronica Rodriguez Tribaldos[4], Angelo Strollo[4], Philippe Jousset[4]

[1]*Geophysical Institute, Karlsruhe Institute of Technology (KIT);* [2]*Institute of Geodesy, University of Stuttgart;* [3]*Black Forest Observatory (BFO);* [4]*Helmholtz Center Potsdam, German GeoResearch Center GFZ, Potsdam;*

Distributed Acoustic Sensing (DAS) has become very popular for recording seismic waves in recent years as it provides dense spatial sampling along an optical fiber with only one single interrogator unit (IU) needed for thousands of channels. Fibers can be several tens of kilome- ters long and in some applications so-called dark-fibers can be used, which were deployed for telecommunication purposes, but currently not in use. This greatly reduces the necessary effort for field deployment. While the IU is calibrated to record 'fiber strain' or strain-rate, the properties of the cable and its coupling to the rock control the 'strain transfer rate' and hence how much of 'rock strain' is represented in the recorded signal. The 'strain transfer rate' can be significantly smaller than 1, which goes along with a reduction of signal to noise ratio, as instrumental noise levels do not depend on the coupling. At Black Forest Observatory (BFO) we cemented eight optical fibers into a groove in the floor of the gallery. The fibers are made up of a 9 μm thick core, 116 μm thick cladding, 125 μm thick coating, and a 650 μm thick tight buffer adding up to a total thickness of 0.9 mm. This type of installation shall provide the best achievable coupling of the fiber to the rock. The 'strain transfer rate' is expected to become close to 1, making 'fiber strain' equal 'rock strain'. We use this installation as a test-bed for DAS IUs and show preliminary results from a huddle test run in spring 2024 with four types of IUs.

2.42 On the plane wave approximation for converting particle velocity into strain

Thomas Forbriger[1,2], Walter Zürn[2]

[1]*Geophysical Institute, Karlsruhe Institute of Technology (KIT);* [2]*Black Forest Observatory (BFO)*

When analyzing strain data, in particular in the context of distributed acoustic sensing (DAS), occasionally a comparison with particle velocity recorded by seismometers is used. For plane waves the waveforms of linear strain and of the particle velocity component in the direction of the strain measurement are identical. Particle velocity recordings then can be converted into strain by a simple scaling factor, which is controlled by the apparent slowness and the angle of incidence with respect to the direction of linear strain. The conversion works well in many cases for signals of single non-dispersive plane waves of known ray parameters. In practical applications we identify the limitations of this approxima- tion. Due to propagation in heterogeneous media recorded waves can contain a considerable non-plane component. The linear strain of a plane wave perpendicular to the direction of inci- dence vanishes. Recordings of the linear strain component in near-perpendicular directions to the wave propagation are hence dominated by the non-plane wavefield components. Dispersion and superposition of body-waves with different slowness add to the differences between particle velocity and strain waveforms. Recordings of the array of Invar-wire strainmeters at BFO allow us to obtain linear horizontal strain in any azimuth. We use these data in comparison to the horizontal component recordings of the STS-2 seismometer, to investigate waveform similarity and conversion factors for plane wave strain in various azimuths with respect to the dominant direction of wave propagation.

2.43 Continued unrest and fissure eruptions along the Reykjanes, trans-tensional volcano-tectonic rift, Iceland

Torsten Dahm[1,2], Pınar Büyükakpınar[1], Marius Isken[1], Sebastian Heimann[2], Daniela Kühn[1,3], Simone Cesca[1], Jana Doubravová[4], Egill Árni Gudnason[5], Thorbjörg Ágústsdóttir[5]

[1]*German Research Centre for Geosciences (GFZ), Potsdam, Germany;* [2]*Institute of Geosciences, University of Potsdam, Potsdam, Germany;* [3]*NORSAR, Kjeller, Norway;* [4]*Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic;* [6]*Iceland GeoSurvey (ÍSOR), Kópavogur, Iceland*

Since 2020, the Reykjanes Peninsula (RP) has experienced recurrent cycles of strong surface deformation, faulting, intense earthquake swarms, magmatic intrusions and fissure eruptions along en echelon volcanic systems that cross the plate boundary. Historically, similar patterns have occurred episodically at RP over the past 4000 years, the last one about 700 years ago. We now have a unique opportunity to study such episodic periods of activity and magma transfer in great detail using modern digital data. After the first signs of unrest in the Svartsengi geothermal field in early 2020, GFZ and Iceland GeoSurvey (ÍSOR) intensified the existing seismic networks with additional sensors, repeated gravity campaigns and InSAR studies in a task force mission. A second task force mission was initiated in 2024 due to continued unrest and deformation in the Svartsengi geothermal field. During the 8-month deployment in 2020, more than 40,000 micro-earthquakes were detected and located on the RP, including six with magnitudes greater than M>4.5. We analyse the seismicity and focal mechanisms in the early phase of the unrest before the onset of several fissure eruptions since 2021, the last one starting on 22 August 2024. We derive full moment tensor (MT) solutions for earthquakes with Mw > 2.5. Polarities of Distributed Acoustic Sensing (DAS) data were implemented in the Bayesian inversion. The focal mechanisms are predominantly strike-slip faulting with a few normal faulting events compatible with the regional tectonic regime. Interestingly, significant positive isotropic MT components are resolved, contributing up to 15the larger plate boundary earthquakes are preceded by the slow upward migration of microearthquakes from below, suggesting that intruding magmatic fluids trigger earthquakes. We see the formation of en-echelon strike-slip faults in the shallow upper crust interacting with deeper intrusions with different strike directions. We postulate that isotropic components are related to co-seismic expansion of magmatic volatiles.

2.44 The Einstein Telescope: a new Earthbound Gravitational Wave Detector

W. Vossius, K.-S. Isleif

In this poster, we present the current plans for the Einstein Telescope, a gravitational wave detector and the seismic challenges associated with its construction and operation. When massive celestial bodies such as black holes merge, energy is released during the orbital phase of the merger in the form of gravitational waves— ripples in spacetime with a strain of approximately $1e-21\ 1/\sqrt{Hz}$. These ripples can be detected on Earth using gravitational wave detectors, which are based on laser interferometers of multiple kilometre length. The detections give us valuable insights and advance our understanding of the universe. However, seismic noise is one of the limiting noise sources below 10Hz which is damped using multiple stages of active and passive isolation systems.

In Europe, plans are underway to build the Einstein Telescope (ET), a next generation gravitational wave detector which will improve the sensitivity by multiple orders of magnitude to detect gravitational waves at frequencies down to 2 Hz which will provide insights into the collisions of more massive black holes binary systems and will also expand the cosmological reach towards high redshifts close to the dark age of the universe (Check diesen Satz noch mal). To achieve this, ET will be a 10 km-large detector and will be constructed 250 meters underground. Several measures are being researched to mitigate seismic and Newtonian noise (hier noch erklären was Newtonian noise ist).

This poster will explore the general principles of gravitational wave detection and the specific seismic challenges and opportunities presented by the construction of the Einstein Telescope, including coherent noise cancellation systems for seismic and Newtonian noise and novel distributed seismic strain sensor development so ensure a high sensitivity of the detector.

SESSION 3

AK Wind

3.1 Amplitude ratios of denoised signals

Martina Rische[1], Janis Heuel[2]

[1]*RUB;* [2]*KIT*

Signals from seismological stations are often disturbed by noise. The expansion of wind turbines exacerbates this problem and may lead to conflicts of interest between wind energy and seismological monitoring. During the MISS project, a denoising autoencoder was developed, that learns from millions of earthquake and noise samples how to supress noise at seismological stations. In the follow-up project DBMISS, this autoencoder was tested in a broader field to check whether the autoencoder can be used in seismological data routines. As already shown in other studies, the amplitude of the original waveform is not well preserved after denoising. However, for earthquake with larger magnitudes (> 1 -2.5 ML ; depending on the data set) the amplitude is preserved well enough for further analysis. Here we show the limits of the denoising autoencoder and how the amplitude is changed for different magnitudes using various data sets.