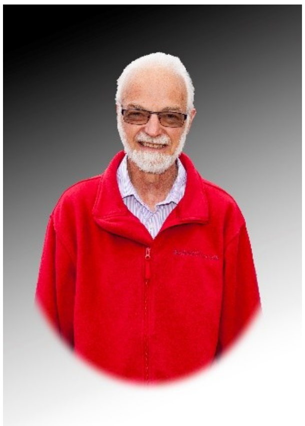
The 55th Nordic Seminar in Seismology

Abstracts


Crispy fieldwork at temporary station SJV

State Seismologist Søren Gregersen – in memoriam

P.H. Voss



Søren Gregersen

(Photo Credit: Peter Brandi)

On 28 September 2023, Søren Gregersen Dr. Scient. State Seismologist Emeritus at the Geological Survey of Denmark and Greenland, passed away in Hørsholm, Denmark, at the age of 81.

At University of Copenhagen, Søren studied geophysics and specialized in seismology, earning the master of science degree in 1968. In 1970 Søren went to the Lamont-Doherty Geological Observatory at Columbia University in New York, U.S.A., where he graduated with a Ph.D. in seismology in 1974. His thesis was on the amplitudes of horizontally refracted Love waves.

As a researcher, he returned to the Danish Geodetic Institute and continued his work in seismology focusing on earthquakes in Denmark and Greenland, Lg wave propagation and Lg wave tomography.

Søren's studies on Lg waves constituted a major part of his Dr. scient thesis which he successfully defended at University of Copenhagen on 6 December 1985.

In 2009 Søren retired after a 40-year professional career at the seismic service in Copenhagen, it was a career where he had a strong focus on seismological research and international cooperation, which resulted in multiple scientific papers, reports and presentations, supervision of students and public outreach. For 16 years Søren was part of the IUGG leadership, and he took part in and was the principal investigator of multiple international research projects. After Søren’s retirement he continued as emeritus where his research was focused on earthquakes and post-glacial uplift in Scandinavia.

Søren was very engaged in the Nordic seismological community taking part in the Nordic Seminars as often as possible and driving and promoting Nordic cooperation. As a leader of the seismic service in Copenhagen it was mainly in the Nordic community that Søren searched for inspiration, gained advises and exchange ideas on how to improve the ongoing development on the seismic service and the earthquake monitoring in Denmark and Greenland.

The Nordic cooperation was a key component during Søren's leadership of the Teleseismic Tomography experiment across the Tornquist Zone, in short, the TOR project, one of the first large multi-national deployments of broad band and short period digital mobile seismic stations, in Germany, Denmark and Sweden. Providing unique data for students and researcher that have lead several studies of the large scale geological structures of the region.

We have lost a valued colleague and a good friend.

Recent development of the seismological network in Denmark and Greenland

Peter H. Voss, Emil Fønss Jensen, Trine Dahl-Jensen, Tine B. Larsen,
Nicolai Rinds & Aurélien Mordret

Geological Survey of Denmark and Greenland – GEUS

This presentation will give an overview of the recent main development of the seismological network in Denmark and Greenland undertaken by GEUS. The seismic stations operated by GEUS in Danmark and Greenland have undergone an update on the data communication system, from a system that has reached end of life to a newer more flexible system with integrated connectivity and multiple interfaces. Four stations in Greenland have been or are in the process of being upgraded with new digitizers. Three stations have been reopened and two new stations have been installed in Greenland. In Denmark the seismic monitoring at a geothermal site has ended, upcoming monitoring at potential CCS sites is expected.

Distributed Acoustic Sensing (DAS) is being developed for integration with the seismic monitoring. GEUS is now operating two DAS interrogators, where one is currently being deployed on a fiber south of Bornholm and one is used in data collection parallel to seismic nodes and vibro-seismics near a gas storage facility east of Copenhagen. DAS data from earthquakes and mine blasts have been recorded and are used in the ongoing data integration campaign.

Recent seismic network developments in N Germany and derivation of a local velocity model from explosion monitoring

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Northern Germany is a weak seismicity region with low level of exposure to seismic hazard. At the same time, challenging observational conditions in the North German Basin are a limiting factor for seismic monitoring. Over the last decade, and in a multi-institutional collaboration, we have been able to increase the number of permanent broadband stations in the North German Federal States of Schleswig-Holstein and Mecklenburg-Western Pomerania from previously four in the year 2013 to currently seventeen. All data of the network are freely available through the EIDA node at the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover. Additionally, seventeen broadband stations are deployed in local networks/arrays across northern Germany.

Marine explosions constitute a significant portion of observed seismic events in northern Germany. They mostly relate to either military exercises or destruction of unexploded ordnance (UXO) from World War II. Monitoring of offshore explosive events is relevant for various reasons: known„„ground truth“ events can be used to derive a local velocity model that can improve seismic event locations on- and offshore, irrespective of the source. In addition, unexpected seismic events, such as the destruction of the Nord Stream pipelines or a suspected UXO detonation in summer 2023 in the bay of Lübeck, require precise localisation to support authorities in quick response. Currently used velocity models do not provide sufficiently precise epicenter locations that allow to locate the source area on the seafloor in a short amount of time.

We use a series of controlled explosions with known locations and charge sizes in the bay of Kiel to derive a best-fit velocity model based on observed waveform arrivals. In addition to seismic stations of the permanent monitoring network, we temporarily deployed additional stations closer to the source area. P-wave arrival times are fit against a range of gradient-over-halfspace velocity models using a gridsearch scheme. Results suggest that a consistent velocity model for this specific source location and station network geometry can be derived. We compare event locations of other events along the German Baltic Sea coast using standard and the newly derived velocity model and discuss the transferability of this local model to a regional scale.

The German Seismological Networks Available at the EIDA Node BGR

Klaus Stammler

Federal Institute for Geosciences and Natural Resources (BGR)

The EIDA[1] node BGR in Hanover[2] operates the German backbone network, the German Regional Seismic Network (GRSN)[3]. This network is complemented by the networks of states and universities in Germany. Almost all data are now collected at the BGR data center, the waveforms and metadata are accessible via EIDA/FDSN web services[4]. Several measures are applied to ensure a high data quality. Standard quality algorithms are applied in the frame of EIDA[5] complemented by additional procedures implemented at the data center of the BGR. The latter include noise investigations, wind dependent spectra and statistically analyzed waveform correlation data[6].

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

Balancing legacy, standards, and usability

Matt Gardine

University of Helsinki

With small budgets, limited personnel, and constantly evolving technology, most seismic monitoring groups face numerous difficulties in growing their scientific capacities while managing technical debt. This talk will look at the current seismic monitoring operation in Finland from a software perspective and discuss future plans, challenges, and opportunities for collaboration with the greater community.

Status and developments of the Swedish National Seismic Network

Michael Roth

Uppsala University

The Swedish National Seismic Network currently consists of 80 stations (67 permanent and 13 temporary installations). In spite of the aging station equipment - many digitizers and instruments older than 15-20 years - we could achieve a very high data availability (98% for the permanent and 90% for the temporary network) for last year 2023. In total we had 34 at-site maintenance trips at 24 stations over the year.
We increased direct waveform data exchange with our Nordic partners and expanded the virtual seismic network with 9 station of the Sodankylä Geophysical Observatory. The virtual larger Fennoscandian network comprises now approximately 200 seismic stations that are processed in realtime with the Seiscomp and Earthworm processing systems at SNSN. Seismic events independently detected and located by both processing systems are subsequently classified, and basic event parameters are made available on two webpages - a public page for Swedish media and private persons with the last week's events, and a web page for the Nordic seismological colleagues which contains events of the last 2 months.
Events classified as earthquakes with magnitude > 2 are reported automatically with complete parameters (phase picks, phase types, amplitude readings, etc.) to EMSC.
SNSN provides waveform overview plots for all stations containing automatic event solutions which prove useful for SNSN analysts and for rapid responses to media. Waveform plots and monthly power spectral density plots for all data channels are provided on public, but unlinked, web pages ready to be used by seismological colleagues to their discretion.

Hagfors array update

Presenter: Henrik Olsson[1]

Co-authors: Jon Grumer[1], Monika Ivandic[1], Anders Ringbom[1]

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The Swedish Defence Research Agency (FOI), through its predecessor organizations, has been conducting seismological measurements in Värmland since the 1960s. The Hagfors array, established in 2001, serves as an auxiliary seismic station within the International Monitoring System (IMS) network, hosted by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). In 2021, the station underwent significant upgrades, including the installation of new seismometers and data acquisition hardware. Around that time, it also became the site for co-locating an automatic radioxenon system, the SAUNA cube. Additionally, in 2024, FOI began installing a small infrasound array consisting of four elements. In this talk, we will present the status of the Hagfors station and recent efforts to strengthen the waveform analysis capabilities at FOI

Establishing the Forsmark seismic network: challenges and lessons learnt

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The Swedish Nuclear Fuel and Waste management company (SKB), in collaboration with the Swedish National Seismic Network (SNSN), have established a microseismic network in Forsmark to monitor the Swedish site for permanent underground storage of nuclear fuel and waste.

The purpose of the Forsmark seismic network (FSN) is to seismically characterize the host rock and repository volume, as well as its seismic evolution prior to, during, and after the underground construction of the nuclear waste repositories.

Previous studies indicate a high level of seismic background signals associated with the operations at the nearby Forsmark nuclear powerplant. The high noise levels together with relatively high intrinsic attenuation and low natural seismic activity required the use of high-sensitivity sensors and deployment at depth. Additional challenges include damage to equipment due to corrosion and lighting strikes.

The current operational network comprises 9 stations distributed over an area of about 3 x 3 km. The sensors used are high sensitivity 3C 14 Hz borehole geophones deployed at varying depth in fully or partially grouted boreholes. Two stations are located on little islets just offshore. The network is maintained by SKB. The real-time automatic data analysis and subsequent manual analysis are performed by the SNSN team at Uppsala University and reported back to SKB.

The current network layout represents the first stage of seismic monitoring in Forsmark with the primary objective to establish a baseline dataset of natural seismicity with target magnitude down to -1 prior to the start of excavation work in the area. The monitored area includes part of the so-called Forsmark lens, a geological, lens-shaped unit of intact rock enclosed by high strain belts. Part of the current network covers the already operational repository for short-lived nuclear waste. Future plans for FSN are to extend and densify the network layout with additional sensor locations in order to increase resolution and detection capability in areas of interest as construction of additional repositories progresses.

Monitoring and processing of seismic activity in the Forsmark Seismic Network

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The Swedish National Seismic Network (SNSN), in collaboration with the Swedish Nuclear Fuel and Waste Management Co. (SKB), conducts data analysis and scientific development for the local seismic network (FSN) at the Forsmark nuclear waste repository site. Since autumn 2023, the FSN has been operational with nine recording stations situated at depths ranging from 2 to 200 meters in different boreholes across the site. Two of these stations are equipped with multiple instruments at varying depths. The stations utilize high-sensitivity 14 Hz borehole geophones provided by The Institute of Mine Seismology (IMS) and Güralp Affinity digitizers. With the exception of one, all instruments are three-component sensors. All data are transmitted to a server at SKB and, via Seedlink, to SNSN in Uppsala.

A simple homogeneous velocity model for the FSN region was developed based on prior studies and the initial arrivals of 25 calibration shots conducted over two days in October 2023. These results estimate a P-wave velocity of 5700 m/s, with an S-wave velocity of 3300 m/s derived from a Vp/Vs ratio of 1.73. The calibration shots were also used in a polarization analysis to determine the orientation of the sensors in the boreholes.

Noise levels at FSN stations were analysed through power spectral density plots during periods free from seismic events or construction activity, while sensor coupling was evaluated during seismic energy events.

SeisComP, a software package designed for real-time earthquake and seismic event monitoring, is employed for detection of seismic phases and processing of the data. While SeisComP's default settings are designed for global seismicity, modifications are necessary for the highly localized seismicity studies conducted for the FSN. Offline testing of the SeisComP modules using the October 2023 calibration shot data has been conducted to optimize settings. Preliminary results demonstrate functional system performance and confirm the applicability of the homogeneous velocity model. Further refinement of processing parameters is ongoing.

Hidden Attraction – Uncovering (Geo-)Magnetic effects on Seismometers

Steffen Uhlman

IGM Geophysik (Nanometrics)

By looking at the May 2024 solar storm events, this talk explores the impact of geomagnetic and artificial magnetic disturbances on seismometer readings, emphasizing the use of proper shielding for critical (especially high-latitude) installations.

Performance of Borehole Broadband Seismometers (Update)

Steffen Uhlman

IGM Geophysik (Nanometrics)

The question whether to install seismic sensors in boreholes has become prominent in the last years. Hence, the short talk shows further data for discussion on performance of posthole and borehole stations by comparing actual events from co-located borehole and surface stations.

Challenges of Rotational Ground Motion Measurements in the Local Distance Range

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Since almost two decades, there is a fast and steady progress in understanding the rotational part of the seismic wavefield and exploring possible applications. These achievements are based on studies using simulated data, array-derived measurements, and direct measurements of large (M > 5), teleseismic earthquakes by ringlasers. Since only a couple of years, direct measurements of smaller (M < 3) earthquakes in the local distance range are also feasible. This was made possible due to new instrumentation developments such as portable rotation sensors.

From experience with translational measurements, seismology has developed a relatively simple description of the seismic wavefield, as long as the observation is recorded in the source far-field, and site-effects at the point of observation can be neglected by choosing an appropriate frequency range for the analysis.

Within the NonDC-BoVo project two portable rotational sensors have been installed in the Vogtland/West-Bohemia earthquake swarm region with the goal to incorporate the rotational waveform data into the inversion for seismic moment tensors. Both sensors are located in an epicentral distance of ~10 km to the center of the swarm activity. Between 2022-06-01 and 2024-05-15, we recorded 311 events with ML≥1 and 10 events with ML ≥ 2.5.

Although we are positively surprised how well we can record rotational ground motion of earthquakes with even very small magnitudes, we encountered challenges in the details of the waveform recordings. At the sensor location in Landwüst (D) we recorded events down to ML ~ 0.5 with good signal-to-noise ratio in a frequency range of 5 to 25 Hz. At the second location in Skalna (CZ) the signal-to-noise ratio is worse and we recorded earthquakes only with ML ≥ 1.5. Relocating the sensor to Wernitzgrün (D), about 25 km to the North of Skalna, did not improve the quality of the waveform recordings. Technical issues with the sensor can be ruled out for both locations.

Here, we want to present details of the challenges with the rotational ground motion data from these small and local earthquake recordings. First analyses hint to a much stronger effect of local site conditions onto rotational than translational ground motion data. In addition, with the above-mentioned setting, we probably have to consider the complexities of the near-field part of the wavefield as well. With our contribution we aim to add another aspect to the understanding of the rotational wavefield.

Automatic waveform measurements for ISC mb and Ms

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

In this presentation I will describe the details of the procedure, the parameters setup and examine the results of the magnitude estimations for a testing dataset of over 69,000 earthquakes ($M > 4.0$) reported in the ISC Bulletin for 2016-2020. I will also present the workflow for the integration of the magnitude estimation procedure into the routine ISC Bulletin analysis for the data-year 2022, currently put in place at the ISC, and present preliminary statistical analysis of the impact of including such measurements into the ISC Bulletin.

Magnitude mb: reducing processing related variability

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It is well known that magnitude mb shows a large variation between different stations and agencies for the same event. In this study we investigate the various causes of this variation and we have found that apart from the regional variation caused by the Earth's 3D structure, a major contribution to the variation is the way the data is processed: Automatic or manual determination of amplitude and period is different for the same signal at different agencies or processing systems and/or there are errors in the amplitude measurements when correcting the signal from the simulated WWSSN-SP response. Part of the problem to objectively investigate the causes for the variation is that few agencies use the IASPEI standard for reporting the observations. To get less variability in mb, a standardized way of reading amplitude and period must be developed and used.

Advancements in Semi-Automatic Seismic Monitoring of Latvia Using Machine Learning

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Since 2008, Latvia has actively engaged in seismic monitoring through the BAVSEN virtual seismological observation network. The Latvian Environment, Geology and Meteorology Centre (LEGMC) has traditionally monitored the region, using manual phase arrival analysis for seismic event identification. However, this process is labor-intensive, as it requires detailed examination of seismic records, which can sometimes result in misclassification.

To enhance the efficiency of seismic monitoring, we have introduced several improvements to the observation system. Leveraging recent advances in machine learning we have created a semi-automatic event detection system using a combination of phase-picking, phase association and event location algorithms. First arrival detection picking is performed automatically using three adjusted neural network pickers – EQTransformer, PhaseNet and GPD models trained on the INSTANCE dataset, as implemented in the Seisbench framework. First arrivals are then processed using GaMMA phase-event association model, with primary locations thereafter calculated using Hypoinverse algorithm. Located events are imported into SeisComp system for manual review and processing. Entire system is written in Python using the ObsPy seismological data processing package.

Initial tests show a strong correlation between the automated system's results and those of human seismologists. Our tests on observations from 2010-2022 showcase that the system has identified several previously undetected events. However, there are still many cases where known events were missed by the algorithm and had to be identified using traditional automatic detection methods, such as short-term/long-term averaging or manually. A complicated issue not yet solved is related to small events only detected in two or less seismic stations, as the GaMMA algorithm cannot process the large uncertainty of such events. Despite these challenges, semi-automated seismic monitoring shows significant potential for enriching the historical earthquake database and facilitating deeper research into the upper mantle and crust of the Baltic States.

Can seismological data contribute to the monitoring of impulsive underwater noise?

Ruth Beckel

Uppsala University

As underwater noise is known to have a harmful influence on marine life, the International Council for the Exploration of the Sea (ICES) strives to provide a register of impulsive noise sources to help government agencies to regulate the use of underwater noise sources. In Sweden, reporting the use of such sources is voluntary, so that the ICES register is expected to be incomplete.
In order to investigate whether events detected by the Swedish National Seismic Network (SNSN) can contribute to the register, we correlated both SNSN's manually revised bulletin and one of SNSN's automatic bulletins with the events in the ICES register. Most offshore explosions close to the network match with SNSN events, but for other types of impulsive noise sources we found no matches, indicating that these sources are not detectable on SNSN's data under current operating conditions. Only 2% of the marine explosions in SNSN's manually revised bulletin correlate with events in the ICES register, confirming that the register is missing a significant number of events in Sweden's coastal waters. A comparison of the sound level of explosions in the ICES catalogue and the magnitude of matching SNSN events showed no clear trend between magnitudes and sound level. However, we noticed that events in the eastern part of the Baltic Sea tend to have much higher magnitudes than events of the same noise level in the western part. The reason for this difference needs more investigation, ideally in cooperation with other networks. Thus, the SNSN data can contribute significantly to monitoring marine explosions but cannot provide an estimation of the explosion's sound level yet.

On the potential of offshore sensors and array processing for improving seismic event detection and locations in the North Sea

Annie Elisabeth Jerkins, Andreas Köhler, Volker Oye

Norsar

Ensuring the safety of oil and gas operations, as well as the future storage of CO2 in the North Sea, requires the effective detection and accurate location of earthquakes. However, the precise location of small-magnitude seismic events in Norway's offshore areas remains a considerable challenge. The primary difficulty stems from the large distances between seismic stations and the events, coupled with the fact that most sensors are located onshore, resulting in significant station gaps. This research explores how offshore sensors, typically utilised for continuous monitoring in oil and gas fields, can be employed to enhance earthquake location through advanced array processing techniques. Our study focuses on sensors deployed at the Grane oil field.

From the 3,400 ocean bottom nodes deployed at Grane, we had ongoing access to data from 10 sensors and obtained specific data segments from a further 30 sensors. These 30 sensors were specifically selected to optimise traditional array processing techniques. In contrast, the 10 sensors, spaced 6 km apart, record incoherent signals, making standard array processing methods less effective. To address this challenge, we have developed a technique that uses the kurtosis characteristic function to improve signal coherence, allowing for effective frequency-wavenumber analysis. This new method has demonstrated promising results for most of the seismic events tested, enabling us to determine both apparent velocity and back azimuth. The 30 sensors, designed for conventional array processing, show significant potential in reducing the high levels of offshore noise, such as that generated by seismic surveys. This study highlights the potential of integrating offshore sensors with array processing techniques to improve the detection and location of seismic events in the North Sea and other regions.

Monitoring Arctic seismicity with ocean bottom seismographs and underwater acoustics

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Seismicity in the High Arctic is mainly related to the ultra-slowly spreading Gakkel Ridge located under the ice-covered Arctic Ocean. Due to the remote location, far from land-based seismic networks, earthquake monitoring in the region is restricted to the larger events. Ocean bottom seismographs (OBS) can supplement the permanent, land-based networks, improving the detectability of smaller earthquakes. However, OBS deployment is typically time constrained, costly, and challenging in ice-covered areas. Within the EU-funded Integrated Arctic Observation System (INTAROS; 2016-2021) and High Arctic Ocean Observation System (HiAOOS; 2022-2027) projects, we explore different approaches to seismological monitoring in the Arctic. We first present the results of a 1-year OBS monitoring campaign along the spreading ridge west of Svalbard. By combining recordings from the land-based seismic networks with data from three OBS systems, we increased the detection by a factor of three and saw a clear reduction in location uncertainties. We also demonstrate that T-phases are well recorded by the hydrophone components of the OBS systems. We then present plans to exploit underwater acoustic data to improve earthquake monitoring in the high Arctic. Hydrophones are currently being deployed on four different moorings placed under the ice cover near the Gakkel Ridge. We present explorative results based on data from previous experiments to demonstrate how underwater acoustics allows us to improve detection threshold and location accuracy in remote offshore areas.

Predicting catastrophic failures: landslides, rockbursts, glacier breakoffs, and volcanic eruptions

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Predicting catastrophic failures is a fundamental goal of many scientific disciplines such as geomechanics, seismology, volcanology, and glaciology. Over the past decades, great efforts have been devoted to develop and deploy high-precision monitoring technologies to observe various geohazard phenomena. Different empirical or physical approaches have also been proposed to forecast imminent catastrophic events, with the failure forecast method based on the power law time-to-failure model being widely adopted. However, only a limited number of catastrophic failure events have been successfully predicted so far. One major uncertainty arises from the burstiness of rupture phenomena in heterogeneous geomaterials, which is typically characterized by a series of progressively shorter quiescent phases interrupted by sudden bursts, rather than a smooth continuous progression of deformation and failure. This seemingly erratic pattern complicates the prediction as it challenges the continuous scale invariance assumed by the simple power law model. Here, we propose a generalized failure forecast method based on the log-periodic power law singularity model to more reliably predict catastrophic events. Amounting mathematically to a generalization of the power law exponent from real to complex numbers, our model captures the partial break of continuous scale invariance to discrete scale invariance that is inherent to the intermittent dynamics of damage and rupture processes. Incorporating a discrete hierarchy of time scales, our model effectively captures the burstiness of rupture phenomena, characterized by accelerated oscillatory behavior as the system approaches catastrophic failure. We conducted a comprehensive comparison between the conventional power law model and our new log-periodic power law model, demonstrating that the latter provides superior performance in forecasting catastrophic events. We have extensively tested our method on approximately 100 geohazard events (including landslides, rockbursts, glacier breakoffs, and volcanic eruptions) using various types of monitoring data, including geodetic observations, geophysical records, and geochemical measurements. The results indicate that our method is general and robust, with significant potential to mitigate extreme geohazards and enhance existing early warning systems.

The historical discrepancy of Estonia as a seismic but aseismic country

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The first notion of an Estonian earthquake, albeit questionable, dates back to the year 1670. This is the first Estonian entry in the earthquake catalogue of the Baltic governorates (approximately the area of modern Estonia and Latvia) of the Russian Empire, meticulously collected and analysed by Bruno Doss (1861–1919), the geology professor at the Riga Polytechnic Institute. He listed several events during the 19th century, which certainly were genuine earthquakes in or offshore Estonia.

A contemporary of Doss, the first Estonian seismologist, Johann Wilip (1870–1942) was active at a different front: in building and developing word-class seismic equipment, which contributed to global seismology. Seismic monitoring had been performed at the Tartu Observatory already before Wilip, from 1896 on. Rearrangement of seismic observations within the Russian Empire halted measurements in Tartu in 1912. Because no local earthquakes had ever been detected, the Pulkovo Observatory was prioritized. A seismic station re-established by Wilip was operating in Tartu in 1931–1939.

The father of Russian seismology, prince Boris Galitzin (1862–1916) was the mentor and later co-operator of Wilip. He gave a lecture series on this novel field of science in Saint Petersburg, published as a monography (Galitzin 1914). It starts with a definition of three major classes of earthquakes: 1. volcanic, 2. collapses of underground cavities, 3. tectonic.

It is unclear, if Wilip was aware of the earthquake catalogue by Doss. However, he was convinced that no earthquakes take place in Estonia. He stated that Finland was the closest area where earthquakes were possible.

The key for understanding the discrepancy can be seen in the title of the earthquake catalogue by Doss (1910): “Die historisch beglaubigten Einsturzbeben und seismisch-akustischen Phänomene der russischen Ostseeprovinzen” or “The historically verified collapse earthquakes and seismoacoustic phenomena of the Russian Baltic provinces”. Doss did not consider earthquakes in the Baltic governorates to be of tectonic origin but interpreted them exclusively as collapses in carbonate rock formations in this region covered by thick sequences of sedimentary rocks.

On the other hand, Wilip meant that no tectonic earthquakes take place in Estonia. Inability to detect local events in the Tartu seismic station during the decades of operation seemingly confirmed this notion, although the used seismographs were sensitive to detecting major teleseismic earthquakes rather than small events in the vicinity.

The idea of aseismic Estonia – with no need for seismic monitoring – prevailed all the way until October 1976, when the country was shaken awake by the magnitude-4.5 Osmussaar earthquake offshore NW Estonia.

Statistical features of earthquake data in Finland and adjacent areas: Insights from model testing

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We tested statistical features of seismicity data in Finland and adjacent areas using a parametric earthquake catalog updated to 2021. Tests were applied to the entire target region and 15 predefined seismic source zones (SSZ). Temporal homogeneity was tested against the Poisson distribution using a Monte Carlo hypothesis test with the ratio of the sample variance and mean as the test statistic. Spatial homogeneity was investigated by comparing the mean nearest-neighbor distance of events to a theoretical value of the Student's t-test and to a value computed from simulated data for the Welch's t-test. The simulated data were generated assuming the validity of the Poisson distribution and the Gutenberg–Richter (GR) magnitude–frequency equation. In addition, a slightly modified epidemic-type aftershock sequence model (ETAS) was applied to three subregions of enhanced seismicity (Bothnian Bay basin, Vyborg rapakivi granite batholith (VRGB), and the Kuusamo block in Finland) to assess overall seismicity.

Many SSZs have little seismicity data, and randomness may affect the testing. When the uncertainties in the completeness magnitude, the estimated Poisson parameters, and randomness in the Monte Carlo hypothesis test are considered, the null hypothesis of temporal homogeneity cannot be rejected in any of the predefined zones in 1992-2021. Seismicity is clustered rather than homogeneously distributed in SSZs comprising neotectonic faults and ample data. Combinations of the ETAS model parameters successfully describe the overall seismicity patterns in the three subregions of enhanced seismicity. Declustering remains critical for probabilistic seismic hazard analysis to estimate the GR b-value that is used to extend the observed magnitude range to unobserved magnitudes of engineering relevance. The protracted, shallow low-magnitude earthquake clustering characteristic of the VRGB may be connected to the high surface heat flow in the area.

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Physics of the b-value of earthquake aftershocks

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Aftershock statistics are essential for advancing our understanding of the physical mechanisms that drive earthquake processes. The spatiotemporal characteristics and magnitude distributions of aftershocks provide critical insights into the internal dynamics of the Earth's crust following a mainshock, carrying significant implications for seismic hazard assessment and mitigation. The well-established Gutenberg-Richter law has been applied to characterize the frequency-magnitude distribution of aftershock sequences, where the b-value reflects the relative frequency of small versus large events and reveals valuable information about crustal heterogeneity and regional stress conditions. Although the origin of the b-value has been extensively investigated from both geometrical and geomechanical perspectives, there is relatively limited understanding about how frictional properties and processes influence the b-value of aftershocks within a fault network after a mainshock. In this study, we present a novel dynamic three-dimensional numerical modeling approach to simulate rupture propagation along a mainshock fault, which subsequently triggers aftershocks on secondary faults that follow a power-law size scaling and are spatially distributed around the main fault. We explore various scenarios with different slip-weakening friction parameters, including critical slip distance and steady-state friction, and analyze the corresponding frequency-magnitude statistics. Our findings reveal that the cumulative frequency-magnitude distribution of aftershocks exhibits a two-branch scaling behavior. The first branch for small magnitude earthquakes, characterized by a lower b-value, is related to the faults that are partially ruptured, in contrast to the conventional explanation of catalogue incompleteness. The second branch, with a higher b-value, is associated with faults that are (nearly) fully ruptured. The extent of fault rupture is governed by both the triggering effects and the potential for spontaneous rupture, with the latter being significantly influenced by frictional properties and pre-earthquake stress state. These findings and insights have important implications both for understanding the physical origin of the b-value of earthquake aftershocks in the Earth's crust and for the interpretation of numerical models of the process.

Local dense array focal spot imaging

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We present results from numerical experiments and observations from USArray and AlpArray to discuss the effectiveness of the seismic surface wave focal spot imaging technique to resolve the elastic velocity structure. The focal spot method estimates local medium properties together with a measure of the uncertainty from the shape of the spatial autocorrelation field at short distances. Synthetic and noise correlation results demonstrate the overall accurate reconstruction of the phase velocity distribution, and extensive sensitivity tests show that the data range is the most effective tuning parameter to trade off resolution and uncertainty. We discuss how an improved control over the combined effects of the array shape, relative sensor position, anisotropic illumination, and body wave energy can lead to high-resolution images of elastic material properties. The effect of weak azimuthal anisotropy is studied using focal spots synthesized with SeisSol (https://seissol.org/). The autocorrelation field exhibits an elliptical shape that is indicative of the orientation and magnitude of the Rayleigh wave anisotropy. We discuss analytical expressions that can be used for the parameter estimation, and strategies to account for potentially interfering anisotropic illumination. Together our results demonstrate that the local imaging approach excels in dense array applications, with implications for the analysis of spatially dense data sampled by distributed acoustic sensing systems.

The crustal structure of the Varanger Peninsula, northern Norway - Preliminary results

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From 2022 to 2024, 15 broadband seismometers were deployed in a transect approximately following the Tana river from Karigasniemi in Finnish Lapland, crossing the Varanger Peninsula to the Norwegian Barents Sea coast. Additionally, several 3-component geophone arrays were deployed in the inland covering the Kaldoavin and Vätsärin areas. The purpose of the deployment are to develop a lithospheric model along the transect and investigate ancient tectonic events from the Archean and Palaeoproterozoic formation of Fennoscandia to the most recent Timanian orogeny, as well as potential Caledonian overprint. Furthermore, the data will be used to investigate intraplate seismicity in the region.

Here we will present the first section of a crustal transect based on one-year of data primarily from the stations based on the Varanger peninsula.

Estimation of the in-mine stress field using microseismic source mechanisms in the Kiruna mine

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Knowledge of the in-mine stress field could potentially aid the assessment of rock stability in deep underground mines. This study will estimate stresses using inversion of microseismic source mechanisms, comparing four different stress inversion methodologies and investigating the dependency of the results on the amount of shear slip, or double-couple (DC) motion, in the mechanisms. The stress estimates will be compared to direct in-situ stress cell measurements.

Best fit strike, dip and rake angles from microseismic moment tensors from the Kiruna mine have been used for the inversions, together with estimates of the amount of DC in the mechanisms. We have extracted seismic data within various distances of the stress cells and investigate how both distance and the amount of DC affect the resulting principal stress directions and stress ratios (R-value). Stress inversion software by Lund & Slunga (1999), Arnold & Townsend (2007), Martínez-Garzón et al. (MSATSI, 2014) and Vavrucuk (2014, STRESSINVERSE) have been tested in the study. As the stress cells provide both principal directions and absolute stress magnitudes, we are able to compare both directions and the R-value from the stress inversions.

We find that the software packages provide similar results in terms of principal stress directions, but that the R-values vary more. There are also significant differences in the uncertainty estimates provided by the different packages. The results show a predominance of reverse to strike-slip faulting in the mine, with both tensile and compressive failure mechanisms in the moment tensors. Comparing to the stress cells show mixed results which are under evaluation.

The threshold of induced microseismicity is related to plasticity
Case study: hydroshearing in fractured crystalline rock at the Bedretto Underground Laboratory (Switzerland)

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Hydroshearing, or shear stimulation, is recognized as the main method to exploit geothermal energy in hot low-permeability crystalline rocks at depth. It consists of enhancing permeability via injection-induced shear slip and dilation of preexisting fractures. Hydroshearing usually causes some induced microseismicity, sometimes of sufficient magnitude to be felt on the surface. Thus, high-pressure fluid injection to enhance fracture permeability should be made carefully to avoid inducing earthquakes above the acceptable magnitude.

The process of hydroshearing is theoretically well understood and numerical models are capable of simulating it. However, fundamental investigations at the field scale are limited. This study focuses on the modeling of a hydraulic stimulation carried out at the Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG), in Switzerland, to investigate hydro-mechanical coupled processes due to fluid injection into fractured granite. We examine three numerical models with increasing complexity (a model with calibrated time-variable permeability, a model with strain-dependent permeability, and a model incorporating viscoplasticity with strain weakening and dilatancy) to improve the simulation and capture the hydro-mechanical response of the fractured rock mass.

The first model yields a reasonable fitting to measured overpressures at the injection borehole. Yet, the pore pressure distribution and the corresponding poromechanical response of the rock are not well captured. Employing an embedded model to calculate permeability changes as a function of volumetric strain improves the temporal evolution of overpressure at the injection borehole at the early stages of stimulation, but overestimates it once the fracture undergoes shear slip. Using a viscoplastic constitutive law with strain softening and dilatancy results in an additional enhancement of fracture permeability and thus a better reproduction of the monitored overpressures. The results show that the timestamps of monitored microseismic events correlate well with the times when permeability enhancement surpasses the previously maximum amount in each injection cycle

Contemporary GIA in Iceland: preliminary results from the ISVOLC project

Peter Schmidt and the ISVOLC team

Uppsala University

Glaciers cover about 11% of Iceland. Varying climate conditions have however caused the glaciers to gain or lose mass through time with a general mass loss trend since ~1890. The associated mass changes cause Glacial Isostatic Adjustment (GIA) in Iceland. Currently the dominating surface deformation in central Iceland is due to this process, with uplift rates up to 35 mm/yr. Interpretation of geodetic data, e.g. in post-seismic studies or to estimate emplacement and volumes of intruded magma, therefore requires the removal of the GIA signal from the data. The GIA process is however not restricted to surface deformation but also associated with stress changes in the crust and mantle. In an active volcanic setting as in Iceland these stress changes will affect volcanic systems in several aspects, ranging from stability of magma chambers in the crust, likelihood of eruption vs. intrusion to magma production rates in the mantle. The stress changes further stand to modulate the stability of faults potentially leading to less frequent but larger earthquakes. Yet GIA studies in Iceland have not been updated with glacier changes occurring the last ~20 years. The first half of this period was characterized by continuous high annual mass loss, and the latter half by more mass balance variability with some years even close to zero-mass balance. The ISVOLC project aims at progressing the knowledge and understanding of the impact of climate change, through the 20'th century till present day and into the future, on Volcanic systems in Iceland. This is done by taking on a broad approach from the collection of and merging of new observations of glacier mass changes as well as geodetic data, through updated/improved GIA modelling, to the study of Individual volcanic systems in Iceland and ultimately hazard assessment and forecasting. Here we present preliminary results of the GIA modelling in the project and updated estimates of magma production rates in the mantle. In general we find that the glacier mass changes since 1890 used in previous GIA studies were over-estimated by about 34%. As a consequence, a softer mantle is required to fit geodetic data (~3 x 1018 Pa s, vs. 1019 Pa s in previous studies). However, the high mass loss since 1994 results in a preliminary estimated present day threefold increase of magma production in the mantle beneath Iceland.

A new national seismic hazard assessment for Norway

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The last publicly accessible national hazard evaluation for earthquakes in Norway was published in 2000. In the 24 years since this study was published, the quantity and quality of available data has increased significantly. New methods and tools have become available, and there has been an exponential increase in computational power, leading to more complex processing routines and calculations. This all contributes to reducing the epistemic uncertainty connected to seismic hazard assessment. Norway is located on the western edge of the stable, cratonic Fennoscandian shield. The level of seismicity is low to moderate, with events rarely exceeding magnitude 5.5. This study aims to develop a new probabilistic seismic hazard model for Norway. The study area covers continental Norway, including a 300 km perimeter, and the seismic hazard model has been harmonized with the neighbouring countries. The hazard estimates are calculated using the Open Quake Engine. Input earthquake data are mainly from the Norwegian National Seismic Network, supplemented with data from other national and international catalogues. The data is harmonized and quality assured using automated routines, with manual quality control to ensure a consistent, reliable, and representative catalogue. The analysis results in an up-to-date and improved open access evaluation of the seismic hazard in Norway. This new hazard model can support better preparedness and an improved understanding of the economic and societal risk earthquakes may pose. The methods and input data used for the analysis will be presented together with preliminary results.

Consequences of small to moderate earthquakes: Examples from Fennoscandia in 1882 and 1904

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This investigation searches for contemporary written documentation on non-structural earthquake consequences in Sweden and Finland. Augmenting information is expected to improve the success of intensity assignment and the subsequent determination of non-instrumental magnitude and epicenter. Ultimately, such examples would provide helpful validation of the intensity scale. This is demanding, however, because damage levels in the region can typically be linked to the masonry parts of houses, timber being resilient to ground shaking, and only ordinary buildings are recommended to be used for intensity assessment by the EMS-98 guidelines.

Once the contemporary newspapers have been exhaustively scanned, the search for archived documentation about the non-structural earthquake impact faces several challenges. Many documents were not written in the first place for dwellings that sustained some damage but were not insured. Documentation lost over the decades is all too familiar. Earlier work on an earthquake of 1898 showed that both direct and indirect earthquake effects occurred: Ground shaking fractured unreinforced masonry chimneys and stoves, which posed a serious fire hazard in predominantly wooden towns. Additional cases from the (Mw~4.2) earthquake on 23 June 1882 and (MS5.4) earthquake of 23 October 1904 – widely known as the Oslofjord earthquake – are explored. The purpose is twofold: to gather information on non-structural damages from newspapers and attempt a comparison to archived data when such have been uncovered.

Indirect earthquake hazards can occur at long epicentral distances, but establishing a time frame for them can be difficult. Estimates of earthquake-related costs at a few localities are attempted. A reasonable assessment of the economic impact of past earthquakes would make them more existent outside the seismological community.

Comparing European Seismic Hazard Models in Fennoscandia

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The European seismic hazard model 2020 (ESHM20) supersedes the 2013 version (ESHM13) while following the same principle of state-of-the art procedures homogeneously applied for the entire pan-European region, without country-borders issues. ESHM20 includes updated datasets (earthquake catalogues, active faults, ground shaking recordings), information (tectonic and geological) and models (seismogenic sources, ground motion). For Fennoscandia, the earthquake dataset increased by eight events, but the seismic source zones were updated in the north, there was a complete change of ground motions models and the logic tree was significantly expanded. We uncovered a mistake in the update of recurrence parameters in one source zone in ESHM20, which likely has led to an overestimate of the hazard in that zone.

There are systematic differences for Fennoscandia between the two versions, where western Norway, southwestern Sweden and Denmark see a decrease in hazard while the hazard has increased in most of Sweden and Finland. Investigating the effect at the five nuclear power plant sites in Fennoscandia, we found that the hazard, in terms of mean peak-ground-acceleration (PGA), has increased from ESHM13 to ESHM20 at the nuclear power plants (NPPs) in Olkiluoto, Forsmark, Oskarshamn and for long return periods in Loviisa. It has decreased at Ringhals and for short return periods at Loviisa. In addition, the standard deviations of the PGA distributions have increased considerably at all locations except at Ringhals, where the increase is more modest. The differences between ESHM13 and ESHM20 are likely due mostly to the complete update of ground motion models, the significantly expanded logic tree and improved methodologies and algorithms.

Assessing the significance of the differences between two hazard models is a long- standing problem in seismic hazard. We applied four different tests to the models, addressing different aspects of the model results. The test results were inconclusive in that some tests indicated robust differences while others did not. It is important to note that neither ESHM13 nor ESHM20 are intended as site-specific hazard models, they are not applicable to annual probabilities of exceedance below 2·10-4, or return periods beyond 5000 years, and do not replace national hazard models.

Assessment of impact on seismic hazard at NPPs in Sweden based on European Seismic Hazard Models ESHM13 and ESHM20

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Swedish hard rock ground response spectra are based on a regional seismic hazard study (SKI, 1992). Uniform hazard ground response spectra for various exceedance frequencies were outlined, which are applicable for a “typical hard rock site” in Sweden. Consideration of site effects leads to a reduction by 15% to account for the favorable site conditions as all plants are sited on solid rock.

In Sweden only the last two units Forsmark 3 and Oskarshamn 3 have a seismic design basis. DBE were chosen in accordance with RG 1.60 scaled to PGA of 0.15g horizontally and 0.1g vertically. For units without a seismic design basis, the experience-based method SMA (Seismic Margin Assessment) and design code analyses have been used to fulfil seismic requirements. For SMA the E-5 spectra was used as Review Level Earthquake (RLE), factored by 0.85.

ESHM13 (European Seismic Hazard Model) is a database and model for describing seismic hazard across Europe and Turkiye. The result from ESHM13 show an increased seismic risk for southwest of Sweden.

SSM (Swedish regulator) compares the results from ESHM13 to SKI Technical Report 92:3 in SSM 2018:27. The results show a significant higher seismic hazard for Ringhals, while the results for Forsmark and Oskarshamn are almost unchanged. The safety significance in this issue is further emphasized in SSM 2024:04.

ESHM20 is an update of ESHM13, which was made public in April 2022. In ESHM20 hazard has increased in much of Sweden as compared to ESHM13, but decreased in the Swedish southwest.

A project was initiated within Energiforsk (The Swedish Energy Research Centre) to better understand the difference between ESHM13 and ESHM20. The project focus on the difference between ESHM13 and ESHM20 for the five nuclear power plant locations in Sweden and Finland. The report is now available (Energiforsk, B Lund et al, 2024)

Conclusions

- Neither ESHM13 nor ESHM20 are intended for site-specific hazard assessment, they are not suitable for return periods of more than 5000 years and they do not substitute national seismic hazard models (Woessner et al., 2015; Danciu et al., 2024)
- The statement in SSM 2018:27 and SSM 2024:04 that there is a significant higher seismic hazard in Ringhals is based on a model for seismic hazard, ESHM13, with large uncertainties for low seismic areas like Sweden and long return periods.
- The conclusions from the updated model ESHM20 indicates a lower seismic hazard for Ringhals and the seismic hazard is equivalent at all Swedish sites. However, also ESHM20 has large uncertainties for Sweden, mainly due to lack of data.
- Both ESHM13 and ESHM20 only use a small subset of the available earthquake record in Fennoscandia. There is therefore potential to obtain better constraints on the hazard.

Depth of earthquakes offshore Thy in Denmark

Trine Dahl-Jensen, Peter H. Voss, Tine B. Larsen and Nicolai Rinds
GEUS

The area offshore Thy, NW Denmark, experiences many of the earthquakes we record in Denmark. The locate (too) deep in our routine monitoring. Here we analyze the depth using a local earthmodel and restricting data to stations within 500 km.

A preliminary seismic hazard map of Finland

L. Fülöp[1], P. Mäntyniemi[2], A. Korja[2] and SEISMIC RISK working group*

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In a low-seismicity country, such as Finland, earthquakes may pose some risk to critical and sensitive infrastructure such as hospitals, data centres and underground construction. Very high-consequence risk scenarios, such as in nuclear power plants, must also be reviewed against very low-probability earthquake hazards. Within these boundaries, reviewing seismic hazard estimates becomes topical as knowledge and data accumulate.

A new probabilistic seismic hazard analysis (PSHA) model is developed for Finland and adjacent areas. An updated parametric earthquake catalogue (FENCAT17) is used, and a new seismic source zoning model (SZ2024FI) is delineated. Challenges of delineating seismic source zones (SSZ) in low-seismicity regions are addressed by integrating geological and seismological data. The model uses activity parameters for the different SSZ, but a smoothed seismicity option has also been tested. The model emphasizes the importance of disruptive but non-destructive earthquakes to background hazard estimates.

At country scale, the difference between northern (i.e., more seismically active) and southern (i.e., quieter) regions is visible. To map some of the drivers of the difference in regional hazard, the results are analysed in relation to three territorial parameters (1) smaller micro SSZs (2) larger unified SSZs and (3) smoothed seismicity separately. The basic results are peak ground acceleration (PGA) hazard for 10% and 2% exceedance in 50 years. The hazard values on bedrock are generally low <0.05g, not warranting design consideration for ordinary residential, commercial, and industrial buildings.

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The Finnish node of the European Plate Observing System - EPOS-Finland (EPOS-FI) is an umbrella organization of distributed National Research Infrastructures (NRIs) in Solid Earth Sciences. EPOS-FI (https://www.helsinki.fi/en/infrastructures/fin-epos) has been established to provide state of the art research facilities to academia, modern and competent services for the society, and to facilitate Finnish actions in EPOS-ERIC (http://www.epos-eu.org/). The geoscientific NRIs are owned and operated by the EPOS-FI consortium partners: Universities of Helsinki and Oulu, Geological Survey of Finland, Finnish Meteorological Institute, Finnish Geospatial Research Institute of the National Land Survey, VTT - Technical Research Centre of Finland Ltd, and CSC – IT Center for Science Ltd. NRIs comprise the Finnish permanent seismic, geodetic and geomagnetic observatory networks, geophysical and geochemical laboratories, laboratories for national timekeeping, a mobile geoscientific instrument pool FINNSIP(https://finnsip.fi/), data and computing centers, and data portals. The instrumentation forms the basis for the Finnish reference frames for national time, space and positioning, geomagnetic field as well as seismic monitoring.

The NRIs provide Open Access, FAIR geoscientific data management for science and the society. They also provide online data to international data centers and field specific Thematic Core Services (TCS) of EPOS that focuses on collecting and disseminating observations of geological, geochemical, and geophysical processes within Earth and its near space. EPOS-FI is used by academia, government, and industry as well as millions of indirect users across wider society: satellite and flight routing, navigation systems, mobile networks, exploration, and extraction of raw material. The NRIs are providing data to several EPOS TCSs: Seismology, Anthropogenic Hazards, GNSS Data and Products, Geomagnetic Observations, Geological Information and Modelling, and Multi-Scale Laboratories.

Advantages and Issues of Applying Machine Learning Based Denoising

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We train and test a machine learning based denoising algorithm on seismological records of on earthquakes in southern and northern Germany and on selected Democratic People's Republic of Korea nuclear tests. The denoising of waveform records using machine learning has obvious advantages on the picking of phases and signal detection but the question is if the currently available techniques can be used beyond that. We investigate the impact the denoising has on the event detection. Furthermore we test the reliability of source mechanism inferences by comparing the seismic moment tensor inversion results of original and denoised data. We find that care needs to be taken using the modified waveform data but also find promising results hinting at possible further use of the technique in the future for standard analyses.