Abstracts
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Geophysikalischer Gerätepool (GIPP) – Statusbericht 2022

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Der "Geophysikalische Gerätepool" (“Geophysical Instrument Pool Potsdam”, GIPP) am GFZ stellt seismische und magnetotellurische Geräte und Sensoren für temporäre Feld-Experimente von Universitäten, GFZ-Gruppen und anderen Forschungseinrichtungen zur Verfügung. Seit der Inbetriebnahme 1993 hat der GIPP fast 450 geowissenschaftliche Projekte mit Geräten unterstützt (jedes Jahr ca. 30 bis 40). Die Gerätebereitstellung läuft über ein transparentes Antrags- und Evaluierungsverfahren (www.gfz-potsdam.de/gipp). Die Anträge werden durch einen extern besetzten Lenkungsausschuss evaluiert.
Heute besteht der seismologische Teil des GIPP aus ~150 EarthData EDR-210 Rekordern, >1000 Omnirecs/DIGOS Cube Rekordern, 215 Nanometrics Trillium Compact Seismometern, >100 größeren Breitbandsensoren und einer Vielzahl von Geophonen nebst notwendigem Zubehör. Er ist damit der größte geophysikalische Gerätepool Europas. Die Geräte sind gut nachgefragt und es kommt regelmäßig zu Überbuchungen. Ebenso betreiben wir ein Datenrepositorium zur Archivierung der gesammelten Daten und entwickeln Hard- und Software.
In den letzten Jahren kamen projektbezogene Arbeiten im Zusammenhang mit EPOS-SP („Best practice for field work, data management and QC of temporary deployments“) und ORFEUS (Bildung einer europäischen „Mobile Instrument Pool“ Gruppe) sowie weiteren Projekten zu Datenmanagement hinzu (häufig in Zusammenarbeit mit GEOFON). Hier wurde auch an der Bereitstellung von Gerätemetadaten über eine Datenbank und entsprechende Webseiten gearbeitet.
In der Präsentation werden der momentane Stand, aktuelle Hardware Entwicklungen, Aspekte der Datenarchivierung sowie zukünftige Vorhaben vorgestellt.

Bericht über technische Arbeiten am Erdbebendienst des Bundes der BGR

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Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover

Überblick über die Tätigkeiten im technischen Bereich des Erdbebendienstes des Bundes der BGR mit folgenden Themen:

- Betrieb des Deutschen Regionalnetzes (GRSN) mit der Vorstellung neuer Standorte
- Entwicklungen im seismologischen Datenzentrum der BGR
- Stand der Integration von permanenten Länder- und Universitätsnetzen in EIDA

Analysis of earthquake swarms in the region of the Albstadt Shear Zone, southwest Germany

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From 2018 to 2020, the state earthquake service of Baden-Württemberg (LED) observed several earthquake swarms near the town Albstadt on the Swabian Alb, a mountain range in southwestern Germany. For one of the swarms during September 2019 they identified more than 800 events, but most of them had very small magnitudes and were not locatable. Such earthquake swarms were not observed so far in this region. In general, continuous microseismic activity is observed along the Albstadt Shear Zone (ASZ), an approximately NS striking sinistral strike-slip fault with no surficial expression. Another tectonic feature is the NW-SE striking aseismic Hohenzollern Graben (HZG), a shallow graben structure with a depth down to app. 2-3 km and an inverted relief at the surface.
Within the AlpArray and the StressTransfer projects 9 seismic stations were installed in 2016 and in 2018/2019 in the region of the ASZ. In combination with permanent seismic stations this dense local network is giving the unique opportunity to identify very small size earthquakes for detailed seismo-tectonic studies of the ASZ area.
We used the multi-station template matching algorithm of the python package EQcorrscan for event detection and automatic P- and S-phase arrival time estimation. All automatic arrival time estimations are manually rechecked and manually redetermined or deleted if necessary. We determined absolute event locations with NonLinLoc and relative event locations with HypoDD. We utilized P- and SH-polarities as well as SH/P amplitude ratios of the event templates used for detection to calculate fault plane solutions with FOCMEC.
Our analysis covers 12 different 30 to 90 days long time spans from 2018 till 2020. Five of those time spans have more than 20 detected events and are used for further analysis. We identified two smaller earthquake swarms (<100 events) during February 2018 and December 2020. During October/November 2018, September 2019 and January 2020 we identified three larger earthquake swarms with 220, 590 and 411 earthquakes, respectively.
The earthquake swarms in October 2018 and December 2020 can be related with the ASZ, as the fault planes are striking about NS (sinistral strike-slip) and the spatial distribution of the hypocenter locations within the single clusters coincide with the corresponding seismicity of the ASZ.
In contrast, the earthquake swarms in February 2018, September 2019 and January 2020 have NW-SE striking fault planes nearly parallel to the orientation of the HZG. However, their hypocenters are located in a depth of around 12 km, so significantly below the assumed depth range of 2-3 km of the HZG. These events are characterized by dextral strike-slip fault planes.
In summary, with our dense seismic network we were able to locate the seismic activity on the Swabian Alb in details. Until now earthquakes in this region were generally related with the NS striking ASZ. Our results now indicate that also NW-SE striking fault planes, parallel to the HZG are active in the crystalline basement in this region.

Insights in fracture evolution and earthquake triggering mechanism(s) from high-resolution *in-situ* V_p/V_s-ratio estimates of hydraulic fracturing-induced earthquake clusters

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Fluid injection/extraction activity related to hydraulic fracturing and alternative energy production commonly induces felt earthquakes. Many studies attribute the generation of seismicity to mechanisms such as pore pressure and poroelastic stress changes, and/or fault loading due to aseismic slip, but the relative importance of such mechanisms is still an open question. Reliable estimates of subsurface rock properties, such as crack density, fracture geometry, and fluid pressure distribution, can provide clues about earthquake triggering mechanism(s), particularly in areas such as the Western Canada Sedimentary Basin, which frequently experiences small-magnitude (M<3) and occasionally moderate-sized (M~4.5), induced earthquakes as the result of industrial activity. Here we analyze continuous seismic records of 47 spatially related earthquake clusters in the vicinity of hydraulic fracturing wells to image the *in-situ* compressional-to-shear-wave velocity ratio (V_P/V_S) as a probe of the relative importance of rock damage and fluid pressure.

We use seismic records in the Kiskatinaw area (British Columbia, Canada) between July 2017 and December 2020 to estimate V_P/V_S-ratios associated with individual hydraulic-fracturing injection stages. We compare the temporal variability of ratios with daily injection volume to interpret potential changes in rock material properties through the co-evolution of both parameters. Determining V_P/V_S-ratios employs a method that compares differential travel-time differences of co-located earthquakes to recover the V_P/V_S-ratio of the source rock volume. Our results show ratios ranging from 1.5 - 1.7 corresponding to variations of up to ± 7% with respect to a reference 3D velocity model. They also exhibit generally high spatial variability, with higher V_P/V_S-ratios for earthquake clusters proximal (< 200 m) to injection sites relative to more distal clusters. Temporal variation ranges on scales of a few days, corresponding to the typical duration of multiple hydraulic stimulation stages along a horizontal well. The predominantly small spatiotemporal variations in V_P/V_S-ratio do not point to a significant, broad fluid-pressure increase, and therefore suggest pore pressure increase is an unlikely leading triggering mechanism.

We explore various physical models of fluid-saturated rocks to infer the potential implications of fracture growth on rock strength. We vary crack aspect ratios and fluid volume content in an effective medium analysis and compute effective V_P/V_S ratios. Modeling results produce evolving bulk- and shear moduli (and hence the V_P/V_S-ratio) that are physically consistent with hydraulic fracturing treatment conditions that would lead to decreasing fracture aspect ratios and increased fluid content in the rock volume, followed by abating conditions following treatment. The fracture/fluid evolution can explain changes in V_P/V_S-ratio and suggest seismicity rates may inversely correlate with changing rock strength conditions. A lack of direct evidence for aseismic slip triggering leaves the question open as to the relative importance of aseismic and poroelastic triggering.

Quantifying background seismicity and triggering potential in the Lower Rhine Embayment near Weisweiler, Germany

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The Earth's crust is permeated with faults and fractures due to its long tectonic history. Faults and fractures not only act as zones of weakness, but can increase permeability and act as conduits to circulate fluids in the underground, making them ideally suited for geothermal energy production. However, human-induced changes to *in-situ* pressure fields have a documented history of leading to fault (re-)activation in the form of earthquakes (seismic slip) or aseismic slip that does not generate measurable ground motion.

This study aims to quantify the current background earthquake activity, the spatiotemporal relationship to the seismotectonic setting, and the remote earthquake-earthquake triggering propensity in the Lower Rhine Embayment (LRE) in western North-Rhine Westphalia. The study area is targeted for extensive exploration activities focused geothermal energy production. While measurable horizontal and vertical strain-rates in the LRE do not exceed 0.1 mm/yr, paleo-seismic studies suggest that the normal faulting system hosted a series of ~14 earthquakes of $M_w > 5.0$ since the 14th century, including the 1992 M_w 5.3 Roermond earthquake. Therefore, estimating the background seismicity rate independent of additional stress perturbations from e.g., fluid injection/production is one important element to develop strategies to minimize the probability of felt earthquakes caused by industrial activity.

We evaluate waveform data from a temporary deployment of 48 seismic stations operating between July 2021 and May 2022 in a radius of roughly 10 km around a future exploration well drilling site in Weisweiler. We implement a machine learning-based earthquake detection algorithm, *SeisBench*, to denoise the continuous seismic waveforms and estimate P- and S-phase arrivals using *PhaseNet* and the *Generalised Phase Detection (GPD)* algorithm. We associate earthquake phases to seismic events using a Bayesian Gaussian mixture model (*GaMMA)*. We detect and locate 110 seismic events between July 2021 and December 2021 with magnitudes ranging from $0 < M_L < 1.3$ using the local 48-station array. By comparison, the Earthquake Observatory Bensberg locates a total of 185 local and regional earthquakes, 40 of which fall within the same study area. Preliminary remote dynamic triggering results suggest that the passing surface waves of the July 2021 M 8.2 Chignik, Alaska earthquake may have triggered a seismic sequence of about 16 locatable earthquakes. Our continued work will build the catalog for the remainder of the deployment period, perform clustering analysis to quantify background earthquake rates, earthquake statistics and where data quality permits, earthquake relocations, and source parameter estimates.

From Small to Large: Tectonic Stresses and Seismic Activity in the Lesser Antilles Subduction Zone

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Seismic activity in the Lesser Antilles (LA) is characterized by strong regional variability along the arc reflecting the complex subduction setting and history. In this study we examine the source mechanisms of different large to small scale structures along the arc using regional waveform data of permanent land stations and from a temporal OBS deployment. Full-waveform inversion is done using our novel inversion approach, AмΦB - “Amphibious Bayesian”, taking into account uncertainties associated with OBS deployments.

Combining our newly derived 45 MT results with existing solutions, we subsequently analyze a total of 151 MTs in a focal mechanism classification (FMC) diagram and map them to the regional tectonic setting. We also perform stress tensor inversions along the LA subduction zone. On the plate interface, we observe the typical compressional stress regime of a subduction zone and find evidence for upper-plate strike slip and normal fault behavior in the north that becomes a near arc-perpendicular extensional stress regime towards the south. A dominant slab perpendicular extensional stress regime is found in the slab at 100-200 km beneath the central part of the arc.

This region hostes the to date largest instrumentally recorded seismic event; the Mw7.4 Martinique earthquake. We argue that the Martinique event is a doublet composed of two subsequent perpendicular normal faults, associated to a subducted, and under a different stress regime re-activated, ridge-transform fault at the plate boundary of the Atlantic/Proto-Caribbean lithosphere.

Keywords:

Subduction Zone, Stresses, Regional Moment Tensor, Ridge-Transform Fault, Bayesian Full-Waveform

The 2021 Tyrnavos earthquake sequence in Greece: complex fault activation at the surface and at depth

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In March 2021 an earthquake sequence including three Mw>6 earthquakes on the 3rd, the 4th and the 12th of March shook northern Thessaly, Greece. The sequence took place as a propagation of these three large normal-faulting earthquakes in the south-east north-west oriented Tyrnavos Graben system along the graben direction. The back then very frequent SAR imagery based on two Sentinel-1 satellites – Sentinel-1B broke in December 2021 - allows for a separation of surface displacement caused by each of the three larger shocks from an ascending look direction. These observations reveal not only the subsequent activation of faults along strike, but also and on both sides of the graben structure, realizing a complex activation in an immature fault zone.

The first and largest earthquake of the sequence shows a clear causative fault rupture up to the surface on a western graben fault. The displacement pattern indicates that at depth additionally a westward-dipping fault of the eastern side of the graben has been activated. The following two large earthquakes remained blind normal faults for which the fault geometry is more ambiguous from a first glance. First reports find that most likely eastward-dipping normal faults ruptured during these events.

Interestingly, the broad surface displacement signal of subsidence caused by the first large earthquake is offset to the east from the known center of the graben system. Also, the surface rupture of the first event did not occur on one of the main graben faults but west in its footwall, and with a more NNE strike, compared to the mapped orientation of the Tyrnavos Graben system. The second rupture, according to our results, occurred on the east side of the graben. The third and smallest large earthquake ruptured at the northern termination of the graben along an east-west striking fault.

The short revisit times of the SAR images result in excellent interferometric coherence and high quality displacement maps. A detailed analysis of the ascending interferogram, which covers the first main shock only, shows further an abundance of fault slip at the surface on mapped faults, which have clear morphological expressions, such as the Vlachogianni Fault and the Mesochori fault. These slip features do not exceed a few centimeters of slip and seem to be not directly connected to fault slip at depth. Rather, they appear to be secondary features that accommodate bending of the free surface. Due to this, the small surface slip observed at the Vlachogianni fault, normally east-side-down, has been east-side-up and reversed compared to it normal mechanism.

We present these interesting and complex surface displacement signals measured by space-borne InSAR and the earthquake source modeling results based on a combined modeling of InSAR, GNSS and teleseismic waveforms.

Microseismicity in relation to the rise of the mine water level and the regional stress field in the eastern Ruhr area

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Using data from permanent seismological stations of the Ruhr University and the short-period FloodRisk network in the eastern Ruhr area, microseismicity in the area of the former coal mine “Bergwerk Ost” is observed. The database is supplemented by the levels of the mine water table, which are regularly measured and made available by Ruhrkohle AG (RAG) at various measuring points distributed over the study area. A special focus is on the relation of the microseismicity to the rising mine water level after the end of mining. Since the beginning of the flooding, more than 2000 induced events in a magnitude range from -0.7 up to 2.6 M_{Lv} have been localised. The spatial distribution of hypocentres is divided into two areas, with few events in the central study area and over 95% of earthquakes in its eastern part. Many of these events are spatially clustered and some show quite high waveform similarity. This allows relative localisation to increase the accuracy of the location.
Comparing the old galleries, which today serve as the main underground waterways, with the localisations from the relative seismicity localisation, strong correlations can be seen. The measured temporal trend of the mine water level, after pumps were shut down in mid-2019, shows a strong correlation with the temporal evolution of the observed microseismicity.
In addition to investigating the spatial and temporal distribution of seismicity, fault plane solutions could be determined for larger seismic events. These are compared with the regional stress field derived from independent investigations.

Ambient seismic noise sources at the bottom of the Arctic Ocean: Implications for wave action and the state of the sea ice

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In a pilot experiment from September 2018 to September 2019, we deployed four broadband ocean bottom seismometers at eastern Gakkel Ridge, Arctic Ocean, at water depths of about 4000 m near a volcanic structure. The ocean bottom seismometers were modified to ensure safe recovery in a sea ice-covered ocean. The survey location is situated underneath perennial sea ice. Only in August and September, the marginal ice zone of the Laptev Sea extended to the OBS position.
We calculated spectrograms showing the seasonal variations of the ambient seismic noise in several frequency bands. Long-period double-frequency microseisms are slightly stronger in winter time. Their source is outside the Arctic Ocean. Short-period double-frequency microseisms are strongly seasonally modulated and start to appear when the Laptev Shelf area becomes ice-free. The longest periods of this noise band increase as the fetch area for swell generation increases. Short-period double-frequency microseisms are also recorded, when the entire deep-water area of the Arctic Ocean is frozen, suggesting that deep water conditions are not necessary to produce mid-ocean microseisms. At high frequencies (>6Hz), considerable noise sources are present, that stem from active seismic profiling some 400 km away in September 2018. Otherwise, short, distinct noise bands covering frequencies of 6-50 Hz are mostly seen in winter time. We associate these signals to noise generated by the sea ice. In order to better understand the seasonality of the noise sources, we extracted the spectral power in various frequency bands for one entire year and compared the variations with variations of the significant wave height from Wave Watch III hindcast models and of the sea ice concentration from satellite data. This comparison reveals that the sea ice-related noise decays suddenly in late May while sea ice concentration is still 100%, suggesting that the physical properties of the sea ice change at this time prior to break-up. Likewise, sea ice only gradually develops its noise-generating capabilities after the freezing period. During autumn, several swell events cause large-amplitude short-period double-frequency microseisms and simultaneously high-frequency ice noise although ice-noise is otherwise not present in this season. Ice concentration decreases following the swell events, showing the impact of swell on the state of the sea ice during the freezing season. Our first-time record of the ambient seismic noise at the bottom of the Arctic Ocean clearly reveals a large potential of such records in monitoring the state of the cryosphere above and in particular the interaction between swell and sea ice.

Noise characteristics of ocean-bottom seismometer data in the Bransfield Strait, Antarctica

Mechita C. Schmidt-Aursch, Javier Almendros, Wolfram H. Geissler and William Wilcock

All seismological data contain not only desired source signals, but also noise. There are various natural and artificial noise sources like wind, waves, traffic, industry, etc. Data recorded by ocean-bottom seismometers (OBS) show a different content of noise than onshore data; mainly because the OBS are located directly in one of the major noise generators: the oceans. Oceanic microseisms dominate the recordings over a broad frequency band, and there are several noise sources not known onshore, e.g. marine mammals, ship traffic, marine seismic surveys and especially in the polar regions sea ice and icebergs.

In the framework of the BRAVOSEIS project, eight broadband ocean-bottom seismometers were deployed for one year in the Bransfield Strait, Antarctica. The ambient noise was helpful to correct the clock drift of the data loggers by means of noise cross-correlations. High-resolution probabilistic power spectral densities and spectrograms were calculated for all stations and channels to study the noise-generating processes. An analysis of tidal signals were performed for various time series including temperature recordings.

Although all OBS were located within the same basin, they differ significantly in their noise characteristics. The noise spectrum was divided into several frequency bands. Some bands show seasonal variations, others are persistent during the entire year. A few noise signatures are coherent between all OBS, this is typical for origins far away. Most noise sources occur very locally and are specific for each OBS depending on parameters like water depth or the abundance of deep water currents. Generally, the noise properties are complex and show a great variation in time and space.

Seismological activities around Neumayer Station, Antarctica
Tanja Fromm

The Alfred-Wegener-Institut (AWI) operates the year-around research station Neumayer III in Dronning Maud Land, Antarctica. The station has three long term observatories for Air chemistry, Meteorology and Geophysics. Here we report on our recent activities around the seismological network of the Geophysics Observatory including technical developments and first analysis of temporary seismic installations focusing on tidal effects in seismological data.

Unsupervised Deep Representation Learning for Icequake Detection at Neumayer Station, Antarctica

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As the seismological community is continuing to gather more and larger datasets of uncurated continuous waveform data, the interest in machine learning methods is rising. In particular, unsupervised machine learning can be a useful tool for the first exploration of large datasets. Recently, a new type of unsupervised learning, namely contrastive learning, has shown great success in various domains, e.g. image and audio processing, and we aim to transfer these methods to the domain of seismology. We apply contrastive learning to a dataset containing various event types detected by an STA/LTA algorithm on continuous waveform recordings from the geophysical obervatory at Neumayer station, Antarctica. Results show that the approach can separate different hand-labelled groups and detect meaningful groups within unlabelled data. We discuss potential applications and limitations.

Title: Lithospheric evolution of eastern Arabia

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The geology of eastern Arabia is dominated by a vast cover of mostly Phanerozoic sedimentary rocks and little was known about the architecture of the middle and lower crust. On the easternmost margin, obduction of the Semail Ophiolite during late Cretaceous times is the youngest first-order tectonic process that shapes the present-day geology across the Oman Mountains in northern Oman and the eastern United Arab Emirates. Within the obducted units, Neoproterozoic to Cretaceous autochthonous rocks of the Arabian shelf are exposed in two tectonic windows and provide a detailed view of the geodynamic evolution of the shallow Arabian continental crust during and after obduction. A new, unprecedented 3-D anisotropic shear-wave velocity (V_s) model reveals that - prior to obduction - the assembly of the eastern Arabian lithosphere in Neoproterozoic times and its modification during the Permian breakup of Pangea strongly control the present-day lithospheric architecture. Building upon previous geodynamic models that were restricted to the upper crust, reconstruction of the entire lithospheric evolution resolves some key unknowns in eastern Arabia's geodynamics:

1. The NNE-striking Semail Gap Fault (SGF) is primarily an upper crustal feature but another NE-striking deep crustal boundary zone west of the Jabal Akhdar Dome segments the Arabian continental crust in two structurally different units.

2. While Permian Pangea rifting occurred on both eastern and northern margins of eastern Arabia, large-scale mafic intrusions occurred mostly east of the SGF. Eastward crustal thinning localizes at the eastern limit of obducted units, east of which the lower crust is strongly intruded and likely underplated.

3. Late Cretaceous exhumation and overthrusting at the end of ophiolite obduction is the likely cause for crustal thickening below today‘s topography of the Oman Mountains.

4. Lithospheric thickness is ~200-250 km in central Arabia but only ~100 km below the Oman Mountains. Thinning of the continental lithosphere is attributed to late Eocene times, which explains contemporaneous basanite intrusions into the continental crust and provides a plausible mechanism for observed crustal-scale extension and the broad, margin-wide emergence of the Oman Mountains. Thus, uplift of the mountain range might be unrelated to Arabia-Eurasia convergence.

Seismicity and state of stress in eastern Arabia

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The eastern Arabian margin in northern Oman has a generally low level of seismic activity. However, damaging earthquakes are historically reported in northern Oman and its vicinity to active plate margins in the Arabia-Eurasia collision zone place the region in a tectonically complex framework. Continental collision of northern Arabia with Iran localizes deformation in the Zagros belt with a high level of shallow crustal seismicity that extends eastwards until the longitude of the Musandam peninsula. There, the deformation front is offset to the south by ~200km to the Sea of Oman where it transitions into the western end of the Makran subduction system with its remarkably low level of seismic activity.

With the establishment of a permanent regional seismic network in Oman in 2003, low-magnitude seismicity can be reliably detected and located, as confirmed by a dense, temporary seismic network that was operable from 2013-2016. Both datasets provide the opportunity to evaluate the present-day seismicity and state of stress on the eastern Arabian passive margin in the regional context.

On the Arabian continent, seismic activity rapidly vanishes south of the Musandam peninsula towards northwestern Oman, where seismicity is close to absent. Occasional weak events are located on the northern flank of a small tectonic window. In the Central and Eastern Oman Mountains, where topography is higher, shallow, low-magnitude seismicity occurs regularly along topography bounding normal faults.
The offshore domain in the Sea of Oman is segmented by two NE-trending lines - one in continuation of the onshore Semail Gap Fault Zone, the most prominent surficial fault in northern Oman, and one in continuation of the Masirah Line, a zone of seismic activity that follows the southeastern Arabian margin from south and central Oman towards the Makran trench. Except for an isolated patch at the intersection of the SGFZ with the Makran trench where repeated seismicity occurs, the trench and the Arabian offshore domain is seismically quiet.

For 14 events, focal mechanisms were determined from first-motion polarity which show an overall transtensional stress regime in the Central and Eastern Oman Mountains. Stress field inversion suggests that the overall NE-SW oriented background stress field related to the convergence of Eurasia and Arabia is locally compensated onshore Oman by gravitational deviatoric stresses of the mountain range.

Reimaging the aftershock sequence of the 2016 Mw=7.8 Pedernales (Ecuador) earthquake with the latest machine learning-based event detection techniques

Hans Agurto Detzel, Jack Woollam, Andreas Rietbrock
GPI KIT

High-resolution earthquake locations are one of the most fundamental components in imaging subduction zone interfaces. The accurate association and location of seismic events in these regions are vital in understanding the physical processes associated with the largest earthquakes on record. The last decade has seen the continued increase in the scale and densification of both onshore and offshore seismic deployments, aiming to better capture the variety of seismogenic processes occurring throughout these dynamic environments. Such large deployments in seismically active areas often produce large (10s to 100s TB) amounts of continuous waveforms which are typically processed using a combination of traditional automated methods (e.g STA/LTA picking) and manual refinement by a human expert. The trade-off in performance and accuracy afforded by this hybrid approach can result in under-exploited catalogs, when compared to a human expert exhaustively identifying and associating all arrivals manually. Fortunately, in recent years Machine Learning (ML) methods have shown significant improvement in the task of automatically detecting seismic events. ML methods now potentially operate at a similar standard to a human expert, whilst running orders of magnitude more efficiently than comparable techniques. This provides a unique opportunity to revisit the continuous data recordings of past large aftershock sequences.

Here we reprocess a 1-year period of the 2016 Mw 7.8 Pedernales sequence using the PhaseNet (Zhu & Beroza, 2018) deep learning picker, and the HEX (Woollam et al., 2020) associator. Previously, this sequence was investigated using a combination of manual and traditional automated approaches (Agurto-Detzel et al., 2019). Compared to the ~6,000 well-located events found in the previous work, our ML-based approach finds ~12,000 well-located seismic events that have relocated hypocentral depth errors < 5km. Our newly derived seismic catalog offers a denser and better-resolved image of the subduction interface, and may provide additional insights into the velocity structure, the timing and spatial relation of slip on the interface, and new seismogenic structures not previously observed.

Keywords: Subduction zones, AI, seismicity, aftershock sequences

Applying machine learning for event detection: From curated datasets to practical case study for the Durres, Albania, aftershock sequence

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Machine Learning (ML) techniques have emerged as leading methods for performing the task of seismic event detection in recent years. With these techniques proven to run orders of magnitude faster than traditional automated approaches (e.g. template matching), whilst detecting events at a similar accuracy to the state-of-the-art of a human expert (Woollam et al., 2019), this has significantly boosted the number of events detected within traditional seismic analysis pipelines. Such a step-change in the accurate, timely recovery of low signal-to-noise ratio seismicity has huge implications for enhancing the physical understanding of many seismological processes. Various ML event detection methods are, therefore, being widely deployed across seismic processing pipelines. To evaluate which ML techniques are best suited for such pipelines, benchmarking studies are becoming vital to assess the current state-of-the-art (Munchmeyer et al., 2021). The systematic answering of such questions is now easily possible as specific ML toolboxes have recently emerged for the rapid answering of such research questions (e.g. SeisBench, Woollam et al., 2022). Due to the heterogeneity of seismic wave propagation, further practical case studies comparing leading ML methods across a wide range of environments are still needed. This will further validate the conclusions of the initial benchmarking works, and also provide quantifiable constraints on the ability of ML techniques to recover the highly-active seismic periods vs. traditional methods. Here, we compare the performance of the leading ML-detection methods in analysing 2-weeks of seismicity following the 2019 Durrës aftershock sequence in Albania. EQTransformer (Mousavi et al., 2020), and PhaseNet (Zhu & Beroza, 2019) & HEX (Woollam et al., 2020; PN-HEX), are applied to analyse the seismic sequence. These end-to-end seismic detection workflows are benchmarked against the results of 2 independently operating seismic experts who also processed a subset of events from the aftershock sequence. We find that the achieved locations are comparable to the manual approach, but the increased number of picks per event for the ML pickers, especially PN-HEX, yields smaller hypocentral errors

Keywords: AI, continental collision, aftershock sequence, seismicity

Cross- and in-domain training of machine learning pickers for land- and ocean bottom datasets

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A number of deep learning based picking and detecting algorithms have been published in recent years and been applied with great success mostly in local and regional seismicity studies where they often yield a far larger number of locatable events than those based on manual analysis or traditional automated approaches, at far less computational cost.
In addition, a number of benchmark datasets have been assembled such as STEAD (Mousavi et al. 2019) or INSTANCE (Michelini et al 2021), which can support standardised testing. Nevertheless, new algorithms are often just tested on specific datasets, making comparisons difficult. Also, it is not clear to which extent DL models (architecture + coefficients) can be applied to new datasets, or need to be retrained.
The SeisBench framework has unified the access to benchmark datasets, added several additional benchmarks sets and provides a unified API for several of the most popular Deep Learning models for picking.
We will summarise the results of a large-scale evaluation study considering both in-domain and cross-domain applications, giving some recommendations.
Recently, we assembled a large dataset of ocean bottom data with manual picks (from a total of 15 experiments, comprising 355 stations, 13,190 events, 109,210 traces and about 90K P and 63K S picks from different regions and tectonic environments. We trained popular DL pickers PhaseNet and EQTransformer on this data set, extending the models so that they can process 4-channel data (3 velocity components + hydrophone). The resulting model shows good performance, and returned confidences are shown to be a good guidance of the quality of the results. The trained models are able to cope with missing components, which are not infrequent in OBS experiments.

Towards a High Resolution 3D P- and S-wave velocity model of the Greater Alpine Region using Local Earthquake Tomography

Benedikt Brazus

Seismic data availability and automated picking algorithms drastically improved since the last orogen wide crustal P-wave velocity model of the European Alps was compiled by Diehl et al. (2009).
Especially, the abundant seismic data recorded by the AlpArray Seimic Network (AASN) which was in operation from 2015-2021 provides a unique high resolution seismic data set. The aim of our project therefore is to create a comprehensive 3D P- and S-wave crustal velocity model for the European Alpine region using Local Earthquake Tomography (LET). Such a model is not only needed to sharpen high resolution teleseismic tomography studies imaging subducted slabs but also to relate surface structures to mountain building processes in the mantle.
To achieve this aim precise onset times of seismic crustal phases are needed. Here we show our first results of automatic onset time determination obtained through the deep-neural-network PhaseNet. When compared to catalogues of manual travel time picks, we find its performance as accurate as a human analyst's. This confirms the transferability of machine learning approaches to our area and data set. An evaluation of other neural network based picking algorithms is conducted using "SeisBench - A toolbox for machine learning in seismology".
The large amount of evenly distributed seismic stations yields up to a total of 720 P and S arrival picks with epicentral distances up to 700km for events with ML > 3.5. Earthquakes with magnitudes of ML=2.5 are generally detectable for epicentral distances up to at least 200km and contribute approximately 200-300 arrivals per event.
As a first step towards a high resolution 3D model we present a thorough analysis of the consistency of the automatically determined arrival times, which facilitates a reliable removal of outliers.
Conventionally, outliers in the onset time picks have been discarded based on their residual with reference to a minimum 1D model including a station correction term. We show that for ray paths larger than 300km a coarse 3D model which already incorporates the main 3D anomalous structures outperforms a minimum 1D model and is therefore more suitable to consistently and accurately remove erroneous arrival time picks.

Estimation of the Magma Intrusion Volume Rate beneath the East Eifel Volcanic Field, Germany

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Deep low frequency seismic events are detected in the East Eifel Volcanic Field (EEVF) since 2013. To well detect and locate such events the Deep Eifel Earthquakes Project - Tiefe Eifel Erdbeben (DEEP-TEE) started in July 2014 which now is composed of ca. 10 permanent and 15 mobile recording stations. Up to now, the DEEP-TEE seismic dataset contains close to 8 years of continuous seismic records and the network has been reconfigured and continuously developed to achieve an optimum configuration regarding detection and location of seismic events.

In order to detect the weak deep low frequency (DLF) events we developed a seismic event detector, called Adaptive 6-Dimensional Floating-search Multi-station Seismic-event Detector (A6-DFMSD). Using this detector we found 333 localizable DLF events in 2014-2021. The DLF hypocenter distribution outlines a near-vertical structure beneath the Laacher See Volcano (LSV) which is interpreted as the magmatic plumbing system of the volcano. Here we try to estimate the mass flux (magma and volatiles) which are related with the seismicity. We apply Aki et al.'s model (JVGR, 1977) for describing the magma movement (so called chain of cracks connected by narrow channels) and estimate the related magma intrusion volume rate in the EEVF lithosphere. We assume an initial set of model parameters and evaluate sensitivity/stability of the modelling results by allowing a reasonable possible range of each individual input parameter. At the end we consider 3 possible scenarios and present the estimated extremes for the magma volume intrusion and the most plausible value according to the geometry of the plumbing system.

Current crustal movement in the East Eifel Volcanic Field – anthropogenic or volcanic?

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Monitoring crustal movements is essential to volcanic hazard assessment in areas of active volcanism. These surface movements occur on a wide range of time scales and wavelength. However, the origin of crustal movements is not always associated with volcanic activities, particularly in areas with rigorous human activities (i.e., ground water extraction). It is challenging yet critical to distinguish between the ongoing volcanic and anthropogenic activities. In this study, we focus on the East Eifel Volcanic Field, which consists of multiple active Quaternary volcanoes. We report areas of uplift and subsidence 2-3 km away from each other near the Laacher See volcanic crater (2-3 km distance) and investigate the mechanisms responsible for the reversed deformation in such close proximity.

PS-InSAR measurements by the BodenBewegungsdienst Deutschland (BBD) show notable ground displacements in this area for the period between 2014 and 2019. The deformation is clearly mapped by three different tracks of the Sentinel-1 satellite – two ascending and one descending, which confirms the robustness of the signal being detected by PS-InSAR. The main deformation is round in shape, and the rates peak up to 10 mm per year in line-of-sight (LOS) for the uplift area near the village Glees and reach down to -4 mm LOS for the subsidence zone in the vicinity of the village Wehr. To investigate the likely mechanism responsible for the ground displacements, we model the crustal movements with two spherical pressure point sources (i.e., the Mogi sources) simultaneously using a combined global and local optimization scheme. In the inversion, we search for the optimal combinations for a set of four parameters (latitude, longitude, depth and volume) for each Mogi source. The global optimization is achieved by Multi-Level Single-Linkage algorithm, and we use the PRAXIS algorithm to find the local minimum. We include all three tracks of data, of which the different satellite viewing geometries help stabilize the inversion.

Our results show that the uplift trend in Glees can be explained by an additional volume of 13000 m^3 per year at 530 m depth. The subsidence near Wehr can be best fitted by a decrease in volume of 1700 m^3 per year at 340 m depth. The modelling results show a trade-off between depth and volume, however, the uncertainties are smaller for the subsidence source near Wehr. Residuals trending in SW-NE direction are observed at the Glees uplift area, and the relatively large parameter uncertainties for Glees uplift zone are likely due to sparse persistent scatters there. Given the shallow depth of the Mogi sources, we interpret the Glees uplift being predominantly associated with fluid refilling in the respective volume caused by former CO_2 extraction. The subsidence around Wehr is linked to ongoing industrial CO_2 extraction. Our study identifies anthropogenic factors that may cause ground deformation in an active volcanic region and has implications for future volcanic hazard assessment.

Keywords: Eifel, Deformation, Uplift, InSAR

The Active Ochtendung Fault Zone Seismic Experiment – Shallow refraction tomography in the East Eifel Volcanic Field, Germany

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Persistent microseismicity in the East Eifel Volcanic Field occurs along the Ochtendung Fault Zone (OFZ) just SE of Laacher See Volcano. In addition, deep-low-frequency earthquakes close by are a strong indication for active magmatic processes. No surface expression is known for the OFZ, therefore an active seismic study was conducted in the summer 2021 aiming to detect the near-surface structure of the fault.

The survey follows a line nearly perpendicular to the assumed fault orientation. The total length of the survey is 4,500 m with 5 m geophone distance and a maximum offset of 1000 m. Additional to these vertical component geophones, 3-component sensors were deployed at several sites along the profile in order to record far offsets. A drop-weight served as a seismic source.

1,022 shots lead to a total of more than 225,000 channels with maximum offsets of up to 1km, if including the 3-component sensors even up to 5km. Standard QC procedures and the stacking of the single shots at each shot point was done. The data set comprises 177 shot gathers with up to 221 receivers active at the same time. On these data the first onset P-wave arrivals were determined resulting in more than 35000 picks.

The refraction tomography uses an innovative inversion technique harnessing the power of a transdimensional, hierachical Markov chain Monte Carlo (McMC) algorithm without the need of a priori assumptions. The number of Voronoi cells describing the Earth structure model and the level of data noise is automatically determined during the inversion process. The forward modelling is performed by a fast, finite-difference based eikonal solver. Starting several hundred McMC-chains across multiple CPU-cores leads to the parallelism needed for efficient sampling of the model space, thus computing of a refraction tomography 2-D Earth structure model including its uncertainty.

We achieve a good resolution in depth down to about 200 m throughout our model. The thickness of the tephra layer covering the Rhenish shield is increasing from SW (few meters) to NE (80 m) along the profile. Further studies are still needed to illuminate the shallow structure of the OFZ.

Keywords: Seismics, Refraction, Eifel, Ochtendung Fault

Titel:

Abbildung der Krustenstruktur im Bereich der Eifel durch Reprozessierung der tiefenseismischen Profile DEKORP87-1A/B

Abstract:

Die beiden seismischen Profile DEKORP87-1A und -1B, die im Rahmen des belgischen und deutschen kontinentalen reflexionsseismischen Programms (BELCORP bzw. DEKORP) aufgezeichnet worden sind, wurden reprozessiert, um die Krustenstruktur im Bereich des Eifelvulkanfeldes mit modernsten Methoden abzubilden und Hinweise auf den Vulkanismus im Rheinischen Schiefergebirge zu finden. Die Messungen wurden im August 1987 mit einer asymmetrischen Split-Spread-Geometrie mit maximal 400 Einkomponenten-Geophonen durchgeführt. Als Anregung wurde eine Vibroseis-Quelle verwendet. Der Abstand zwischen den Schuss- und Geophonpunkten betrug 40 m, was eine Gesamtzahl von 1891 (1A) bzw. 1049 (1B) Schusspunkten und 2329 bzw. 1249 Geophonpunkten ergab. Die Profillängen ergaben sich dann zu 93 km (1A) und 50 km (1B), und verfügten über einen maximalen Offset von 12 km. Für die Neubearbeitung wurde zunächst eine Ersteinsatztomographie durchgeführt, um ein oberflächennahes Geschwindigkeitsmodell zu erstellen. Dieses wurde mit Geschwindigkeitsmodellen aus der Literatur für die tieferen Krustenbereiche kombiniert, um ein Migrationsgeschwindigkeitsmodell für die gesamte Kruste zu erstellen. Die Datensätze wurden dann im Zeitbereich pre-prozessiert und mit der Kirchhoff pre-Stack Tiefenmigration (KPSDM) und der Fresnel-Volumen Migration (FVM) für verschiedene Geschwindigkeitsmodelle bearbeitet. Die aus der Migration resultierenden Untergrundabbilder zeigen ein reichhaltiges strukturelles Inventar mit deutlich ausgeprägten Reflektoren innerhalb der gesamten Erdkruste. Darüber hinaus zeigt der Vergleich der beiden Migrationsmethoden die Vorteile der jeweiligen Bildgebungsmethode, so dass bestimmte unterirdische Strukturen je nach Methode unterschiedlich aufgelöst und interpretiert werden konnten. Die resultierenden Migrationsabbilder wurden mit Hypozentren der lokalen Seismizität in einem 3D-Untergrundmodell kombiniert und können so als Grundlage für die Interpretation der geologischen Strukturen sowie der vulkanischen Prozesse in dem Gebiet dienen.

1-D Seismic Velocity Model KIT5 and Hypocentres in the East Eifel Volcanic Field

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The observation of deep low-frequency microearthquakes in the upper mantle and lower crust of the East Eifel Volcanic Field (EEVF) motivated the Deep Eifel Earthquake Project – Tiefe Eifel Erdbeben (DEEP- TEE). As a part of DEEP-TEE we densified the seismic network in the area since 2014. This dataset allows new studies to improve the understanding of the magmatic processes beneath the EEVF. Basic requirements are precise regional *P* and *S* wave velocity models for the EEVF to enhance the quality of the hypocentre locations. For this purpose, we compile a dataset based on local earthquake waveforms of the state earthquake services of Rhineland-Palatinate, Hesse and North Rhine-Westphalia as well as the BGR.

We analysed 1675 events between 2010 and 2021 using the permanent recording stations and the 26 mobile stations from KIT KABBA (2014-2021) and GFZ GIPP (2014-2016). The outputs are new minimum 1-D seismic *vp* and *vs* velocity models called KIT5 as well as corresponding station delay times for earthquake relocation based on VELEST. Compared to previous studies, the extended dataset allows to sort out phase picks with low quality to minimize location errors. To sample the model space, we use different velocity starting models for the inversion process, also to investigate the uncertainty ranges. The final minimum 1-D models are chosen from the simplest layering with minimized RMS-values. As the data coverage is poor below the Moho we use a previous seismic refraction model and petrological constraints to estimate *vp* and *vs* down to approx. 45 km depth. The recovered hypocentre distribution reveals two main features: 1) there is a steep translithospheric magmatic channel outlined by deep low-frequency events just south of the Laacher See Volcano (LSV), 2) the location of the active part of the Ochtendung Fault Zone is outlined by a narrow band of tectonic events between Kobern-Gondorf and the east of the LSV at 5-15 km depth with a near-vertical dip.

TURNkey: Insights into the 2021 Reykjanes Peninsula, Iceland, volcano-tectonic episode from processing new small-aperture arrays

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* presenter

Abstract: An intense period of volcano-tectonic unrest in the Reykjanes Peninsula Oblique Rift (RPOR) zone in Southwest Iceland commenced on 24/02/2021 with a Mw5.64 earthquake in the central part of the Peninsula, followed by a drastic increase in seismic activity over the western-central RPOR and clear deformation signals associated with a dike intrusion. The sequence that saw six NS-striking earthquakes of Mw5 and larger along the ∼10 km long NE-SW striking dike intrusion culminated on 19/3/2021 in an eruption in Mt. Fagradalsfjall near the centre of the dike. Thereafter, magnitudes and intensity decreased along with generally ceasing seismicity. The movement of the magma front repeatedly caused remarkable accelerations of seismicity with increases in the frequency of phase detections, known to reduce the sensitivity and reliability of real-time hypocenter location estimates of regional networks. This potentially had practical implications due to the proximity of the unrest to the capital region of Reykjavik (15-25 km NE) and the town of Grindavik (6 km SW). Therefore, both the improved seismic monitoring of the advancing magma front was essential to cope with the high seismicity as well as mapping the spatial differences in ground motion amplitudes inside the closest town of Grindavik, 6 km SW of the volcanic eruption. We therefore set up a new seismic and strong-motion array consisting of 6 stations in Grindavik (on 12 March 2021) that streamed data in real-time to a local SeisComP server. Calibration of the array processing involved tuning Gempa's interactive and automatic LAMBDA and AUTOLAMBDA modules applying the Progressive Multi Channel Correlation and FK-analysis methods. We calculated back-azimuth and slowness values for known earthquakes and compared them with official permanent network locations. For most events, the back-azimuths deviate by less than 10° and on average, the distribution of residuals is Gaussian. The ground motions in Grindavik itself show resonance at 3 Hz, typical of lava-layers in the region. In addition, a new seismic array was deployed on 23 March 202 in the mountains about 6 km E of the dike intrusion, improving hypocentral locations of small events and tracking the magma migration in the sub-surface.
Automatic tracking of the seismicity in December, 2021, revealed periodic changes in backazimuth on a linear trend which we interpret as earthquakes due to repeated pulsed lava injections.

Keywords: SeisComP, TURNkey, RISE, dike, detection, backazimuth

Correlated low-frequency tremor bursts and very low frequency surface deformation at Villarrica volcano, Chile

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Volcano seismology is an essential tool for monitoring volcanic processes in the advent and during eruptions. A variety of seismic signals can be recorded at volcanoes, of which some are thought to be related to the migration of fluids which is of primary importance for the anticipation of imminent eruptions. We investigate the volcanic crises at Villarrica volcano in 2015 and report on a newly discovered very long period (VLP) signal that accompanies phases of periodic long period (LP) signal burst. Despite their low amplitude emergent character, we can locate the source region of the 1 Hz LP signals to the close vicinity of the volcano using a network-based correlation method. The source of the VLP signal with a period of about 30- 100 s appears to locate in the vicinity of two stations a few kilometers from the summit. Both stations record very similar VLP waveforms that are correlated with the envelope of the LP bursts. A shallow magma reservoir was inferred by Contreras (2017) from surface deformation as the source of inflation following the eruption in 2015. Cyclic volume changes of 6 m3 in this reservoir at 3 km depth can explain the observed amplitudes of the vertical VLP signal. We propose that the LP signal is generated by the migration of gas or gas-rich magma that is periodically released from the inflating reservoir through a non-linear valve structure which modulates the flux, and thereby causes bursts of flow-related LP signals and pressure changes observed as VLP deformation. Our model predicts that the correlated occurrence of LP bursts and VLP surface motion depends on the intensity of the fluid flux. A weaker flux of fluids may not exceed the opening pressure of valve structure, and higher rates might maintain pressure above the closing pressure. In both cases, the VLP signal vanishes. Our observation provides constrains for models of fluid transport inside volcanoes. At Villarrica the VLP signal, and its relation to the LP activity, reveal additional information about fluxes in the magmatic reservoir that might aide forecasting of volcanic activity.

A global analysis of atmospheric waves and seismoacoustic observations from the January 2022 Hunga eruption, Tonga

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The January 2022 volcanic eruption of Hunga, Tonga in the South Pacific Ocean produced the most powerful blast recorded in the last century. The blast energy was mainly propagated through the atmosphere as a long-period (>2000 s) surface-guided Lamb wave. Other observed wave types comprised acoustic-gravity and infrasound waves. Infrasound waves were captured by the entire infrasound component of the International Monitoring System (IMS) after circumnavigating Earth up to eight times. Therefore, the eruption was the strongest infrasound source since the installation of the IMS started. The globally observed Lamb wave exhibited an energy comparable to that of the 1883 Krakatoa event – at least four circumnavigations of this pressure wave were recorded by the IMS infrasound stations.

This talk provides a comprehensive description of the eruption chronology of the Hunga volcano based on the IMS technologies. The powerful event is further analysed using infrasound and seismoacoustic observations. The Lamb and acoustic-gravity wave characteristics allow estimating the equivalent TNT yield of the eruption in the order of 100-200 megatons.

Three component ground response to the passage of the atmospheric Hunga-Tonga Lamb wave at stations of the global seismic network (GSN).

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At frequencies below 20 mHz horizontal component background noise is typically dominated by ground tilts due to atmospheric pressure variations.

The observation of the atmospheric Lamb wave in the period band 600s – 3600s as excited by the January 15, 2022 Hunga Tonga eruption constitutes a unique opportunity to study the relationship between the propagation direction of an approximately plane atmospheric pressure wave and the direction of the induced ground tilt as observed by broad-band seismometers of the GSN.

We model the observed horizontal component acceleration as a linear combination of the locally recorded barometric pressure and its Hilbert transform. Following Zürn et al. (GJI, 2021) we can hereby separate the ground response into a local deformation tilt (LDT) that is predicted to be proportional to local barometric pressure fluctuations and a traveling wave tilt (TWT) that is predicted to be 90 degrees out of phase from pressure. The vector sum of the North-South and East-West Hilbert component regression coefficients is expected to point along the great circle connecting the station with Hunga Tonga.

We analyze also the response of the vertical component seismometers to the passage of the Lamb wave and test our expectation that at the dominant frequency of the Lamb wave (0.5 mHz) the vertical ground acceleration is proportional to local barometric pressure with a regression coefficient close to -3.5 nms^{-2}/hPa.

This is work in progress and results will be presented.

SEISMO-ACCOUSTIC EVENT DETECTION AND LOCALIZATION BY ARRAYS AND DISCRIMINATION OF A MISSILE IMPACT IN WESTERN UKRAINE ON MARCH 18, 2022

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Abstract: We present the seismo-acoustic signal analysis of a Russian missile attack near an airport close to Lviv, Ukraine on March 18, 2022. We processed the seismic records of seismological stations in Poland, Slovakia and Hungary, as well as the infrasound records at Hungarian and Romanian infrasound arrays using the LAMBDA and KAPPA software packages within the SeisComP framework. While LAMBDA automatically detected and located the event using array techniques, KAPPA distinguished the signal from regular mining explosions to find the source type. The resulting location is 20 km WSW from the impact location near Lviv airport reported by news media. KAPPA, supporting custom plugins to classify signals, describes the source as a the missile impact signal discriminating it from common detections caused by nearby quarry blasts. The plugin for KAPPA analyzes several features of the pixel family derived from the PMCC processing within LAMBDA like backazimuth, slowness, duration, frequency range, slope of onset/coda, maximum amplitude, trends in backazimuth and slowness as well as time of the detection. The signal shows significant differences to the quarry blast activity especially in the slope of onset and coda as well as in its duration.

Keywords: infrasound, array, PMCC, LAMBDA, KAPPA

GEOREAL – Adaptive Stimulation an der KTB

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Im Rahmen des GEOREAL Projektes wird Anfang 2023 ein Injektionsexperiment am Standort des Kontinentalen Tief-Bohrprogramms der Bundesrepublik Deutschland (KTB, https://www.gfz-potsdam.de/ktb-tiefenlabor/) in Windischeschenbach/Oberpfalz durchgeführt, um kritische Forschungsfragen zur tiefen Geothermie anzugehen. Die beiden KTB-Bohrungen stellen einen einmaligen Zugang zu einem petrothermalen Fluidreservoir bis mindestens 9 km Tiefe und Temperaturen deutlich über 100°C in >3 km Tiefe in metamorphen Gesteinen dar, welches typisch für weite Teile der Erdkruste Deutschlands ist. Mit Hilfe des hydraulischen Stimulationsverfahrens sollen in Tiefen über 3.8 km unter Realbedingungen von Überlagerungsdrucken und Temperaturen einer Geothermie-Bohrung adaptive Stimulationsansätze mit bestmöglicher seismischer Echtzeit-Überwachung getestet werden. Dies umfasst eine Serie von hydraulischen Tests, mit denen gezielt der Effekt von Druckaufbau und -abbau, maximalen Injektionsdruck, verpressten Fluidvolumina, Wechsel von kontinuierlichen zu periodisch veränderlichen Fließraten, und Relaxationsphasen auf die räumliche Ausbreitung von minimalen induzierten Erdbeben im Reservoir und die zeitliche Entwicklung der Magnituden erfasst und unmittelbar durch adaptive Anpassung von Druck- und Fließraten während der Stimulation gesteuert werden. Ziel ist es, spürbare seismische Ereignisse zu vermeiden. Außerdem soll die Entwicklung der hydraulischen Reservoir-Eigenschaften und der optimale Betriebsmodus für seismische Echtzeitbeobachtung untersucht werden.

GEOREAL baut auf mehreren, früher durchgeführten Injektionsexperimenten mit anderem Fokus am KTB-Standort auf. Zwischen 1994 und 2005 wurden an der KTB insgesamt drei größere Fluidinjektions-Experimente durchgeführt, von denen zwei (1994, 2000) Injektionen im offenen Bohrlochabschnitt der Hauptbohrung und eines (2001-2005) Langzeit-Fluidproduktion mit anschließender Injektion in der Vorbohrung beinhalteten. Mit seismischen Messnetzen aus bis zu 73 Oberflächenstationen und einer Bohrlochsonde in knapp 4 km Tiefe wurden zwischen 150–400 Mikroerdbeben pro Experiment nahe der Stimulationsintervalle, aber auch in anderen Tiefenabschnitten lokalisiert. Letztere weisen wahrscheinlich auf Verrohrungsleckagen hin. Das größte induzierte Erdbeben hatte eine Magnitude von 1.2 und ereignete sich während der Phase der höchsten Fließrate.

Die zwei tiefe Bohrungen mit 4000 und 9101 m Bohrtiefe direkt nebeneinander eignen sich ausgezeichnet, um mithilfe einer Geophonkette in wenigen hundert Metern Entfernung zum Injektionsintervall das GEOREAL-Experiment hochgenau zu überwachen. Zusätzlich werden bis zu 40 weitere Seismometer an der Oberfläche rund um die KTB und in mehreren 150 m tiefen neuen Bohrlöchern installiert und in Echtzeit zum Bohrplatz übertragen und dort direkt ausgewertet.

Mit diesem seismischen Netzwerk erwarten wir eine deutlich höhere Anzahl an lokalisierbaren Mikroerdbeben und damit detailiertere Informationen zur raum-zeitlichen Ausbreitung der Seismizität. Mit dem geplanten Experiment sollen existierende Best-Practice Verfahren für die technische Umsetzung verbessert und potentielle mit der Technologie verknüpfte Risiken verringert werden, um so die Akzeptanz der Tiefen Geothermie in Deutschland zu verbessern. GEOREAL wird ein umfassendes Informationsprogramm beinhalten, das sich sowohl an die lokale Bevölkerung als auch an Studenten richtet. Um den Verlust wissenschaftlicher Erkenntnisse aus dem KTB-Programm 1990–2005 zu verhindern werden Workshops durchgeführt, bei dem gezielt Nachwuchswissenschaftler eingebunden werden.

Darüber hinaus wird im Zuge der geplanten Arbeiten ein einzigartiges Geothermie-Tiefenlabor für die Nutzung durch mögliche weitere Projekte der geowissenschaftlichen Gemeinschaft als state-of-the-art Forschungsinfrastruktur zur Verfügung stehen.

Using seismic envelopes to separate the effects of source, site and path

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Using the physical model of radiative transfer seismic envelopes are modeled and compared to observed shear wave envelopes from small earthquakes. By using the full envelope including direct shear wave and coda waves, intrinsic attenuation and scattering strength can be independently determined. Byproduct of the inversion are other important observables, namely site amplification at the stations and source displacement spectra of the earthquakes. The latter can be fitted with a source model to determine source parameters as seismic moment, moment magnitude and corner frequency. The functionality is bundled in the Qopen package and ready to be applied in different settings.

Intrinsic attenuation, scattering strength as well as site amplification for high frequency shear waves (1 Hz to 15 Hz) across the contiguous US and its implications for macroseismic observations are briefly discussed.
The second show case are results in the frequency range 3 Hz to 200 Hz from the 2018 and 2020 Helsinki geothermal stimulations suggesting systematic differences in the corner frequency, stress drop, and magnitude scaling relationships.

Determination of the frequency- and depth-dependent intrinsic and scattering S-wave attenuation using the example of the Leipzig-Regensburg fault zone

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The frequency- and depth-dependent determination of absorption and scattering attenuation is a new challenge we want to approach. Using Monte Carlo simulation of radiative transfer theory with isotropic scattering coefficients, we generate seismic envelopes of the S-wave, which are then compared to the coda normalized observed data. The Monte Carlo simulation takes into account reflection and transmission at layer boundaries as well as S-wave velocity, density, scattering and absorption of several layers. The depth dependence can be inverted by varying the scattering and absorption. To test the code, the first step is to generate synthetic envelopes, which are then used as observation data in the Monte Carlo simulation and subsequently inverted. Then, we use real earthquake data to determine the frequency and depth-dependent absorption and scattering attenuation between 3 and 24 Hz along the Leipzig-Regensburg fault zone, a N-S oriented, seismically active band between Leipzig and the German-Czech border, with several intracontinental swarm earthquake areas.

Shear wave splitting analysis and temporal misalignment of seismogram components

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Shear wave splitting of teleseismic phases such as SKS, SKKS, PKS, or ScS is frequently used to understand the Earth's interior, including both the upper and the lowermost mantle.

The determination of the splitting parameters, fast polarization direction ϕ and delay time δt, as well as the splitting intensity, relies on the correct relative temporal alignment of the single component traces (vertical, N-S, E-W). Unfortunately, the code of the widely used MATLAB package *SplitLab* contains an error source leading under certain circumstances to a wrong relative temporal alignment of the seismic traces. This error then causes wrong shear wave splitting measurements (SWSMs). In this presentation we point out this issue in details. Modified or corrected scripts of the relevant *SplitLab* function are provided via GitHub for the publicly available *SplitLab* versions directly (https://github.com/yvonnefroehlich/SplitLab-TemporalAlignment) and with the last *StackSplit* version v3.0 (https://github.com/michaelgrund/stacksplit), a *SplitLab* plugin for multi-event analysis.

As example SWSMs from the Black Forest Observatory (BFO) are presented. Especially, we show significant differences between the NE and the SW quadrants, which indicate very small-scale intra-station lateral variation. We focus on the SW quadrant and its dominant *null* observations, which is in contrast to the NE quadrant with a characteristic two-layer anisotropy splitting pattern within a backazimuthal range of 30°-100°. SWSMs from five neighboring broadband recording stations in the Upper Rhine Graben area (inter-station distance 10-80 km) are included to test for lateral variations across stations. Different approaches are proposed to explain the so-called *null anomaly* at BFO.

Testing observables for teleseismic shear-wave splitting inversions: ambiguities of intensities, parameters, and waveforms

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Abstract

We assess the capabilities of different observables for the inversion of core-refracted shear waves (XKS phases) to uniquely resolve the anisotropic structure of the upper mantle. For this purpose, we perform full-waveform calculations for simple, canonical models of upper-mantle anisotropy. The models are characterized by two and four domains of different anisotropic properties. We assume hexagonal symmetry with arbitrarily chosen strength of the anisotropy and orientation of the horizontal fast axis. XKS waveforms generated from plane-wave initial conditions, traverse through anisotropic models and are recorded at the surface by a single station (in case of vertical variations) and by a dense station profile across the laterally and vertically varying structure.

In addition to waveforms, we consider the effects on apparent splitting parameters and splitting intensity. The results show that, generally, it is not possible to fully resolve the anisotropic parameters of a given model, even if complete waveforms (under noise-free conditions and for the complete azimuthal range) are considered. This is because waveforms for significantly different anisotropic models can be indistinguishable. However, inversions of both waveforms and apparent splitting parameters lead to similar models that exhibit systematic variations of anisotropic parameters. These characteristics may be exploited to better constrain the inversions.

The results also show that splitting intensity holds some significant drawbacks: First, even from measurements over a wide range of back-azimuth, there is no characteristic signature that would indicate depth variations of anisotropy. Secondly, identical azimuthal variations of splitting intensity for different anisotropic structures do not imply that the corresponding split waveforms are also similar. Thus, fitting of observed and calculated splitting intensities could lead to anisotropic models that are incompatible with the observed waveforms.

We conclude that XKS-splitting inversions and related tomographic schemes, even if based on complete waveforms, are not sufficient to fully resolve the heterogeneous anisotropic structures of the upper mantle and that combinations with methods based on, e.g., receiver-function splitting or surface waves, are required.

Seismic signals from wind turbines and their relation to acoustic emissions and resident annoyance

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Wind turbine (WT) vibrations and sound are major sources of objection against wind farms from local residents. We study how residents are affected and evaluate their concerns against objective data using interdisciplinary measurement campaigns conducted in the framework of the project Inter-Wind. During these campaigns, at first residents are interviewed and then offered to use a noise reporting app throughout times when also acoustic, ground motion, and meteorological data are gathered. We conducted two measurement campaigns for ground motions at wind farm Tegelberg on the Swabian Alb in Southern Germany. Campaign 1 was in autumn 2020 and campaign 2 in spring 2022.

The nearest municipality, Kuchen, where most opposition against the wind farm is found, also features a major railway line and a federal road. The emissions of each noise source are quantified and compared in amplitude to the wind farm signals. While measured ground motion amplitudes are below the human perception threshold, continuous measurements give indications about the time of occurrence and relative amplitudes of the different vibrations. These measurements provide additional information to acoustic measurements at the wind farm and within the municipality. At the wind farm, ground motion spectrograms recorded with seismometers exhibit strong similarities to sound pressure spectrograms, showing generator and gearing signals for frequencies up to 150 Hz. In noise reports, residents name the generator and gears as noise sources, coinciding with recorded emissions. Furthermore, annoyance reports can be correlated with wind farm operation through operating data, to assess the credibility of the registered complaints. Most reports are registered during the evening (campaign 1 and 2) and early morning hours (campaign 1). Traffic noise from a federal road and a major railway line is reduced at night time while the wind farm can operate continuously when favorable meteorological conditions are present. Potentially, with other noise sources reduced, WT sounds are perceived as especially annoying during the more quiet night hours, even though signal amplitudes are low.

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A 3D Vs model of the Pannonian region from joint earthquake and ambient noise Rayleigh wave tomography

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& The AlpArray Working Group

Abstract: To decipher the evolution of the Pannonian Basin and the transition to the eastern Alps, we determined a high-resolution three-dimensional S-wave velocity model of the crust, the lithospheric mantle and the asthenosphere of the broader Pannonian region using joint tomographic inversion of ambient noise and earthquake data. For this purpose, we collected continuous waveform data from more than 1280 seismic stations from the greater Pannonian region for ambient noise cross-correlation measurements. This dataset embraces all the permanent and temporary stations operated in the time period from 2005 to 2018. The Rayleigh wave ambient noise phase velocity dispersion curves were combined with existing measurements from earthquake data to cover the broad period range of 3-300 s. A correction term was defined by comparing phase velocity curves from both data sets for the same station pairs to compensate for the systematic discrepancy between the two methods. Phase velocity maps for periods from 3 s to 250 s were calculated jointly from earthquake and ambient noise phase velocities. The lateral resolution varies between <50 km in the center of the Pannonian Basin and the eastern Alps to about 150 km in less well covered areas. Local dispersion curves extracted from the phase velocity maps were inverted for Vs and Moho depth using a stochastic inversion algorithm based on Particle Swarm Optimization. Map views and vertical cross sections of the resulting 3D model are shown and main features are discussed: for example, the extensional horst and graben structure of the upper crust in the Pannonian Basin, its thinned lithosphere, slabs beneath the Alps, Apennines, Dinarides, and Carpathians, as well as evidence for (deeply downgoing) orogenic wedges above the slabs. The relationship of these features to the evolution scenarios of the Pannonian Basin are pointed out briefly.

AdriaArray: a passive seismic experiment to study plate deformation in the central Mediterranean

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Abstract: AdriaArray is a passive seismic experiment covering the broader central Mediterranean area from the Massive Central in the West to the Carpathians in the East, from the Alps in the North to the Calabrian Arc and the Kefalonia Transform Fault System in the South contemporaneously in the time period from 2022 to 2024. According to the current plan, its backbone component will consist of 1378 broad-band stations (974 permanent ones including 89 formerly non-EIDA stations and 404 temporary ones). The temporary stations are provided by 21 mainly European pools of mobile broad-band seismometers. About 200 temporary broad-band stations are already operational. 100 broad-band DSEBRA stations will be deployed and operated by German universities. The backbone network will be densified at key sites by local experiments. The deployment of the stations, the data acquisition and the seismological scientific work will be coordinated by the AdriaArray Seismology Group (AdASG) founded in May 2022. The main aim of the experiment is to decipher properties of the disintegrating Adriatic Plate that reduced in size by about 70 % since the onset of convergence between Europe and Africa in Mesozoic time by orogenic accretion and delamination of lithospheric mantle. The area is well suited to study the evolution of continental lithosphere and to model plate deformation and associated geohazards quantitatively. In this presentation, we briefly summarize the status of the experiment as well as the organization of the AdASG.

Die seismische Momenten-Rate des Mars im Lichte von Event S1222a

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Am 4. Mai 2022, dem 1222. Sol der InSight mission auf dem Mars, wurde ein seismisches Ereignis detektiert, welches sich als das stärkste bis dahin registrierte herausstellte. Mit einer Momenten-Magnitude von 4.7 setzte dieses Ereignis so viel seismisches Moment frei wie alle zuvor von InSight registrierten Ereignisse zusammen, und deutlich mehr als das zweitgrößte Ereignis S0976a.

Wir nehmen das Event S1222a zum Anlaß, die seismische Momenten-Rate des Mars nach der von Knapmeyer et al. (2019, BSSA, doi: 10.1785/0120180258) entwickelten Methode zu schätzen. Unser Ziel dabei ist es, aus dem vorhandenen Katalog von 2706 Ereignissen (Stand: 7. Juni 2022) eine Teilmenge von Ereignissen zu extrahieren, welche repräsentativ für die endogene seismische Aktivität des gesamten Planeten ist.

Auszusortieren sind demnach Meteoriteneinschläge, Artefakte durch Windböen oder andere Störungen (d.h. alle 1969 im Katalog als Qualität "D" klassifizierten Ereignisse), und thermische Ereignisse in der Umgebung des Landers (1383 SHF events).

Nutzbar sind weiterhin nur solche Ereignisse, die unabhängig von den täglichen und jahreszeitlichen Schwankungen des Hintergrundrauschens (Wind) zu jedem Zeitpunkt registrierbar gewesen wären (konkret fordern wir 95% der Zeit, da 100% nicht erreichbar sind), und die von jedem Ort an der Oberfläche des Planeten registrierbar gewesen wären. Wegen der geringen Größe des Mars ist die globale Vollständigkeitsmagnitude selbst bei starkem Wind mit $M_t = 4.1$ niedriger als auf der Erde.

Es gibt genau ein Ereignis, das alle Kriterien erfüllt, nämlich S1222a. Knapmeyer et al. (2019) haben gezeigt, wie aus einem einzelnen Ereignis eine Schätzung der Momenten-Rate abgeleitet werden kann.

Diese Schätzung erfordert außerdem eine Abschätzung des *b*-Werts der Magnitude-Häufigkeits-Verteilung anhand des Katalogs. Hierbei ist zu berücksichtigen, daß ein Großteil der Ereignisse wegen des Hintergrundrauschens eben nicht zu jeder Zeit registrierbar gewesen wäre. Wir versuchen die Anzahl unbemerkter Ereignisse zu schätzen unter der Annahme, daß Ereignisse zu allen Tages- und Jahreszeiten gleich häufig auftreten. Damit ist die kumulative Häufigkeitsverteilung der Amplitude des Hintergrundrauschens ein Maß dafür, wie viele Beben zusätzlich zu den beobachteten anzunehmen sind, so daß in der maximum likelihood Schätzung eine geeignete Gewichtung angebracht werden kann. Dies führt zu einer Abschätzung von $b \approx 1.25$. Da ein großer Teil der lokalisierten Beben im Cerberus Fossae Gebiet liegt, welches vulkanischen Ursprungs ist, und der *b*-Wert in vulkanischen Gebieten gegenüber dem globalen Durchschnitt erhöht sein kann, betrachten wir auch eine Lösung mit einem geringeren, global aber vielleicht plausibleren $b = 1$. Die Unsicherheit von *b* läßt beide Werte zu.

Mit nur einem einzigen relevanten Ereignis kann nur eine untere Grenze der Momentenrate abgeschätzt werden. Dennoch ist es möglich, einen Vergleich mit publizierten Vorhersagen sowie der beobachteten Seismizität von Erde und Mond anzustellen.

Empirical H/V spectral ratios at the InSight landing site and implications for the martian subsurface structure

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Abstract

The H/V spectral ratio inversion is a traditional technique for deriving the local subsurface structure on Earth. We calculated the H/V from the ambient vibrations at different wind levels at the InSight landing site, on Mars, and also computed the H/V from the S-wave coda of the martian seismic events (marsquakes). Different H/V curves were obtained for different wind periods and from the marsquakes. From the ambient vibrations, the recordings during low-wind periods are close to the instrument self-noise level. During high-wind periods, the seismic recordings are highly contaminated by the interaction of the lander with the wind and the martian ground. Therefore, these recordings are less favorable for traditional H/V analysis. Instead, the recordings of the S-wave coda of marsquakes were preferred to derive the characteristic H/V curve of this site between 0.4 and 10 Hz. The final H/V curve presents a characteristic trough at 2.4 Hz and a strong peak at 8 Hz. Using a full diffuse wavefield approach as the forward computation and the Neighbourhood Algorithm as the sampling technique, we invert for the 1D shear-wave velocity structure at the InSight landing site. Based on our inversion results, we propose a strong site effect at the InSight site to be due to the presence of a shallow high-velocity layer (SHVL) over low velocity units. The SHVL is likely placed below a layer of coarse blocky ejecta and can be associated with Early Amazonian basaltic lava flows. The units below the SHVL have lower velocities, possibly related to a Late Hesperian or Early Amazonian epoch with a different magmatic regime and/or a greater impact rate and more extensive weathering. An extremely weak buried low velocity layer (bLVL) between these lava flows explains the data around the 2.4 Hz trough, whereas a more competent bLVL would not generate this latter feature. These subsurface models are in good agreement with results from hammering experiment and compliance measurements at the InSight landing site. Finally, this site effect is revealed only by seismic events data and explains the larger horizontal than vertical ground-motion recorded for certain type of marsquakes.

Re-Evaluation des Erdbebens am 10.2.1871 bei Lorsch und dessen Nachbeben

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Das Schadenerdbeben am 10.2.1871 um etwa 05:30 Lokalzeit war bereits mehrfach Gegenstand von Einzeluntersuchungen (Landsberg 1933; Gutdeutsch, Hammerl 1999; Gutdeutsch et al. 1999). Während die maximale Intensität des Erdbebens geklärt zu sein scheint (VII EMS), sind Epizentrum und Herdtiefe noch fraglich. Homuth 2015 zufolge war z. B. die Herdtiefe deutlich größer als in früheren Studien angenommen.
Ziel dieser Untersuchung ist, alle auffindbaren Berichte zu dem Erdbeben auf Basis der EMS-98 neu zu bewerten und eine genaue Einschätzung von Intensität, Schütterradius und Herdtiefe vornehmen zu können. Des Weiteren werden auch die bislang kaum erforschten Nachbeben untersucht; laut Leydecker-Katalog von 2011 sind lediglich 9 Nachbeben bekannt. Die Untersuchung begann im Juli 2021 und wird voraussichtlich im März 2023 abgeschlossen. Bislang sind zwei Teilbereiche, Erschließung und Bewertung der Quellen, abgeschlossen; die Auswertung mit Bestimmung der Intensitäten steht noch aus.
Das Datenmaterial besteht hauptsächlich aus Berichten in zeitgenössischen Zeitungen, die weitgehend von Lehmann, Kracht 2021 sowie in der Bibliographie von SiSFrance 2020 aufgeführt werden. Insgesamt wurden 85 Zeitungen ausgewertet, die rund 345 Berichte zu dem Hauptbeben enthalten. Alle Berichte wurden zuerst im vollständigen Wortlaut in einem vorgegebenen Erfassungsformular transkribiert und anschließend nach bestimmten Kriterien bewertet. Handelt es sich um eine Einzelbeobachtung oder beziehen sich die geschilderten Wahrnehmungen auf den ganzen Ort? Stammen sie von einem Augenzeugen? Wie ist der zeitliche Abstand des Berichts zum Erdbeben? Sind die Wahrnehmungen detailliert genug für eine Intensitätsbestimmung nach EMS-98? Außerdem wurden die Zeitungen durch aufwendigen Textvergleich dahingehend bewertet, dass möglichst die früheste und beste Überlieferung für die Auswertung herangezogen wird und nicht etwa ein (ungenauer) Nachdruck eines Berichtes in einer späteren Ausgabe einer anderen Zeitung. Da in einigen Fällen Berichte dutzendfach nachgedruckt wurden (bis zu 38-mal in verschiedenen Zeitungen), wird so sichergestellt, dass unnötige Mehrfachüberlieferung nicht ausgewertet wird. Von den 345 Berichten konnten dadurch 145 als Nachdrucke identifiziert werden.
Grundsätzlich ist die Überlieferung zu dem Erdbeben gut, und das trotz des deutsch-französischen Krieges 1870/81, der in der Berichterstattung der Zeitungen Anfang 1871 einen sehr breiten Raum einnimmt. Allerdings wurden mehrfach durch Zeitungsredaktionen Berichte gekürzt, summarisch abgehandelt oder darauf verwiesen, dass noch mehr Berichte vorlägen, diese aber aufgrund des zur Verfügung stehenden Platzes in der Zeitung nicht abgedruckt werden könnten.
Die Archivrecherchen in Darmstadt, Strasbourg, Lorsch und Lauterbourg erbrachten wenige zusätzliche Quellen. Die Überlieferung von Schadenberichten für das Erdbeben am 10.2.1871 um 05:30 konnte etwas erweitert werden; eine deutliche Verbesserung ist aber nicht erreicht worden, insbesondere nicht für Lorsch, wo die größten Schäden überliefert sind. Bei den folgenden Erdbeben weichen die angegebenen Uhrzeiten teilweise stark (bis zu einer Stunde) voneinander ab, was die Zuweisung eines Berichtes zu einem bestimmten Erdbeben erheblich erschwert. Die Überlieferung wird etwa ab dem 13.2.1871 deutlich schlechter; abgesehen von zwei stärkeren Nachbeben am 12.2. und am 25.2. liegt häufig nur ein Bericht für ein Nachbeben vor. Insgesamt sind bis zum 9.3.1871 etwa 53 Nachbeben überliefert. Die Identifizierung von sogenannten „Fake" Erdbeben ist ein wesentlicher Bestandteil dieser Studie. Diese sind zum einen auf die ungenaue Überlieferung von Daten in Zeitungsberichten, zum anderen auf die ungeprüfte Übernahme in Erdbebenkatalogen zurückzuführen.

Literatur

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Simulations of ground motions emitted from the wind farm Tegelberg on the eastern Swabian Alb, SW Germany

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The eigenmodes of the wind turbine (WT) tower and blades as well as the rotation of the latter cause ground motion emissions with a predominant frequency range of 1 Hz to 10 Hz. These emissions have an impact not only on the acceptance by local residences, but also on sensitive measurement equipment within a radius of several kilometers.

In the project InterWind we study the seismic emissions of two wind farms, Tegelberg (3 WTs) and Lauterstein (16 WTs), on the eastern Swabian Alb. Part of this project is a 3-D finite-difference (FD) simulation of ground motion emissions with various models, including geologic and petrophysical properties and topography. We perform the FD simulation to investigate the influence of subsurface properties and to predict the amplitude decay over distance using the numerical power law relationship $A \approx 1/r^b$. This enables us to investigate complex seismic wave fields emitting from wind farms and thus to improve the prediction of the resulting ground motions.

This study is supported by the Federal Ministry for Economic Affairs and Energy based on a resolution of the German Bundestag (03EE2023D).

Seismic velocity estimation for amplitude decay modeling of wind turbine emissions

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Wind turbines (WT) excite seismic signals related to the eigen modes of their towers and blades as well as the interaction between the passing blade and the tower. Thus, rotating WTs are a source of permanent background noise at distinct constant frequencies mostly below 10 Hz. These signals are a major concern for the performance of regional seismic networks and, therefore, are studied extensively.

Within the interdisciplinary project Inter-Wind we investigate WT emissions (vibrations and sound) and their effect on residents of wind farms. In the framework of this project we performed line measurements at two wind farms on the Swabian Alb which consist of three and sixteen WTs, respectively. Ten to twelve seismometers were installed along the lines of up to 2.5 km (wind farm Tegelberg) and 5 km (wind farm Lauterstein) distance to the respective wind farm. The Tegelberg profile had a layout towards north and the Lauterstein profile towards the east of the WTs.

To improve the prediction of the amplitude decay of ground motion emissions from WTs, we simulate WT ground motion emissions with realistic source-receiver geometry and topography using finite difference simulations. For this purpose, we generated a geological model for the region and analyzed our recorded ground motion data to determine seismic velocity estimates for the subsurface. In this study we present results for phase velocity estimation from measured data recorded at both wind farms. The estimated seismic velocities are significantly lower for the shallow subsurface than geological and petrophysical information implies. Furthermore, the analysis shows that the main wind direction and the geographical layout of the measurement lines influence the performance of the seismic velocity estimation. These findings confirm that the emitted surface wave type of the WTs dependents on wind direction.

This study is supported by the Federal Ministry for Economic Affairs and Energy based on a resolution of the German Bundestag (03EE2023D).

Das NRW.progres - innovation-Projekt dbMISS.

Horst Rüter und dbMISS team

Das NRW.progres - innovation Projekt "dbMISS - Aufbau einer belastbaren Datenbasis zum Konflikt zwischen Windenergieanlagen und Erdbebenmessstationen unter besonderer Berücksichtigung größerer Anlagen (über 4 MW)" hat das vorrangige Ziel, eine belastbare nachhaltige und öffentlich zugängliche Datenbasis zum Konflikt zwischen Windenergieanlagen und seismologischen Stationen zu schaffen.

Notwendig sind hierzu:

- Reihenuntersuchungen der Erschütterungsleistung an aktuellen WEA-Typen, nach einem standardisierten Verfahren (50-100 Einzelmessungen).
- Detailliertere Untersuchungen an Anlagen größerer Leistung (>4 MW).
- Eine homogenisierte Auswertung vorhandener Daten zur Dämpfung von Oberflächenwellen in Abhängigkeit von der oberflächennahen Geologie in NRW. Bezug zu verfügbaren Karten.
- Validierung der Ergebnisse durch Profilmessungen, also Messungen auf Langprofilen.
- Sicherung eines öffentlichen nachhaltigen Datenzugangs.

Ziele des Projektes darüber hinaus sind:

- Fortschreibung des KIT-Prognosetools insbesondere für Anlagen mit Nennleistungen über 4 MW.
- Weiterentwicklung intelligenter Datenfilter. Einbindung in die Routinedatenerfassung.

Das Projekt hat am 01.04.2022 begonnen, so dass zunächst nur über Projektziele und noch nicht über Ergebnisse berichtet werden kann.

Modelling seismic signals from wind turbines – amplitude prediction, signal correlation, and borehole effects

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In the framework of the KWISS project we work on the characterization, prediction and modelling of seismic signals produced by wind turbines. We show how numerical modelling can account for the seismic radiation pattern of wind farms, the amplitude prediction in the far field as well as for complex effects of surface topography. We demonstrate the importance of calculating a representative radiation pattern considering possible wave field interferences from multiple wind turbines.

Furthermore, we apply correlation methods to determine the propagation speed of the signals registered at a wind farm in Uettingen along two seismic profiles. At distances larger than 1.5 km from the wind farm we derive stable results for the propagation velocity. In the vicinity of the wind turbines, there are larger deviations of the measured velocities. Application of the correlation methods to numerically modelled wave fields reveal a remarkably similar pattern and indicates that the measured values at close distances are apparent rather than true velocities, resulting from the interference of the individual wind-turbine signals.

Currently, we numerically investigate the effectivity of borehole installations with the goal to reduce the impact of seismic noise produced by wind turbines on seismological recordings. We study the requirements and conditions for noise reduction within the borehole. In perspective, this could be an effective method to decrease the protection radii around seismological stations, without compromising the quality of the seismic records.

Poster

Structure of mantle transition zone and its connection to subduction in the Caribbean

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We are mapping the topography of the mantle transition zone discontinuities near subduction zones around the Caribbean by using precursors to PP and SS that reflect off those discontinuities. Our main focus is on three major subduction regions: 1) underneath the subduction zone of the Lesser Antilles, 2) near the Mexican coast and 3) north-western edge of South America where subduction of the Nazca lithosphere takes place. Events occurring between 2000 and 2020 and $M_W \geq 5.8$ have been analysed to generate a large amount of source receiver combinations with reflection points in the area. Using array methods, we identify precursors and verify their in-plane propagation. The measured time lag between PP/SS arrivals and their corresponding precursors on robust stacks are used to measure the depth of the mantle transition zone boundaries. We find a complex behaviour of 410 and 660 km discontinuities in all three regions, with indication of a curved slab with sub-lithospheric flow around the slab beneath the eastern Caribbean. Beneath Mexico, our results agree with previously suggested broken fragments of a subducted slab. Under the north-western South America, we find an elevated 410 km discontinuity and a normal to elevated 660 km discontinuity suggesting that our 410 km reflections are inside the slab, whereas only part of our 660 km reflections can be associated with the slab location.

Large distance P_{diff} coda at high frequencies

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The observation of main phases reaching the core shadow beyond 100° is known as coming from the core of the Earth like the PKP or $PKiKP$ waves. Besides, the P_{diff} wave that diffracts along the Core-Mantle Boundary (CMB) also can propagate into the core shadow, but its amplitude decreases with increasing frequency due to diminishing efficiency of diffraction at high frequencies. More advanced studies show that PKP is not really the first wave that arrives in the shadow zone. Scattering of PKP at the CMB or the whole mantle creates the precursor to PKP arriving a few seconds before actual PKP. However, there is an even faster way for seismic energy to propagate to more than 150° distance without interacting with the core or its boundary to the mantle. Scattering of P wave in the lower- and mid-mantle allows waves to arrive more than 100 s prior to the PKP precursor. Since this energy arrives after the theoretical arrival of the P_{diff} phase, we still define it as the P_{diff} coda although its origin is not related to scattering of P_{diff}. We present global stacks of several earthquakes with huge magnitude in the frequency $1 \sim 2\ Hz$. Individually P_{diff} coda can be observed at very long distances beyond 150° in these events but deeper events allow for more obvious observations. Monte Carlo method is used to simulate the global earthquake scattering in a 1D spherically symmetric heterogeneous model which matches the observation of P_{diff} coda. An analysis about the origin of P_{diff} coda is discussed by the simulation with different scattering layers from lithosphere to CMB. We demonstrate the single scattering in the whole mantle explains the essential features of the observed P_{diff} wave trains.

A large-scale seismological experiment to study magmatic processes under the Eifel region

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The Quaternary and Tertiary intracontinental volcanic systems of the Eifel are characterised by large basalt fields with hundreds of distributed cinder cones and maars with episodic activity since about 60 Ma. The last eruptions occurred 12 and 13 thousand years ago, and recent observations of volcanic earthquakes, CO2 degassing and large-scale uplift indicate ongoing magmatic activity in the upper mantle. The state of the transcrustal magmatic system beneath the Eifel is poorly understood, which also makes it difficult to assess the volcanic hazard to date. A large-scale seismological experiment with more than 350 seismic stations (Eifel Large-N) will help to better map the transcrustal structure of the magma system under the Eifel and both fossil and active crustal magma reservoirs under volcanic centres.

Due to the large number and high density of stations, experimental and logistical challenges arise in the planning and execution of the passive experiment as well as in the handling of data and metadata. For the first time, we are using an interactive, GIS-based tablet application to collect all metadata and protocols. The data service of GEOFON (GFZ) is used to archive and evaluate the waveform data.

The high data density will allow the application and development of new and different techniques for a large community of seismologists. Planned are different methods of crustal imaging from waveform correlations, receiver function studies, ambient noise tomography on different scales, shear wave splitting, attenuation mapping, acoustic sensing, as well as source studies of earthquake and tremor signals with different methods.

For further information please visit www.gfz-potsdam.de/sektion/erdbeben-und-vulkanphysik/projekte/

Mineralogy, fabric, and deformation domains in D" across the southwestern border of the African LLSVP

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Abstract

Recent advances in seismic anisotropy studies that jointly use reflections and shear wave splitting have proven to place tight constraints on the plausible anisotropic and deformation scenarios in the D" region. We apply this novel methodology to a large area of the D" region beneath the South Atlantic, in proximity to and within the African large low seismic velocity province (LLSVP). This area of the mantle is characterized by a transition from fast to slow seismic velocity anomalies and it is thought to be the location of deep-seated plumes responsible for hotspot volcanism. Attempting to probe mantle composition and deformation along the LLSVP borders may provide key information on mantle dynamics. By analyzing seismic phases sampling this region, we detect a D" discontinuity over a large area beneath the South Atlantic, with inferred depth ranges ~170 to ~240 km above the core mantle boundary. We find evidence for a D" reflector within the area of the LLSVP. Shear wave splitting observations suggest that anisotropy is present in this region of the mantle, in agreement with previous studies that partially sampled this region. We model the observations considering lattice- and shape-preferred orientation of materials expected in the D" region. A regional variation of mineralogy, phase transition boundaries, and deformation direction is required to explain the data. We infer two distinct domains of mineralogy and deformation: aligned post-perovskite outside the LLSVP and aligned bridgmanite within the LLSVP. The scenario depicted by this study agrees well with the current hypotheses for the composition of the LLSVP and with the prevalence of vertical deformation directions expected to occur along the LLSVPs borders.

Receiver function analysis of noise reduced OBS data recorded at the ultra-slow spreading Knipovich ridge

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Ultra-slow spreading ridges are characterized by huge volcanic complexes which are separated by up to 150 km long amagmatic segments. The mechanisms controlling the ultra-slow spreading ridges are not yet fully understood. We aim to constrain the crustal and mantle structure beneath the segment of the Knipovich ridge (Greenland Sea) by using Receiver functions calculated from teleseismic events.
Seismic data, recorded on the ocean bottom, are highly contaminated by different noise sources, which are dominating at frequencies below 1 Hz. Hence, most teleseismic signals are masked by a high noise level, especially on the horizontal components. However, a good signal to noise ratio (SNR) on both, the vertical and horizontal components is crucial for seismological analysis, especially for the Receiver function method. Applying the HPS (harmonic-percussive separation) noise reduction algorithm on OBS data allows to separate percussive or transient signals, such as the teleseismic earthquake from more harmonic signal components, such as most of the noise generated at the ocean bottom. Using this technique we can reduce OBS noises from both, vertical and horizontal components, without distortion of the broadband earthquake waveforms.
We show how much the raw data and the Receiver function results have been improved by applying the HPS-noise reduction algorithm: the noise level has been significantly decreased and more Receiver function traces could have been used for station stacking, allowing for more reliable interpretation. The SNR of P-wave arrivals on the vertical and S-wave arrivals on the horizontal (R), has been improved by a factor of about 1.5-2 and 2-6, respectively, depending on the type of noise.
Improving the SNR on OBS records reveals the superposition of water and sediment reverberations on the crustal structure information. Especially reverberations within sediment layers are strongly hindering the structure interpretation. The removal of reverberations using a dereverberation filter is crucial for the further analysis. In a first step, we construct the dereverberation filter by estimating two-way travel times and reflectivity of the waves trapped in the water column.
Here, we present P-Receiver functions calculated from the original signal and compare them with P-Receiver functions from noise-reduced waveforms. Further, we demonstrate the effects of multiples in the water column and sediment reverberations on P-Receiver function results.

Local noise sources retrieved from seismic double cross-correlations: A feasibility study in the region of Landwüst (Germany)

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The ICDP project “Drilling the Eger Rift“ focuses on the investigation of geodynamic processes in W-Bohemia (Czech Republic) and Vogtland (Germany), such as earthquake swarms and degassing of CO_2 originating from the Earth’s mantle. In order to get new insight into the dynamics of these processes, three boreholes were drilled in this region and will be used to install high-frequency 3D seismic arrays. The pilot 3D array is located 1.5 km south of Landwüst (Vogtland, Germany). In the test phase the borehole with a depth of 402 m was equipped with a vertical array of 8 geophones (now changed to 10) with a corner frequency of 10 Hz. The borehole chain is complemented by a 400 m aperture seismic surface array of 12 4.5 Hz geophones. The continuous data of the 3D seismic array with a sampling rate of up to 1000 Hz are integrated into the ICDP-Eger virtual network.

In this study, we aim to investigate whether weak continuous noise sources, such as those that can arise from the movement of fluids through narrow fractures near the surface, can be detected and localized. For this purpose, we have developed a new approach to localize such tremor sources using a seismic array in combination with a regional seismic network. It is based on a double cross-correlation between a real data cross-correlation in selected windows and cross-correlations of synthetic data for a 3D grid of point sources with variable mechanisms. The most probable source position is the grid node with the highest zero time lag amplitude of the double cross-correlations of each station pair.

We evaluate the location accuracy from synthetic deep tremor signals calculated for different source positions and source mechanisms (e.g., double couples, tensile opening cracks and compensated linear vector dipoles) in a 1D stratified Earth model. We test the sensitivity of the location approach for known and unknown source mechanism. Our synthetic tests indicate an accurate location of continuous tremor sources to depths of up to 7 km.

Poster: Evaluating the impact of source mechanism on earthquake ground motion

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The surface effects of an earthquake are typically evaluated using ground motion maps. These ground motion maps are often based on empirical ground motion prediction equations (GMPEs) which however largely neglect source physics and therefore the radiation pattern of seismic energy. We calculate shakemaps based on forward modelling of full seismic waveforms for different sources, e.g. full seismic moment tensors and finite rectangular sources. This allows for the fast creation of physics based shakemaps, which can also retrieve a time-frequency dependent ground motion.
The use of 1-D and 2-D Green's function stores allows to rapidly consider a large number of statistically significant scenarios, Earth structure models, site effects and sources.
We quantify the difference between the ground motions predictions based on the waveform simulations and from regionalized GMPEs for synthetic cases.
Real data test cases are the Mw 4.7 2011 Goch earthquake, the Mw 2.8 Halle-Leipzig earthquake, as well as several Mw >4 aftershocks of the Mw 7.2 2019 Ridegcrest earthquake.
We find that the sources radiation pattern is of significant importance for the creation of realistic and improved ground motion maps.

Title: Comparison of Greens Functions calculated from high frequency marine ambient noise recorded in the Eckernförde Bay

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The recording of ambient seismic noise is a relatively young approach, but has fastly developed over the past two decades into a wide range of applications to investigate the shallow subsurface or crustal structures. Nevertheless, at this point there are only a few studies investigating the sedimentary structure under shallow marine conditions based on ambient noise recordings. For that reason, we operated a set of six three-component Ocean Bottom Seismometers (OBS) near Boknis Eck in the Eckernförde Bay by setting up a profile of 50 m in length with a spacing of 10 m. The OBS recorded continuously over 30 days with a sampling of 1000Hz.
Spectral results demonstrate a significant dominance of very low frequencies in terms of amplitude values but indeed also contain some high frequency content up to about 60 to 80 Hz, especially on horizontal components. The dominating frequency band < 10Hz is mainly contributed to by the wind‘s influence. The spectrum‘s variation over time of high frequency ambient noise under marine conditions seems to be strongly influenced by wind speed, duration and direction of wind as well as corresponding sea state.
In order to investigate subsurface structures, cross correlations of the vertical and transverse component were calculated between all available combinations of stations. Temporal variations of the cross correlation functions (CCF) are clearly observed and can be related to direction of wind and sea state. The stacked, frequency dependent CCFs were investigated regarding dispersion properties, influence of higher modes, predominant directions of noise sources and group travel times. Moreover, forward modeling allows for a direct comparison of our results with synthetic 1D models. Thus an underground model of a thin ≈ 1m thick layer made up mainly of fluvial sands with a shear wave velocity of $v_{s,sand} \approx 80$ m/s covering glacial till at $v_{s,till} \approx 350$ m/s is proposed which fits our data the best.

AG Seismologie

Uncertainty Quantification in Radial Anisotropy Models Based on transdimensional Bayesian Inversion of Love and Rayleigh Wave Dispersion and Receiver Function: Case Study Sri Lanka

KuanYu Ke, Frederik Tilmann, Trond Ryberg, Jennifer Dreiling

Uncertainty in seismic imaging may arise from measurements errors and data noise, through nonlinearity of the underlying physical relations that connect the physics to the data, to the final interpretation based on estimated parameters and models. The hierarchical transdimensional Bayesian approach provides uncertainty estimates taking fully into account the nonlinearity of the forward problem. Under the Bayesian framework, the mean and the variance of the ensemble containing a large set of models are interpreted as the reference solution and a measure of the model error respectively.

In our study, we applied a two-step radial anisotropy (RA) inversion of surface wave dispersion and receiver function based on Bayesian Monte Carlo search with coupled uncertainty propagation to a temporary broadband array covering all of Sri Lanka. First, we constructed Rayleigh and Love wave phase velocity and errors maps at periods ranging from 0s to 20s. To remove outliers, data uncertainty distribution was expressed as a mixture of a Gaussian and a uniform distribution. This was followed by a joint inversion method to invert the local dispersion curves and receiver functions at each station for the shear wave velocity and RA of the crust. Model errors were propagated from the first step to the joint inversion as relative uncertainties. The method effectively quantifies the uncertainty of the final crustal shear wave velocity and RA model and shows robust results. First, we constructed Rayleigh and Love wave phase velocity and errors maps at periods ranging from 0s to 20 s. To remove outliers, data uncertainty distribution was expressed as a mixture of a Gaussian and uniform distribution. Next, we inverted local dispersion curves and receiver functions jointly to obtain 1D shear velocity and RA models.

The method effectively quantifies the uncertainty of the final crustal shear wave velocity and RA model and shows robust results. The negative RA (Vsv > Vsh) anomalous with low uncertainty found in the mid-lower crust of Central Sri Lanka may show evidence that the charnockite inclusion is associated with the shear zones confined to the cores of some doubly-plunging synforms. In the eastern Highland Complex, the positive radial anisotropy (Vsh > Vsv) anomalous with low uncertainty may reveal the evidence for sub-horizontal shear zones along the thrust boundary.

The eruption of the Hunga Tonga-Hunga Ha'apai volcano on 15 January 2022 as observed at seismic stations in Germany

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On 15 January 2022 at 04:15 UTC, an enormous explosive eruption of the Hunga Tonga-Hunga Haʻapai submarine volcano (short: Hunga) occurred in the Tonga-Kermadec volcanic area in the southern Pacific Ocean. It was one of the strongest volcanic eruption within the last 140 years, larger than the 1991 eruption of Mount Pinatubo and similar to the 1883 eruption of Krakatoa in terms of pressure wave amplitudes recorded around the globe. The eruption column reached a height of more than 50 kilometres causing heavy atmospheric turbulences. A strong Lamb and a tsunami wave were generated. Besides these phenomena also seismic waves could be observed on seismic stations all over the world.

Consequently, seismic body and surface waves of the Hunga main explosion could be clearly recorded at seismic stations in Germany. After about 19 minutes, the PKP phase was the first arriving body wave reaching the broadband stations of the German Regional Seismic Network and the Gräfenberg Array. Using the short-period WWSSN-SP filter, routinely used for teleseismics, it was possible to determine the onset times of relatively weak PKPbc phases at several stations. The onset times as well as slowness and azimuth determined by array methods allowed an unambiguous assignment to the Hunga event. Subsequent localization using the plane wave method resulted in an epicenter deviating approximately 1 to 1.5 degrees from the volcano.

In the short-period range (WWSSN-SP filter) PKP phases are rather faintly visible. However, PKP shows up very clearly in the long-period range (SRO-LP filter) with strong amplitudes. Despite their long-period character, the onset times determined in the long-period seismograms were accurate enough to provide a localization similar to that obtained in the short-period range. Furthermore, at least one additional event can be detected on the long-period seismograms about 4 minutes after the main event.

To assign a seismic magnitude to the Hunga event, we analyzed the surface wave trains. The Ms magnitudes vary between 5.8 and 6.3 within the individual stations of the GRSN, with a mean value of 6.0.

The Tonga-Kermadec subduction zone is characterized by strong earthquake activity. This allows us to compare the seismic recordings of the Hunga event with those of earthquakes from the same area with shallow focal depths and comparable magnitudes between 5.8 and 6.3. It turns out that PKP phases of the Hunga eruption have significantly smaller amplitudes in the short-period range than for the compared earthquakes but similarly strong in the long-period range. We conclude that a long-period excitation is characteristic for the seismically relevant focal process of the Hunga event.

On the importance of using directional information in searching for lower mantle reflectors

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In this study we search for underside reflections off seismic discontinuities arriving as precursors to the main SS arrival, to investigate seismic structures in the Earth's mantle. Precursory signals are a powerful tool to image mantle discontinuities both at global and regional scales. Moreover, the topography of the discontinuities is sensitive to the thermal and compositional structure of the Earth. Thus, detailed information on mantle discontinuities are important for our understanding the mineralogy and dynamics of the mantle.
The depth of mantle discontinuities is usually estimated by using the measured differential traveltime between the main SS arrival and its precursor. However, such approach ignores potential travel path deviations that might occur, influencing the traveltime of precursory signals and thus our estimation of depth and location of reflectors. Here, we use a different approach that takes into account directivity information as well as traveltime measurements to infer depth and location of mantle reflectors. We analyze events occurred beneath Indonesia and recorded at the broadband stations in Germany and in Morocco. By applying seismic array techniques, we measure slowness, backazimuth and traveltime of the precursory signals and then, we use such information to locate the source region of reflection. We find small deviations in slowness and backazimuth for the precursory arrivals with respect to the predicted values. By backtracing the observed precursory signals to their reflection point, we find that the estimated location of the bounce points differs considerably with respect to the predicted location. Moreover, the depths of the bounce points estimated by taking into account the measured directional parameters (slowness and backazimuth) differ with respect to the depths estimated by using traveltime only. Our results show that travel path deviations affect our estimation of depth and location of reflectors and may contribute to a misleading interpretation of mantle discontinuities. By taking into account directivity information as well as traveltime measurements it is possible to better constrain the geographical position and depth of mantle reflectors.

Crustal structure beneath northern Myanmar: preliminary results from ambient noise tomography

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Adjoining the Eastern Himalayan Syntaxis, linking to the Indian slab indentation northward and Andaman slab subduction eastward, Myanmar is one of the most complicated and active tectonic regions in the world, and exposed to a high seismic hazard. The Burmese arc consists of the Indo-Burman Ranges (IBR), an accretionary wedge in the west and the Central Myanmar Basin in the east. It is bounded in the east by the seismically active Sagaing Fault to the Shan Plateau which is part of the Asian plate. Intermediate-depth seismicity below Myanmar occurs at depths up to ~150 km, generally understood to be related to the subducting Burma slab. An important open question concerns the transition from oceanic subduction to continental subduction/collision along the Burmese arc. The transition is also thought to affect the upper plate crust. In this study, we collected ambient noise data set based on 80 seismic stations in Myanmar and its surrounding areas in order to constrain the variation of crustal structure. The stations include 30 broadband stations from a temporary network (code 6C 2019-2021) deployed by the German Research Centre for Geosciences (GFZ) and the Department of Meteorology and Hydrology of Myanmar (DMH) across the eastern IBR and Central Myanmar Basin. Furthermore, 32 permanent stations operated by the China National Seismic Network cover the east of our study area. We also gathered data of 18 stations from different seismic networks in China, Myanmar, India to increase the station coverage and density.We calculated the cross-correlations daily for all available station pairs using the NoisePy code and stacked them over the entire operating period. We measured Rayleigh wave group and phase velocity dispersion from stacked cross-correlations by using the frequency-time analysis (FTAN) and inverted 2-D group and phase velocity maps. As a next step, we will construct a 3-D Vs model of the crustal and upper mantle structure beneath Myanmar, which will be expected to yield new insights on the variation of crustal structure.

Tectonic seismic sequences in southwestern NRW

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Abstract

In 2021, three seismic sequences were detected in southwestern North Rhein-Westphalia (NRW), in the surroundings of Rott and Eschweiler. We analysed the Bensberg (BNS) earthquake catalog between January 2000 and May 2022 to investigate if similar events have occurred in the past and can be assigned to the same clusters. We used the GrowClust (Trugman and Shearer, 2017) and SeisAn (Havskov & Ottemöller, 1999) software to cluster and relocate earthquakes based on P- and S-wave waveform cross-correlations. The cross-correlation coefficients (ccc) for P and S waves were computed using a bandpass filter between 0.8 and 20 Hz. For our relocations, just event pairs with a minimum of 4 phases and ccc > 0.8 are considered. From the initial 772 events, 350 are relocated with an RMS differential time residual of 0.0850 s and 0.0855 s for P- and S-phases, respectively. The majority of the relocated events correspond to the 2021 seismic sequences, but events related to these clusters were also identified in previous years. Focal mechanisms were obtained for the largest events, preferably via Moment Tensor (MT) inversion using the Grond and Fomosto packages from the Pyrocko software (Heimann et al., 2017), but also using first-motion polarities. The inversion process is complex as we deal with mainly low-magnitude events (Ml < 2.7) with small amplitude signals recorded at a few stations. Because of this, the MT inversion is performed by modelling the waveforms of P and S waves in the frequency range 0.5 - 2 Hz and assuming a double-couple point source. The resulting focal mechanisms obtained from first-motion polarities suggest extensional faulting on a NE-SW oriented fault for the events of the Rott sequence, which is in good agreement with the moment tensor obtained for one of the largest events (Ml 2.7). Besides, a dual behaviour is observed for the Eschweiler events, where the shallow events, belonging to one of the sequences, present extensional faulting, whereas the deeper events, corresponding to the other sequence, are related to a strike-slip mechanism.

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Microseismic Kandel Elztal Experiment (MiKaEl-Ex)

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Earthquakes are relatively rare in Southwest Germany, but damaging earthquakes occur about every 20 years. In December 2004, such an earthquake hit Waldkirch and its surroundings in the southern Black Forest with the magnitude *ML* 5.4. This resulted in an offset of about 13 cm at a depth of about 9 km under the Kandel massif along a geological fault.

To measure probable current microearthquakes, which are activated in the natural tectonic stress field in the region, the Microseismic Kandel Elztal Experiment (MiKaEl-Ex) is conducted. For this purpose, 8 seismic recording stations seismometers have been installed in seismologically quiet locations which continuously record ground motion velocity since September 2021. As seismometers we use one 120-s broad band STS-2, four 1-s short period Lennartz 3D and three 4.5-s short period Geophones.

We present the first results of the project. These include noise evaluations of the sites and pre-detections of events using the Adaptive 6-Dimensional Floating-search Multi-station Seismic-event Detector (A6-DFMSD) adapted to the detection of tectonic events. The detected events are localized using VELEST to obtain the probable seismically active extensions of the faults in the region beneath the MiKaEl-Ex network (5D) with a diameter of 15 km. In the next step we will use Artificial Intelligence (AI) methods for a finer detection,

MiKaEl-Ex is a joint project of the Karlsruhe Institute of Technology (Geophysical Institute), the Rheinisch-Westfälische Technische Hochschule Aachen and the state earthquake service Baden-Wuerttemberg in Freiburg. The field work is supported by the local communities and private persons and funded by the Ministry for Science, Research and the Arts Baden-Württemberg.

Seismic Anisotropy Patterns from Splitting Intensity in the Alps and Apennines Region and a Synthetic Subduction Model

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Computational advances over the years made it possible to identify remnant and active slabs up to great depths. But active and past subduction systems, with their complex anisotropic structures influence the interpretation and understanding of current tectonics and velocity structures. Splitting intensity could be a tool to investigate depth dependent anisotropy. With a synthetic model we were able to reproduce apparent splitting parameters, identify an indicator for dipping anisotropy, and produce SWS tomographic images. In the Alps and Apennines region 785 stations were used to calculate splitting intensities in an automated process. Compared to SKS measurements, more stable fast polarization directions were recovered with a pattern paralleling the strike of the mountain belts, with a clockwise rotation in the Alps. Splitting intensity measurements support a possible mantle material flowing through a tear in the Central Apennines. While strong anisotropy has been recovered over the bulge of the Alps and Apennines chain, weaker anisotropy has been found beneath the Po plain, the eastern sector of the Apennines, in the western sector of Sicily and the external European domain. However, the complexity of layered anisotropy, the upper mantle flow through possible slab detachments and the subduction related anisotropy with a dipping axis of symmetry are difficult to recover. Insights into the depth dependent horizontal anisotropy can be recovered including the splitting intensities information into a tomographic inversion. The anisotropic tomography models obtained so far allowed us to recover the most prominent splitting patterns and see some changes with depth, especially for the strength of anisotropy.

Lutz Sonnabend; Sächsisches Landesamt für Umwelt Landwirtschaft und Geologie

Momententensorinversion für schwache Lokalbeben im Herdgebiet Kraslice/Rotava (CZ)

Das Herdgebiet Kraslice/Rotava (CZ) nahe der deutsch/tschechischen Grenze steht bislang wenig im Fokus detaillierter seismologischer Untersuchungen. Seit 2009 wurden in dem Gebiet ca. 130 Erdbeben mit einer Magnitude von ML -0.8 bis ML 1.9 registriert. Die Beben treten in kleinen Schwärmen oder Serien im Abstand von wenigen Monaten bis zu mehreren Jahren auf.

Die Momententensorinversion ist schon lange ein etabliertes Verfahren in der globalen Seismologie. Es gibt zahlreiche Verfahren, um schnell und Zuverlässig Lösungen zu erzeugen. Diese Verfahren stoßen allerdings für kleine Magnituden an ihre Grenzen. Heimann et all. (2018) haben ein Verfahren entwickelt, um auf Grundlage von statistischen Methoden eine robuste Full-Wave-Form-Inversion zur Lösung von MT-Problemen anzuwenden. Die entsprechende Software (Grond) wurde mit Erfolg schon für Lokalbeben in Westsachsen in Nordwestböhmen entlang der Leipzig-Regensburg-Störungszone ausgiebig getestet (Sonnabend 2022).

An die positiven Erfahrungen dieser Arbeit wird hier angeknüpft. Es wurden Berechnungen zur Bestimmung von Momententensorlösungen durchgeführt, um die tektonischen Ursachen für die Bebentätigkeit in der Region zu beleuchten. Dabei wurde die Minimalmagnitude für welche das Verfahren erfolgreich angewendet wurde von 1,4Mw auf 1.0Mw weiter reduziert.

Im Ergebnis fügt sich das Herdgebiet schlüssig in die tektonische Gesamtsituation in Nordwestböhmen und dem sächsischen Vogtland ein. Aus der Routineauswertung vermutete Störungslinien konnten angepasst bzw. verlängert werden.

Lutz Sonnabend (2022): Neotektonik und Seismizität in Westsachen und Nordwestböhmen, Dissertation, Uni Leipzig, (Veröffentlichung in Umsetzung)

Heimann, Sebastian; Isken, Marius; Kühn, Daniela; Sudhaus, Henriette; Steinberg, Andreas; Daout, Simon; Cesca, Simone; Vasyura-Bathke, Hannes; Dahm, Torsten (2018): Grond - A probabilistic earthquake source inversion framework. V. 1.0. GFZ Data Services. https://doi.org/10.5880/GFZ.2.1.2018.003

NonDC-BoVo - Non-double-couple moment tensor components and their relation to fluid flow in the West-Bohemia/Vogtland region

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We introduce the DFG-Project NonDC-BoVo embedded within the ICDP EGER Project. The project aims to more reliably resolve seismic moment tensors, especially their non-double-couple components, in the West-Bohemia/Vogtland region. The area is known for its recurring earthquake swarms, the latest three of which took place in 2011, 2018, and 2020, with several tens of events reaching magnitudes above 2, some even exceeding magnitude 4.

Previous studies found that non-double-couple components (isotropic, CLVD) contribute significantly to the moment tensor of these events. The DC components yielded focal mechanisms which align well with the regional fault system. The non-DC components were interpreted as tensile faulting associated with the migration of deep magmatic fluids through the crust. However, the results were restricted to the largest quakes and the analysis of more events is needed to allow an interpretation in terms of the geodynamical processes in the area.

In this project, we want to improve the accuracy and precision of the moment tensor components in order to better separate the contributions of fault systems and fluid dynamic processes in the area to the source mechanism of the earthquakes. Specifically, we want to 1) include rotational ground motion recordings in the inversion for the moment tensor and 2) explore the potential of asymmetrical moment tensors.

In synthetic test cases, the joint inversion of translational and rotational data improved the resolution of the MT-components, especially for the isotropic ones. In this project, for the first time we will apply this technique to field data. For this purpose, two BlueSeis-3A instruments were deployed in June 2022 in Landwüst (Saxony) and Skalna (Czech republic) collocated with translational seismometers.

An asymmetric moment tensor that includes net torque of the seismic source can be derived from micropolar elastic theory instead of the classic linear elastic theory. Such a source includes internal rotations and could provide a more detailed model of the processes on the fault during the rupture.

Local seismic events recorded by Distributed Acoustic Sensing (DAS) at BFO

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High spatial and temporal resolution of distributed acoustic sensing (DAS) measurements makes them very attractive in different applications in seismology, such as seismic noise analysis and seismic event detection. The quantity measured by DAS is strain or strain rate of an optic fiber cable, which is related to the spatial gradient of displacement and velocity that is usually measured by single point seismometers. The amplitude (and signal to noise ratio, SNR) and frequency resolutions of DAS recordings depend on spatial and temporal acquisition parameters, such as i.e. gauge-length (GL) and derivative time (DT), the latter being of importance only if the device records the strain rate. The coupling of the DAS cable to the ground and the type of cable are also play an important role in the quality of recorded data.

In this study, we show examples of local earthquakes recorded by DAS at the German Black Forest Observatory (BFO), using different cable types and coupling of the cables to the ground. We studied the spectral characteristics of the strain converted from DAS raw data, to analyze the sensitivity of DAS measurements to the GL. The power spectral densities and amplitude of DAS strain data are compared with the strain meter recordings at BFO site as a benchmark, which is recorded using the strain-meter arrays measuring horizontal strain in three different directions independently from the DAS. We concluded about the lower limit of the DAS signal and noise level that is achievable with employing different acquisition parameters.