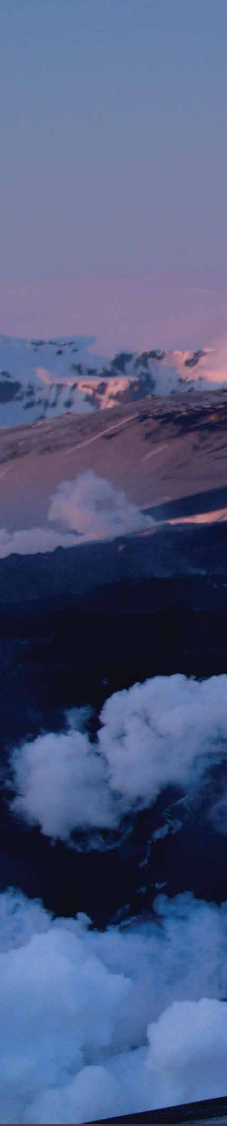
Department of the Seismology



About

Department of Seismology research activity covers a broad range of topics with the main subject of anthropogenic seismicity. All research activities covered by this report can be divided into several general topics: seismicity induced by exploitation of geo-resources, statistical properties of natural and anthropogenic seismic processes, seismicity induced by water reservoirs, engineering seismology and natural seismicity of Poland. The first topic was a subject of 4 research projects dealing with hydrofracturing (SHEER, S4CE), carbon dioxide storage and geothermal energy (S4CE), and underground mining of the copper ore (NCN and FNP projects led by A. Caputa and M. Kozłowska). SHEER project findings allowed for the better understanding of fluid path migrations and development of seismic process related to hydrofracturing. Finally, the project provided guidelines for best practices in environmental monitoring of hydrofracturing operations. S4CE project covers fundamental studies of fluid transport and reactivity, development of new methods for the detection and quantification of micro-seismic events and the deployment of the successful detection and quantification technologies in sub-surface sites for continuous monitoring of the risks. Projects dealing with underground mining are aimed in aftershock studies and detection as well as with the analysis of post-blasting seismic sources aiming in finding some characteristic physical properties of focal mechanisms, which might help in the development of rock burst active prevention. Another research was aimed at tracking possible ground deformation corresponding to a massive collapse in mine after an induced seismic event. The next activity was performed in cooperation with the Luleå University of Technology. The scope was seismic hazards in mines and analysis of seismic patterns and focal mechanisms. Research activity within statistical seismology was mainly focused on seismicity properties evolution in relation to fluid-injection, incompatibility of anthropogenic seismicity with probabilistic models typically used in seismic hazard analysis, the impact of magnitude uncertainties on seismic catalogue properties. A clear and statistically significant positive correlation between seismicity rates and total injection rates was obtained in case of the Geysers Geothermal field. It was proved that neither an exponential distribution of magnitude nor a Poisson distribution of event rate can be used to assess the stationary seismic hazard due to the anthropogenic seismicity from Oklahoma. Seismicity induced by water reservoirs was mainly focused on Czorsztyn and Lai Chau (Vietnam) reservoirs. The latter is a subject of the NCN research project aimed at an exploration of the natural seismicity, which exists in the area of the dam, and then determine the development of anthropogenic seismic activity associated with the impoundment of water in the reservoir. Natural seismicity of Poland research was focused on monitoring the activity: six tectonic earthquakes were noticed; four in Podhale and two in the Krynica region. Other works within tectonic seismicity covered dynamic triggering of shallow slip on forearc faults in Chile. Magnitude – distance relationship of slip triggering was derived. Engineering Seismology branch of our department research was aimed at HVSR methodology application for site effect determination in mining and polar areas. Another part of this activity was SERA project fostering the link between seismology and earthquake engineering. Important work was a prediction of the impact of tremors and surface deformations induced by mining in sections G23 O/ZG Rudna and LU XI O/ZG Lubin on OUOW "Żelazny Most" prepared within the agreement with KGHM Polska Miedź S.A. Hydrotechnical Division, Rudna. Except for significant scientific works Department of Seismology was also involved in the EPOS Programme. In 2018 EPOS-ERIC was established and Poland joined it. It is one of the main achievements of Department of Seismology within 2018 being a result of several years of involvement in EPOS and a confirmation of the key role of IG PAS in the anthropogenic seismicity research community.

Personel

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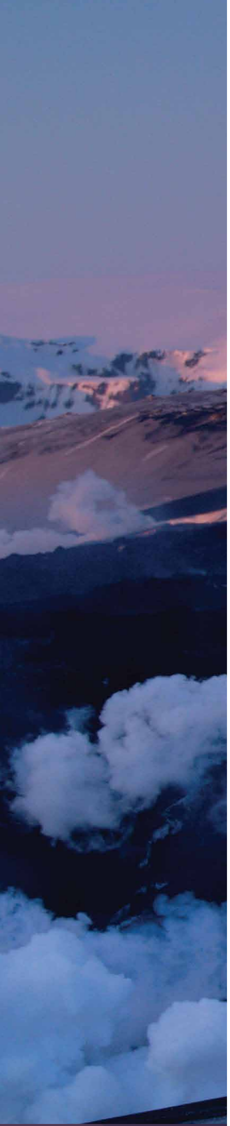


Research Project

- SHEER
  S. Lasocki | H2020 | 2018 -2018
- S4CE
  S. Lasocki | H2020 | 2018 -2018
- SERA
  S. Lasocki | H2020 | 2017 -2020
- EPOS-IP WP14
  B. Orlecka-Sikora | H2020 | 2015 -2019
- EPOS-PL
  D. Olszewska | POIT, OPI | 2016 -2021
- Analysis of post-blasting seismic sources recorded after rock burst active prevention
  A. Caputa | NCN | 2018 -2018
- Comprehensive analysis of the impact of local production conditions, main shock parameters and stress transfer on productivity and distribution of aftershocks in induced seismicity - research for improving the safety of natural resources extraction
  M. Kozłowska | Fundacja Nauki Polskiej | 2018 -2018
- Initialization and development of anthropogenic seismic processes induced by artificial surface reservoirs
  G. Lizurek | NCN | 2018 -2018

PhD Students

Alicja Caputa | Poland
supervisor: Stanisław Lasocki, Łukasz Rudziński

Instruments and facilities

Equipment

Seismic networks:
LUMINEOS – mining induced seismicity in Legnica – Głogów Copper District: 17 - broadband (5s) seismometers (VE-53/BB GeoSIG) and 10 strong motion instruments (AC-73 GeoSIG). Data is used in EPOS IP and NCN projects.

BOIS – very new network above Lubelski Węgiel Bogdanka – 12 broadband (5s) seismometers (VE-53/BB GeoSIG), the network is directly connected with B+R project which is devoted to seismological monitoring of the mine belongs to Lubelski Węgiel "Bogdanka" S.A. Project leader: Department of Seismology IGF PAS. Staff involved in the project: Ł. Rudziński, J. Wiszniowski, I. Dobrzycka, D. Wenc, S. Cielesta, P. Urban, P. Sałek. In the middle of 2018, Department of Seismology started a new collaboration with one of Polish coal mine Lubelski Węgiel "Bogdanka" S.A. The main aim of the collaboration is focused on seismological observation of seismic activity induced in the vicinity of the mine. In October 2018 IGF PAS installed 12 broadband (5s) seismic stations in the area around the mine. During the last three months of 2018, more than 50 seismic events with magnitude above M>1.5 were detected and localized in the mining region. The collaboration will be continued in 2019.

SENTINELS – induced seismicity around Czorsztyn – Niedzica artificial water reservoir: 10 broadband (5s) seismometers (VE-53/BB GeoSIG). Data is used in EPOS IP and NCN projects.

Lai Chau – artificial water reservoir in Vietnam network cooperated with Institute of Geophysics Vietnamese Academy of Science and Technology: 5 broadband seismometers (VE-53/BB GeoSIG, IG PAS), and 5 broadband seismometers (Guralp CMG-6TC, Samtac 801H, IG VAST). Data is used in EPOS IP and NCN projects.

Geodynamic monitoring of Poland, 2018. The service is carried out as a part of the project "Geodynamic monitoring of Poland", contract No. CRZP-240-36 / 20918 between the Polish Geological Institute - National Research Institute (PGI-NRI) and the Institute of Geophysics, Polish Academy of Sciences (IGF PAS). A. Cichowicz, K. Michałowski, B. Plesiewicz, J. Wiszniowski.

The main goal of the project is to monitor the natural seismicity in Poland. The data from 42 seismic stations were used to perform the task. IGF PAS provided 23 mobile stations (LE-3D Lite with NDL data loggers, financed within the project) and additionally 7 permanent broadband stations of the Polish Seismological Network - PLSN (financed from statutory activities). The project also has access to seismological data from 12 broadband stations of the Polish Geological Institute. The software necessary for the analysis of seismic data and the generation of reports and alerts has been fully tested and works correctly. The data collection system is operational, continuous data is stored by the IG PAS Technical Support Department in Warsaw. The completeness of data for stations ranges from 97% to 100%. The Seismology Department of IG PAS generated 37 weekly reports. There was no need to create an alert because there was no natural seismic phenomenon above 3.5 magnitude.

PGE EJ1 - Leader: Institute of Geophysics PAS. Staff involved in the project (form the Department of Seismology): Ł. Rudziński, B. Plesiewicz, L. Stempowski, K. Michałowski.

Department of Seismology in cooperation with Technical Support Department is involved in seismic monitoring of potential nuclear power plant (NPP) site in northern Poland since 2015. During that time, IGF has been operated 10 seismic stations including broadband and short period devices. The signals are recorded continuously and contain information not only deals with possible local seismic activity but also influences of regional earthquakes. All data recorded in the project will be useful for the future analysis of seismic hazards estimated for the NPP site.

Other infrastructure:
EPOS IP - WP14 Thematic Core Service Anthropogenic Hazards (TCS AH)
Leader: Institute of Geophysics PAS. Staff involved: B. Orlecka-Sikora, S. Lasocki, K. Leptokaropoulos, S. Cielesta, P. Urban, G. Lizurek, M. Staszek, D. Olszewska, D. Wenc

EPOS IP is the biggest infrastructural project in Europe within the solid earth sciences funded by the European Commission within H2020. The effect of the EPOS Programme will be pan-European scientific infrastructure open to the Member States and associated countries, facilitating the exchange of knowledge and mobility of researchers within the European Research Area and contributing to the dissemination and optimization of scientific results. EPOS programme has been planned to 2040. Currently, from 2015 to 2019, takes its second stage that is Implementation Phase (EPOS IP). In 2008, the project was approved by the European Strategy Forum on Research Infrastructures (ESFRI). It was also placed on the Polish Roadmap for Research Infrastructures in 2011. Under this project, a research infrastructure multi-layered, multidisciplinary and interoperable research infrastructure in the form of measurement networks and database with standardized metadata will be built. The access to the collected and stored data from the distributed measurement networks, developed, standardized and integrated (data products) will be provided through the website with relevant applications, analytical and dedicated visualization tools. WP14 Anthropogenic Hazards of EPOS IP is led by B. Orlecka-Sikora (IG PAS). Thematic Core Service Anthropogenic Hazards (TCS AH) is being developed by 14 European research institutions from 9 European countries. In 2018 EPOS-ERIC was established and Poland joined it. It is one of the main achievements of Department of Seismology within 2018 being a result of several years of involvement in EPOS and a confirmation of the key role of IG PAS in the anthropogenic seismicity research community. Within WP14 IS-EPOS web portal has been designed to serve as one of the main pillars of the Thematic Core Service - Anthropogenic Hazards belonging to pan-European multidisciplinary research infrastructure created within the EPOS program. More about TCS AH can be found on the website: https://www.epos-ip.org/tcs/anthropogenic-hazards access to IS-EPOS platform resources is available via the website: https://tcs.ah-epos.eu/

EPOS – European Plate Observing System – EPOS-PL
Leader: Institute of Geophysics PAS. Staff involved in the project: Coordinator D. Olszewska, coordinator of task 2 (Induced Seismicity Research Infrastructure Centre – CIBIS) G. Lizurek, K. Michałowski, B. Plesiewicz, P. Urban, J. Wiszniowski.

Infrastructure build within the project EPOS-PL is related to the European programme for the development of Research Infrastructure (RI) for Solid Earth science - EPOS - and it will be an integral part of it. Research Infrastructure EPOS-PL will integrate both existing and newly built National Research Infrastructures (Theme Center for Research Infrastructures), which, under the premise of the program EPOS, are financed exclusively by the national founds. In addition, the e-science platform will be developed. This would be a new/additional module built within EPOS-IP Thematic Core Services Anthropogenic Hazards (TCS AH).

The first layer of RI is built by so-called Research Infrastructure Centers (RICs). RIC provides a complete dataset concerning given research field (e.g. seismic data, geodetic data, geological data). Each national RIC has its own IT support. This solution ensures effective data storage and basic computing resources. Task 2 - Induced Seismicity Research Infrastructure Centre – CIBIS - is the main responsibility of Department of Seismology within the EPOS PL. It is aimed at development of a data acquisition system, storage and seismological data analysis from the anthropogenic seismicity hazard areas. Currently, the data acquisition system named CIBIS is operational and allows sharing and accessing the data via IS-EPOS platform. The second layer of innovative EPOS-PL infrastructure concerns the integration of infrastructure in the scale of Poland. Measurement polygons for the integrated observation of geodynamic processes are going to be built. The first polygons from the group of MUSE - Multidisciplinary Upper Silesian Episode will be built in mining and post-mining areas of Upper Silesian Coal Basin (Poland). Collected data and products will be integrated as a Multidisciplinary Upper Silesian Episode and shared through TCS AH platform (Thematic Core Service Anthropogenic Hazards, https://tcs.ah-epos.eu).

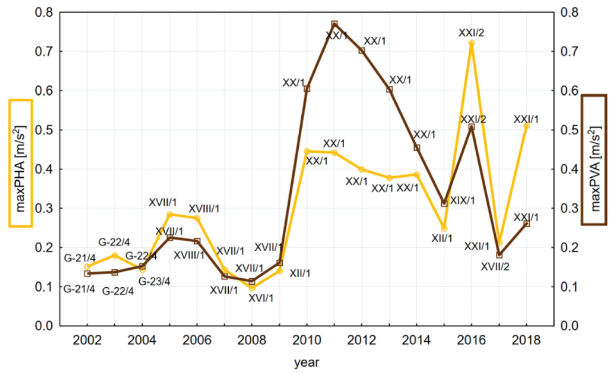
The next layer of innovative EPOS-PL structure is related to Integration of Research Infrastructure at the European level, in so-called EPOS Thematic Hubs. This will happen through the integration of national RI providing specialized services to communities associated in a number of disciplines in the Earth sciences (eg. Seismology, geodesy, etc.) or interested in particular disciplines. Thematic Hubs create an intermediate layer of EPOS integration plan. Thematic Core Service of Anthropogenic Hazards (TCS AH) is being built in Poland.

Following institutes are responsible for the implementation of this project: Institute of Geophysics, Polish Academy of Sciences (IG PAS) – Project Coordinator, Academic Computer Centre Cyfronet AGH University of Science and Technology (ACK Cyfronet), Central Mining Institute (GIG), the Institute of Geodesy and Cartography (IGiK), Wrocław University of Environmental and Life Sciences (UPWr), Military University of Technology (WAT). In addition, resources constituting the entrepreneur's own contribution will come from the Coal Company S.A.

SERA - Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe.
Leader: Eidgenössische Technische Hochschule Zürich, Switzerland. Staff involved: M. Sobiesiak, K. Leptokaropoulos, S. Lasocki, P. Sałek

The major aim of the European Project SERA is to foster the link between seismology and earthquake engineering. The project integrates data, products, infrastructures, and knowledge from both disciplines like earthquake catalogues, analysis software, experimental set-ups to gain new insights in earthquake processes and their influences on the general infrastructure, both of tectonic as well as induced seismicity. Tasks of IG PAS within the SERA project and contributions in 2018:
1) WP22 VA5: Access to data and products of anthropogenic seismicity at IG PAS.
2) WP23 JRA1: Physics of the earthquake initiation.
3) WP24 JRA2: Characterizing the activity rates of induced and natural earthquakes.
More about scientific outcomes of this project are described in research activity Engineering Seismology.

Long term service contracts:
Supervising the monitoring of seismic impact due to mining exploitation on the OUOW "Żelazny most" repository embankment seismic network and the stations monitoring the western foreland of OUOW. Leader: Institute of Geophysics PAS. Staff involved: S. Lasocki, D. Olszewska, S.Cielesta, Ł. Rudziński.



Annual maxims of PHA10 and PVA10 recorded at the embankment repository. Blue line - horizontal influence. Dark blue line - vertical influence. Labels over the marked points present the names of ZG Rudna mine sections, inducing these strongest motions.

Supervising the monitoring of seismic impact due to mining exploitation on the OUOW "Żelazny Most" repository embankment seismic network and the stations monitoring the western foreland of OUOW has been carried out in line with the contract concluded by and between KGHM Polska Miedź S.A. Hydrotechnical Division, Rudna, and Institute of Geophysics Polish Academy of Sciences in Warsaw. This agreement covers a period of three years, 2017-2019, and is accounted for annual stages. Mentioned supervision is being carried out for the last 16 years. According to the scope of work, the project team supervised ground motion monitoring and maintained and processed ground motion records from the accelerometric stations located at OUOW "Żelazny Most" facilities and the west OUOW foreground. The recorded signals are being uploaded to the SEJS-NET system database by the staff of the Geophysics Station of Rudna Mine. Both the SEJS-NET system and the ground motion database of the OUOW region are maintained on computer facilities of the Institute of Geophysics, Polish Academy of Sciences in Warsaw. The database is managed by the project team. Upon request of KGHM „Polska Miedź" SA, Hydrotechnical Division, as the owner of the database, a system administrator grants external users with database access. KGHM Polska Miedź S.A. conducts a new SEZAM system to collect and process the data related to induced seismicity in Legnica--Glogow Copper district, caused by underground mine operation. Therefore, there is a need to develop a data exchange of ground motion registrations and seismic catalogues. Access to the data is necessary due to the analysis carried out at the request of KGHM. One of that work is "Supervising the monitoring of seismic impact due to mining exploitation on the OUOW "Żelazny Most" repository embankment seismic network and the stations monitoring the western foreland of OUOW in 2017-2019". As a result of these consultations will be the scope of data, the form of data and the method of transmission of the data.

Seismometric monitoring consisted of 22 operating measurement stations, with 16 located at the OUOW "Żelazny Most" facilities and 6 located on the west foreground of the OUOW. Every measurement station is equipped with three componential accelerometer sensor. The recorded signals, which are caused by mining events, are transmitted to the Geophysical Station of Rudna Mine and then uploaded as text files to the server of SEJS-NET system database. Within the project, a review of the accelerometric records along with the quality assessments of measurements is being prepared. All accelerometric signals from the reporting period are integrated to ground motion velocity records and peak amplitudes of ground acceleration and ground velocity, as well as duration times, were calculated. For records originated by stronger sources, spectral amplitudes are being computed. Within every report, the description of seismic sources of the recorded ground motion is done along with a presentation of the seismic activities of ZG Rudna, ZG Lubin and ZG Polkowice-Sieroszowice mines. Reports include also seismic events impacts in reporting period with respect to the hazard to the "Żelazny Most" repository, which they evoke. Peak values of the horizontal and vertical components of the ground motion acceleration in the frequency range up to 10 Hz, recorded at the "Żelazny Most" repository facilities, are also being compared with respective estimates calculated by means of the recent ground motion prediction equations.

Laboratory

Department of Seismology is equipped with 78 modern seismic stations: 62 broadband and 6 very broadband seismometers as well as 10 strong motion devices. 44 stations are already installed in seismically active areas: two mining regions in Poland and two regions with seismicity induced by water reservoirs in Poland and Vietnam. The data recorded by the stations are (or will be soon) available on the IS-EPOS Platform (http://tcs.ah-epos.eu/). The e-platform devotes to hazards related to anthropogenic activities. IS-EPOS platform is a gateway for the data and research applications related to anthropogenic hazards. One of the main storages called e-Node is managed by the Department of Seismology, second storage is located and managed by EOST in Strasbourg. Currently, 27 out of 28 datasets called episodes are available on IS-EPOS platform are stored in polish e-Node. Both e-Nodes and IS-EPOS platform are developed within EPOS IP project within WP14 Anthropogenic Hazards.

Research activity and results

Shale gas Exploration and Exploitation induced Risks (SHEER) | (S. Lasocki, B. Orlecka-Sikora, D. Olszewska, G. Lizurek, M. Staszek, S. Cielesta, K. Leptokaropoulos, M. Kozłowska, P. Urban)

The Shale gas Exploration and Exploitation induced Risks (SHEER) project has taken up the very current problem of competent assessment of the possible impact of shale gas production on the environment. It was implemented as part of an international consortium of seven scientific institutions from Italy, Poland, Germany, Netherlands, UK, and USA. Polish scientists from the Institute of Geophysics Polish Academy of Sciences (IG PAS) led three out of eight work packages (WP2, WP3, WP6), responsible for running a multidisciplinary database and integrating it with e-Platform IS-EPOS, environmental monitoring, and assessment of the impact of hydrofracturing on air pollution. Their contribution to the implementation of the other packages and the whole project was also significant: prof. Stanisław Lasocki, the leader of the Polish group, was part of the three-man Project Management Team.

For the first time in Europe, multidisciplinary environmental monitoring was carried out before, during and after hydrofracturing. In the area around the exploration well of PGNiG SA, in the village of Wysin in Pomerania, Poland, equipment for measuring seismicity, groundwater quality and air quality has been deployed. The hydrofracturing in Wysin was carried out in two horizontal holes ~ 1.7 km long (Wysin-2H and Wysin-3H), located at a depth of 4 km, in two ten-day cycles, successively in June and July 2016.

The seismic monitoring of seismicity induced by technological works in the Wysin wells lasted from November 2015 to January 2017 with the use of 31 surface seismometers and three installed in 50m deep boreholes. Two shallow seismic events with magnitude Mw = 1.0 and Mw = 0.5, recorded a few days after hydrofracturing, were located in the close vicinity of the well. Small distances between the well and epicenters and the temporal correlation between technological operations and occurring seismicity suggest a possible relationship between hydrofracturing and the two mentioned seismic events. Four wells reaching the groundwater table were used to monitor the water quality. In the monitored period, no impact of hydrofracturing on groundwater parameters, whether the water level or the chemical composition of groundwater was recorded, both in the short- and medium-term scale. Air pollution was monitored continuously using an automatic measuring station located ~ 1000 m east from the drilling platform. Concentration levels of various pollutants, including NO, NO2, NOx, CO, PM10, O3, CO2, CH4, NMHC, and Radon were analysed. Air quality measurements covered the period from July 2015 to July 2017. Detailed monitoring did not show any significant impact of technological work in Wysin on the condition of the environment. The collected data together with data from other world locations for the use of underground water injection in order to obtain energy and energy resources became part of the SHEER project database, managed and maintained at the IG PAS.

The interdisciplinary nature of the data collected as part of the project and the amount itself required the creation of a "smart" database, integrating seven independent episodes. The SHEER project database has been made available on the IS-EPOS e-Platform for Anthropogenic Hazards located in Poland. From the beginning of May 2018, the data collected in the project is open to all registered users of the free scientific platform available at https://tcs.ah-epos.eu/. The SHEER project database has been used in research conducted by consortium members. Project members developed, among others statistical description of induced seismicity processes and assessment of seismic dependence with operational/technological parameters. Researchers developed methods for tracking and modelling the development of fractures in the rock mass and the permeability changes caused by water injection. As part of the SHEER project, a statistical method for assessing the environmental impact and risks in the entire shale gas exploitation cycle was created. This method integrates many causes of risks and many of the hazards implied by these risks. After testing on the SHEER database, the method was recommended to the European Commission as a way to comprehensively evaluate the possible effects of shale gas exploitation. More information about the project, its results, publications, reports, and reports on individual work packages, bulletins and materials promoting the project are available on the project website: http://www.sheerproject.eu/. Main achievements of the project were published in several publications and a special issue of Acta Geophysica dedicated to SHEER.

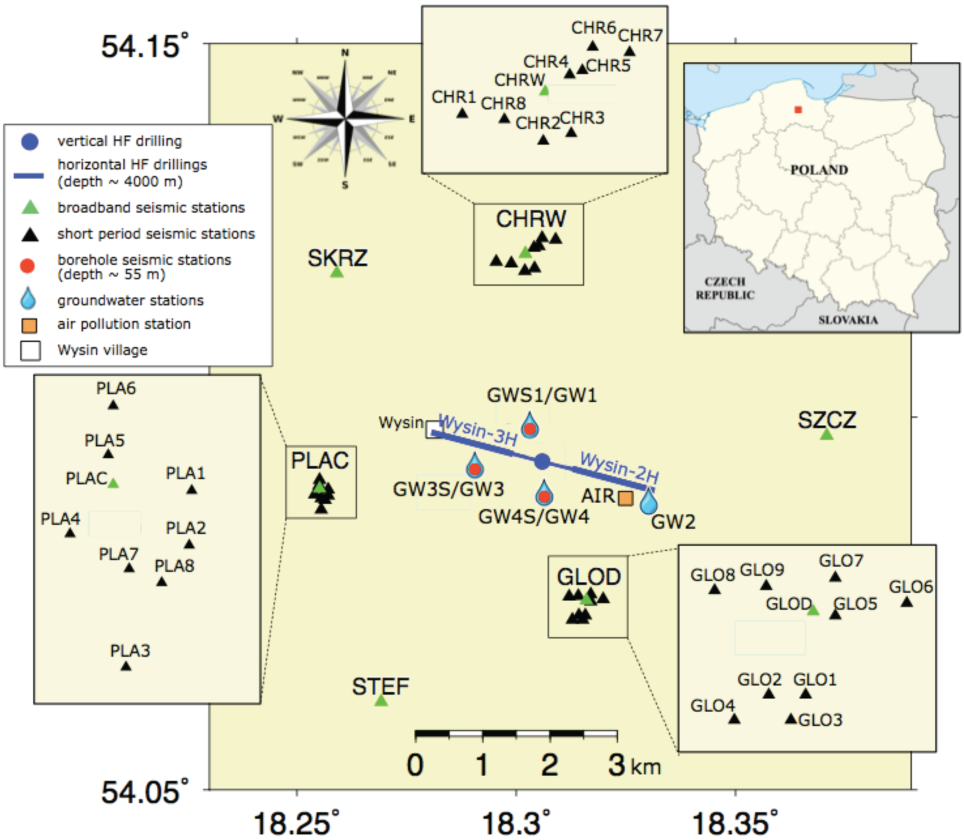


Fig. SI1. Map of seismic, air and groundwater monitoring at the Wysin site (Poland). The seismic monitoring includes broad-band stations (green triangles), small-scale arrays (inset boxes) composed by 8–9 short-period stations each (black triangles), and borehole stations (red circles). The air pollution station (orange square) is located at Stary Wiec village. Groundwater borehole monitoring stations are denoted by water drop symbols; some of them are located next to the borehole seismic stations. Wellhead (blue dot) and horizontal boreholes (blue lines) are shown. The inset map shows the hydraulic fracturing area (red square) in Poland (López-Comino, et al. 2018, Scientific Reports, doi: 10.1038/s41598-018-26970-9)

Tracking the development of seismic fracture network from The Geysers geothermal field | B. Orlecka-Sikora, S. Cielesta, S. Lasocki

The problem of tracking the fracture growth as a possible way for fluid migration in the rock mass is of scientific-wide concern in studies dealing with the exploitation of geo-resources. Most of the possible environmental impacts and risks are linked to undesired evolution of the fracturing process and enhancement of permeability. Understanding how far this enhanced permeability pattern can develop in space and time can be approached by the description of the possible fracture network growth and fracture network connectivity.

In the framework of the SHEER project, the problem of development of fracture networks towards the potential for forming the pathways for fluid migration was studied using the equivalent dimensions approach. In this research activity, an example of this way of fracture system identification was applied to the injection -induced seismicity data from the north-western part of The Geysers (TG) geothermal field in California, USA. Seismicity of The Geysers results from thermoelastic and poroelastic effects that change the local stress field in the reservoir. The seismic activity in TG highly correlates with the injection operations. The analysed north-western seismicity was isolated from the rest of seismic activity in the broader area of TG field. The seismic catalogue for this specific seismicity cluster in addition to occurrence time, location and magnitude contain seismic moment tensors and spectral parameters. Thanks to that and the application of equivalent dimension transforms, criteria for possible linking of fractures in a prescribed direction were formulated, based on (i) fault plane orientations of fractures, (ii) locations of hypocenters with respect to the injection well, (iii) sources radii and (iv) angles between the fault planes of fracture segments. To identify fracture arrays, the hierarchical clustering was used. The potential of an array to link fractures into longer crevices is quantified by the number of fractures' intersections. Considering hydraulically induced fracturing, the information about the fracture segment location and fracture plane orientation is necessary to map a build-up of the fracture network. In this connection, three parameters of the earthquake were selected. The first parameter was the distance between the open hole of Prati-9 well and the event hypocenter, r. This parameter allowed to track the reaction of the rock mass to driving stresses of fracturing, which are assumed to propagate from the well out. The fracture growth depends also on principal stress orientation. This second factor can result in an elongation of the fracture network. Usually, an observed shape of the anthropogenic seismicity clusters is consistent with the regional stress field. Following up, for proper identification of activation of fracture networks potentially comprising linked fractures, which were probably preferentially aligned parallel to the stress field orientation, a deflection parameter was introduced. The deflection, def, was the angle between the position vector of hypocenter of a seismic event and SHmax direction. The third parameter was a 3D rotation, rot. Based on P and T axes' orientations, the rotations of DC sources of events to the fault plane strike/dip/rake: 26/45/-45, were calculated. Assumed fault plane compromises the prevailing orientations of fault planes in the study area. The rotations were expected to be in general consistent with the stresses promoting failures. Similar rot values indicated similarity of fault plane orientations.To identify fracture structures within the data, hierarchical clustering with the agglomerative approach was used. The distance between events was the indicator of the fracture network development - the smaller distance between events the stronger link between them. Linkage method of Ward was used for above quantification. Characteristics of each identified cluster were analysed towards possibility of fracture linking. Each seismic event was attributed with the section of strike line of length equal to two times source radius and centered at the event epicenter. As a proxy of the number of connections among fractures, the number of intersections among these sections was used. These intersections were called nodes. The connectivity coefficient C was calculated. This is the ratio between the actually observed number of nodes in a cluster and the number of possible nodes within the cluster. To get an insight into a relation between connectivity within fracture networks and injection rate, those events, which had occurred during two injection cycles, were extracted (Fig. SI2). The value of connectivity parameter, C, in the families distinctly changes between stages of injection in which the events in the family occurred.

The test indicates that the connectivity values in the stages before and after the peak injection are significantly greater than the connectivity in the peak injection stage. The differences between C values in the stages before and after the peak injection have not been found significant. The test results suggest that lower injection rates favour linking fractures, whereas higher injection rates inhibit such linking tendency.

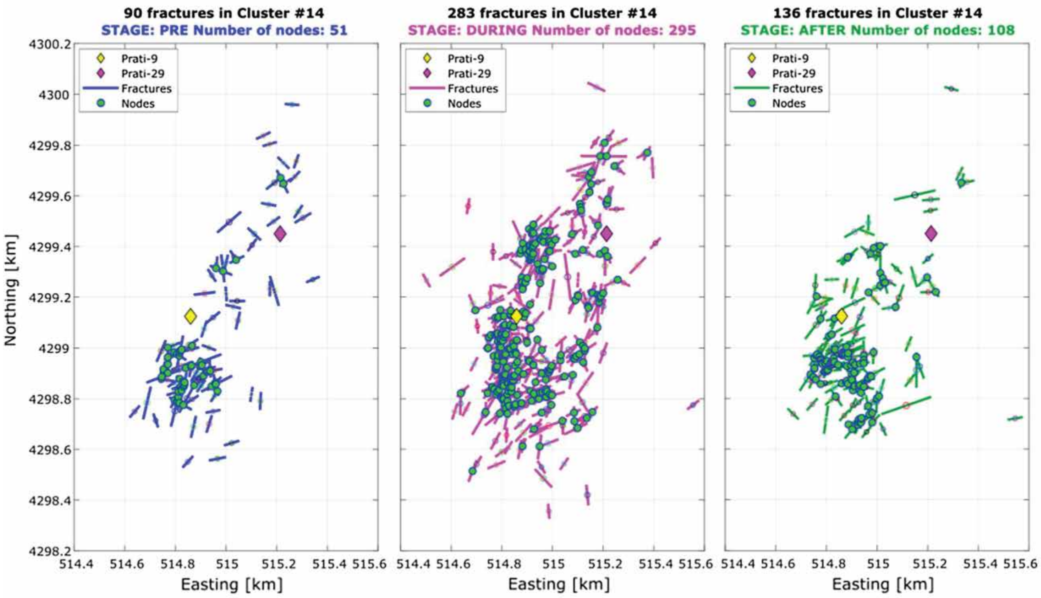


Fig. SI2. Connections among fractures from the extracted 13 clusters in the three stages of injection. Fractures occurred during the stages before, during and after the peak injection are plotted in blue, pink and green, respectively. Intersections (nodes) are marked with green dots. Open holes of Prati-9 and Prati-29 injection wells are shown as yellow and pink diamonds, respectively.

EPOS IP. IS-EPOS Thematic Core Service Anthropogenic Hazards – IS-EPOS platform developement

| B. Orlecka-Sikora, S. Lasocki, K. Leptokaropoulos, S. Cielesta, P. Urban, G. Lizurek, M. Staszek, D. Olszewska

WP14 Anthropogenic Hazards of EPOS IP project is led by B. Orlecka-Sikora (IG PAS). EPOS IP is the biggest infrastructural project in Europe within the solid earth sciences funded by the European Commission within H2020. Thematic Core Service Anthropogenic Hazards (TCS AH) is being developed by 14 European research institutions from 9 European countries. In 2018 EPOS-ERIC was established and Poland joined it. It is one of the main achievements of Department of Seismology within 2018 being a result of several years of involvement in EPOS and a confirmation of the key role of IG PAS in anthropogenic seismicity (AS) research community. IS-EPOS web portal has been designed to serve as one of the main pillars of the Thematic Core Service - Anthropogenic Hazards belonging to pan-European multidisciplinary research infrastructure created within the EPOS program. IS-EPOS platform is open for the research community and general public according to its rules of access, receiving an open-access tool for the experimentation and training of students and young scientists, who want to perform AS research. Several successful workshops and demonstrations for undergraduate as well as postgraduate students on AS and hazard have been carried out in Germany, Poland, Greece, Sweden, Finland, and USA. Collaboration abilities are scheduled to be integrated into the upcoming platform version, enabling team generation and sharing common projects, data, applications, and results among the users. Currently, 28 datasets called episodes from 11 countries from Asia, Europe, and North America are available on IS-EPOS platform. Episodes are stored in two e-Nodes: Polish e-Node hosted by IG PAS and French hosted by EOST Strasbourg. IS-EPOS promotes new opportunities to study and understand the dynamic and complex solid earth system response to human activities by integrating the use of data, data products, analysis models and online facilities. IS-EPOS has been already used to facilitate scientific research in recently published papers connected with anthropogenic as well as natural seismicity by utilizing data, applications and/or the interface and facilities of the platform. Above mentioned research abilities are supported with over 30 web-based research applications available for the users. At the end of 2018 IS-EPOS platform had 877 users from 127 institutions located in 27 countries. The main achievement of this activity is dissemination and a summary of the features and impact of IS-EPOS platform to the IS community so far. More about EPOS WP14 can be found on the website: https://www.epos-ip.org/tcs/anthropogenic-hazards access to IS-EPOS platform resources is available via the website: https://tcs.ah-epos.eu/

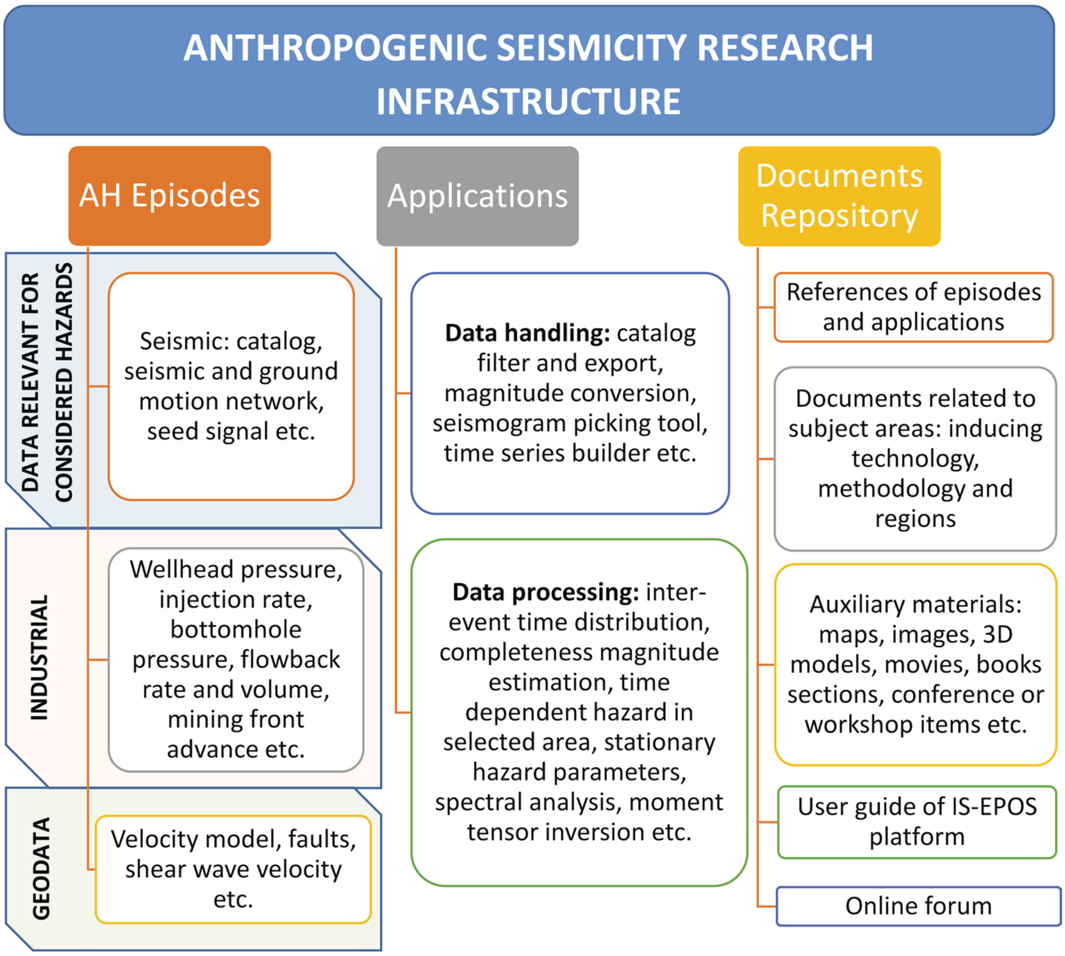


Fig. SI3. Scheme of research infrastructure integrated within IS-EPOS e-platform (Figure 4 from Leptokaropoulos et al., 2018c).

Science for Clean Energy - S4CE | S. Lasocki, K. Leptokaropoulos, P. Urban

Science4CleanEnergy, S4CE, is a multi-disciplinary consortium, of world-leading academics, research laboratories, SMEs and industries. S4CE will develop a project that includes fundamental studies of fluid transport and reactivity, development of new instruments and methods for the detection and quantification of emissions, micro-seismic events etc., lab and field testing of such new technologies, and the deployment of the successful detection and quantification technologies in sub-surface sites for continuous monitoring of the risks identified by the European Commission. S4CE leverages approximately 500M EUR in existing investments on 4 scientific field sites. S4CE will utilize monitoring data acquired during the project in these field sites on which (a) it will be possible to quantify the environmental impact of sub-surface geo-energy applications; (b) new technologies will be demonstrated; (c) data will be collected during the duration of the project, and potentially after the end of the project. Using reliable data, innovative analytical models and software, S4CE will quantify the likelihood of environmental risks ranging from fugitive emissions, water contamination, induced micro-seismicity, and local impacts. Such quantifications will have enormous positive societal consequences because environmental risks will be prevented and mitigated. S4CE set up a probabilistic methodology to assess and mitigate both the short and the long term environmental risks connected to the exploration and exploitation of sub-surface geo-energy. S4CE will maintain a transparent dialogue with all stakeholders, including the public at large, the next generation of scientists, academics and industrial operators, including training of young post-graduate students and post-doctoral researchers. S4CE will deliver the independent assessment of the environmental footprint related to geo-energy sub-surface operations, having as primary impact the assistance to policy making.

S4CE consortium consists of 22 parties. Activities of the Institute of Geophysics Polish Academy of Sciences in S4CE are carried out by the Department of Seismology. The Department is involved in five out of nine work packages, namely:
WP3 - Instruments and Tools: Development and Deployment
WP5 - Data Gathering and Model Implementation
WP6 - Implementation of Novel Technologies
WP8 - International Cooperation and Policy Recommendations
WP9 - Dissemination, Exploitation and Innovation

In WP6 the Department leads the Task 6.5 "Assessing rapid fluid transport probability and tracking fluid pathways in the rockmass". The assessments of the probability of rapid fluid coupling will be based on the methodologies developed for the volcanic environment to the fluid-solid coupling of two phases fluid (gas and water) in the unconventional hydrocarbon reservoirs. Tracking fluid pathways within the rockmass will be based on the transformation to equivalent dimensions of microearthquake parameters. Event clusters will be identified in the multi-parameter equivalent dimension spaces. The identification of these families of events will be achieved by defining prescribed conditions of crack parameters, such as directions, dimensions and mutual distances. The probability of generation of a given length fissure, resulting

from the linkage among smaller cracks of the same cluster will be subsequently determined.

In WP9 the Department of Seismology leads the Task 9.7 “S4CE Database on IS-Epos platform” The IS-EPOS, which is the main technical pillars of the Thematic Core Service Anthropogenic Hazards (TCS AH), belonging to European Plate Observing System (EPOS) platform, is be used in S4CE as storage of newly acquired data.

Comprehensive analysis of the impact of local production conditions, main shock parameters and stress transfer on productivity and distribution of aftershocks in induced seismicity - research for improving the safety of natural resources extraction | M. Kozłowska

The goal of the project is to understand the geological, seismological and/or technological factors influencing the productivity of aftershocks in induced seismicity. Since the beginning of the project the analysis of the aftershock activity in Kiruna mine, Sweden was performed. That research was performed in the cooperation with the foreign partner of the project – prof. Savka Dineva from Luleå University of Technology (LTU) and included 3-weeks training at the LTU. The scientific paper has been written regarding this study and it's now under review. Two relatively strong mining seismic events in Kiruna mine occurring in two seismically active blocks were investigated. Focal mechanisms and source parameters of the two strong events were studied to model the resulting static stress changes. The level and distribution of seismicity occurring before the strong events were evaluated and then used in the modelling of the aftershocks with the rate-and-state model. The model worked well for one of the events – it predicted both the number and area of aftershocks. In the case of the second event, the model performed worse underestimating the number of aftershocks. Perhaps, in that case, some additional processes, not included in the model, took place and influenced the seismic activity, e.g. dynamic triggering.

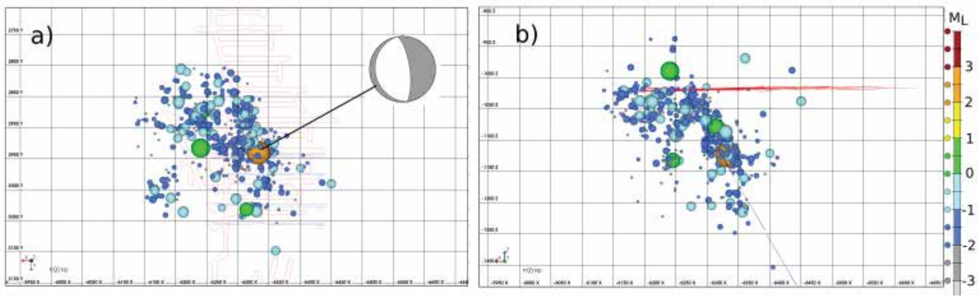


Fig. SI4. The horizontal (a) and vertical (b) distribution of aftershock following one of the studied strong seismic events in Kiruna mine, Sweden.

Under the project, the cooperation with a master student from AGH University in Krakow has started. The scope of this cooperation is studying the seismic activity of Rudna mine, Poland. We seek to find the physical difference between strong events producing a series of aftershocks and strong events producing no aftershocks. This topic is also the topic of a master thesis of a student.

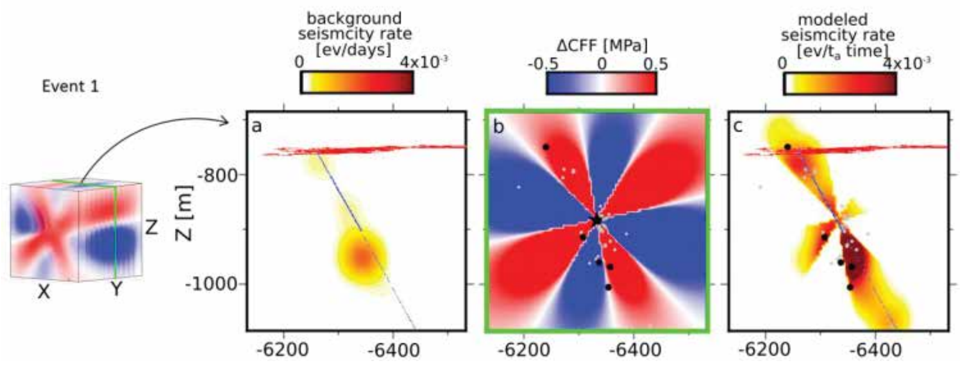


Fig.SI5. Input parameters (a and b) and results (c) of a rate-and-state based modelling for the second studied event.

Studying of possible ground deformation corresponding to a mining induced seismic event followed by a massive collapse in mines |

Ł. Rudziński

The scientific activity is dealt with ground deformations and its possible connection with seismic activity in mining regions. In 2018 research works were focused on a tragic seismic event occurred in Upper Silesian Coal Basin in 2015. On 17 April 2015, the Wujek/Śląsk underground coal mine in Poland was struck by a strong induced tremor of magnitude M4.0. The event was followed by a massive rock burst and a collapse of tunnels in the vicinity of the hypocentre. The earthquake was widely felt in the densely populated surrounding area. Using two different methods based on SAR and seismological observations a possible connection between seismological parameters was described. Special attention was focused on such parameters as the seismic source location and the focal mechanism. Next seismological results with the ground deformation just above the collapsed tunnels, which arose in a very short time after the event occurred, was performed (fig. SI6). It was shown that joint seismological and satellite observation can be very valuable and important tools not only to improve the knowledge concerning mining rock bursts and tunnel collapses but also to find their influences on the ground effects observed on the surface.

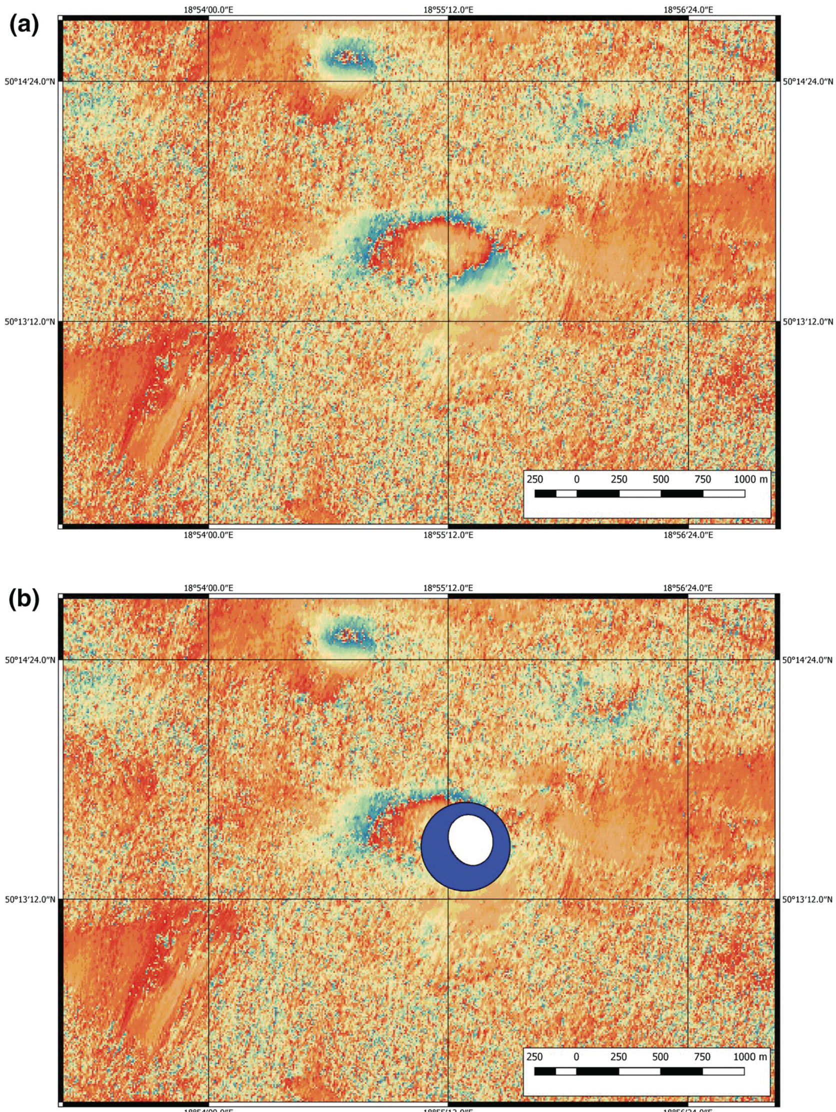


Fig. SI6. a Interferograms of the Wujek/Śląsk mining area between 12 April and 24 April 2015. b The same interferograms together with the source mechanism corresponding to the final MT (Table 3). The location of the focal sphere in the image corresponds to the epicentre, while the size of the beach ball corresponds to the location errors (Fig 4 form Rudziński et al, 2018)

Analysis of post-blasting seismic sources recorded after rock burst active prevention | A. Caputa, Ł. Rudziński

The main aim of the research within the project is focused on the study of mining induced seismic tremors, which occurred during or a short time after the rock burst prevention inside the tunnels of Rudna mine, Poland. The project has started on January 30, 2018, and is going to last till the end of 2019. Research within the project is related to high seismic activity and rock burst hazard associated with exploitation of copper ore deposits in Legnica – Głogów Copper District (LGCD), Poland. During twenty years (1990 - 2010) more than 11 200 strong mining tremors (magnitude M>2) were recorded in LGCD and 323 events were associated with rock burst. This project is focused on induced seismicity provoked by blasting works, which are performed within excavation of copper ore and active rock burst prevention. Blasting is considered as an effective way to destress rockmass in the vicinity of the mining faces. It is noticed that about 30% of all mining events in LGCD were provoked by the active prevention. Currently, the only way to quantify the effectiveness of the stress reduction during active prevention is based on cumulative energy released during the established waiting time, the time which is set up after detonations. However, the physical processes responsible for stress reduction during or after blasting are still not clear. The project aims at the analysis of the seismic sources induced by mining, occurred on Rudna mine. The most important question to solve is whether any features which are common for events in the waiting time and if they exist can be found. Another important issue is how they are related to physical parameters estimated for other, unexpected (common) seismic tremors. In 2018 research activity was focused on tests with synthetic data for both networks. In the tests, all synthetic waveforms were generated for a selected 'ideal' point source models: shear (fig. SI7) and non-double couple models. Sources were located in different locations within Rudna mine panels. It is expected, that these tests will be useful to define specific problems and limitations of the seismic networks and will be essential for the next steps of the project.

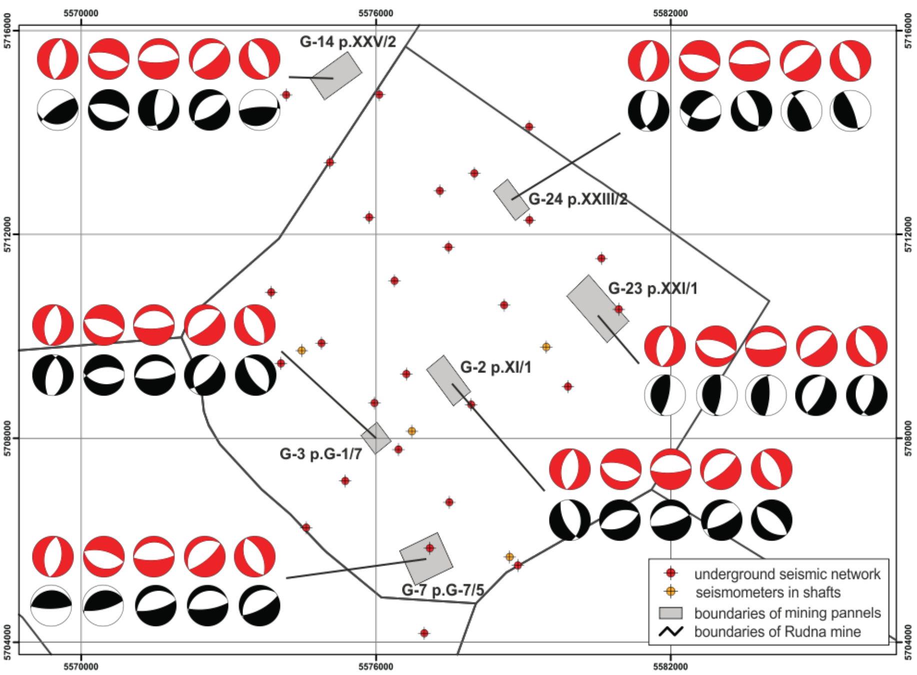


Fig. SI7. Comparison between synthetic (red) and inverted (black) source mechanisms (double - couple) for different locations within Rudna mine panels.

Vinnova SIP STRIM – Swedish Project granted by LKAB A.B Leader: Luleå University of Technology, Luleå Sweden. Department of Seismology IG PAS is a non-profit partner in the project | **S. Lasocki, B. Orlecka-Sikora, Ł. Rudziński, M. Kozłowska, K. Leptokaropoulos**

The main aim of the project is focused on the development of specific criteria due to seismic risk for temporary closing/re-opening of seismically active mines. The issue is a common problem in all seismically active mining regions and is under debate also in Polish copper and coal mines. IG PAS was invited as a partner to consult the scientific and technical ideas, which can improve the current knowledge concerning possible criteria. Two main seismological issues which can help with the project were considered and consulted during last year: seismic hazards in mines (prof. dr hab. S. Lasocki, dr hab. inż. B. Orlecka-Sikora, dr K. Leptokaropoulos) as well as analysis of seismic patterns and focal mechanisms (dr Ł. Rudziński, dr inż. M. Kozłowska).

During last year the characteristics of Kiruna mine Block 34 seismicity was analysed in space-time-size domain together with its relation to blasting activities. The analysis conducted indicated some interesting results, however, it revealed potential problems in the data used. Therefore, revised data are needed before proceeding to (and partially re-performing) the analysis. Based on data recorded on the regional broadband network, the study focused on source mechanisms analysis have started. Next, the results were used to investigate a seismicity pattern, especially aftershock sequences for selected mining tremors occurred in Kiruna mine, northern Sweden (fig. SI8).

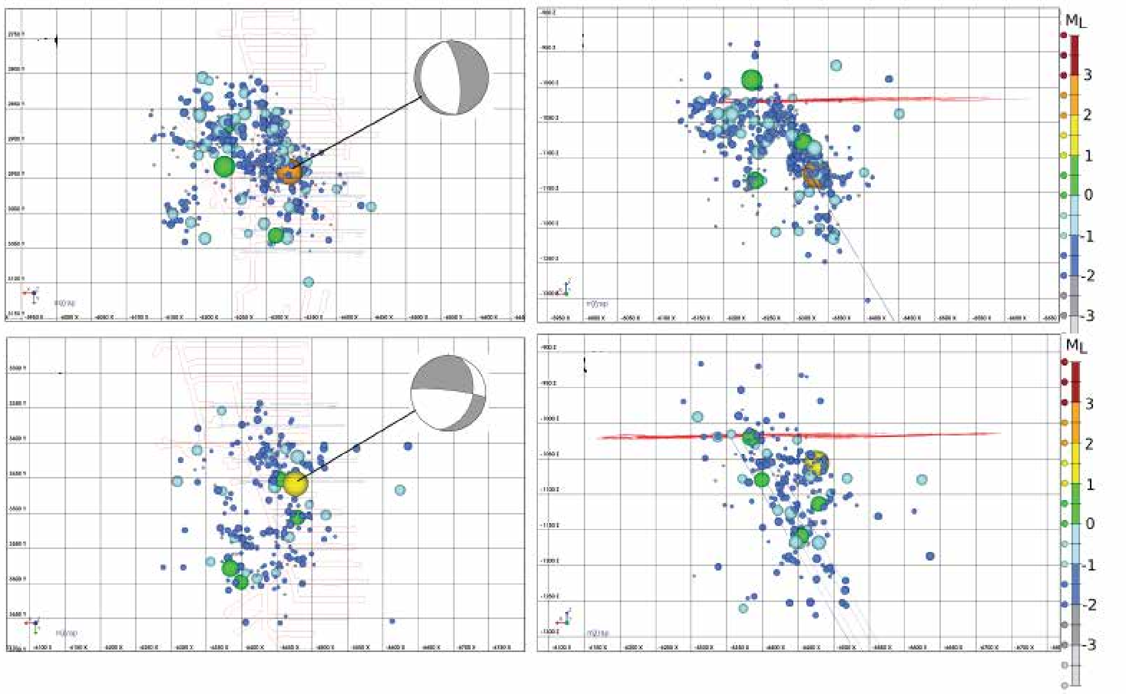


Fig. SI8. Examples of two different seismic sequences recorded on Kiruna mine, Sweden.ls.

Seismicity properties evolution in relation to fluid-injection in The Geysers Geothermal Field | K. Leptokaropoulos, M. Staszek, S. Lasocki, B. Orlecka-Sikora, S. Cielesta

Within this research activity, a detailed correlation analysis between seismicity properties and operational parameters was carried out. The analysis was performed in an isolated cluster from the North-Western The Geysers geothermal field, for which a high-quality seismic catalogue is available. Firstly, the correlation between spatio-temporal seismicity evolution and variation of the injection data was performed by investigation of original and smoothed time-series through diverse statistical tools (cross-correlation function, binomial test for investigating significant rate changes, magnitude distribution analysis). To do so, seismicity and operational data associated with two injection wells (Prati-9 and Prati-29) which cover a time period of approximately 7 years (from November 2007 to August 2014) were used. A clear and statistically significant positive correlation between seismicity rates and total injection rates was obtained. This correlation statistically differs from zero at 0.05 significance level. The maximum correlation occurs with a seismic response delay of ~ 2 weeks, following injection operations, whereas a range between 0-85 days is statistically significant at 0.01 level. This time lag is preserved even after considering hypocentre uncertainties, i.e. when the seismicity cloud is shifted at a shallower location as far as 300 m from its original hypocentre. The analysis also indicated time variations of b-value, which exhibits significant positive correlation with injection rates.

Next, a detailed investigation of the variation of injection rates on microseismicity magnitude distribution was performed. A direct comparison between injection rate changes and the b-value response was attempted after the appropriate selection of data subsets. Due to the relatively small sample (1121 events, corresponding to an average rate of ~ 0.45 events/day), seismic activity into two families corresponding to increasing and decreasing injection rates was aggregated, respectively. The b-values were calculated as a function of time lag related to the injection activity. In agreement with previous studies, a statistically significant direct relation between b-values and injection rate changes, which occurred at a zero or very short time lag (from 0 to ~ 15 days) were found. However, the b-value changes are related to the slope (i.e., the second derivative of injection volume), instead of the absolute values of injection rates. The increasing injection rates correspond to $b=1.18\pm0.06$, whereas the decreasing injection rates correspond to $b=1.10\pm0.05$. The corresponding values estimated by the repeated medians technique are $b=1.97\pm0.20$ and $b=1.50\pm0.13$. Both differences are significant at 0.05 level. Furthermore, Prati-9 injection well, which is located in the close vicinity of the seismicity cloud, was found to contribute mainly, but not exclusively to the b-value fluctuation. Finally, no significant influence of static stress drops, vertical distribution of microseismicity and absolute injection rates on b-values was detected under the performed analysis.

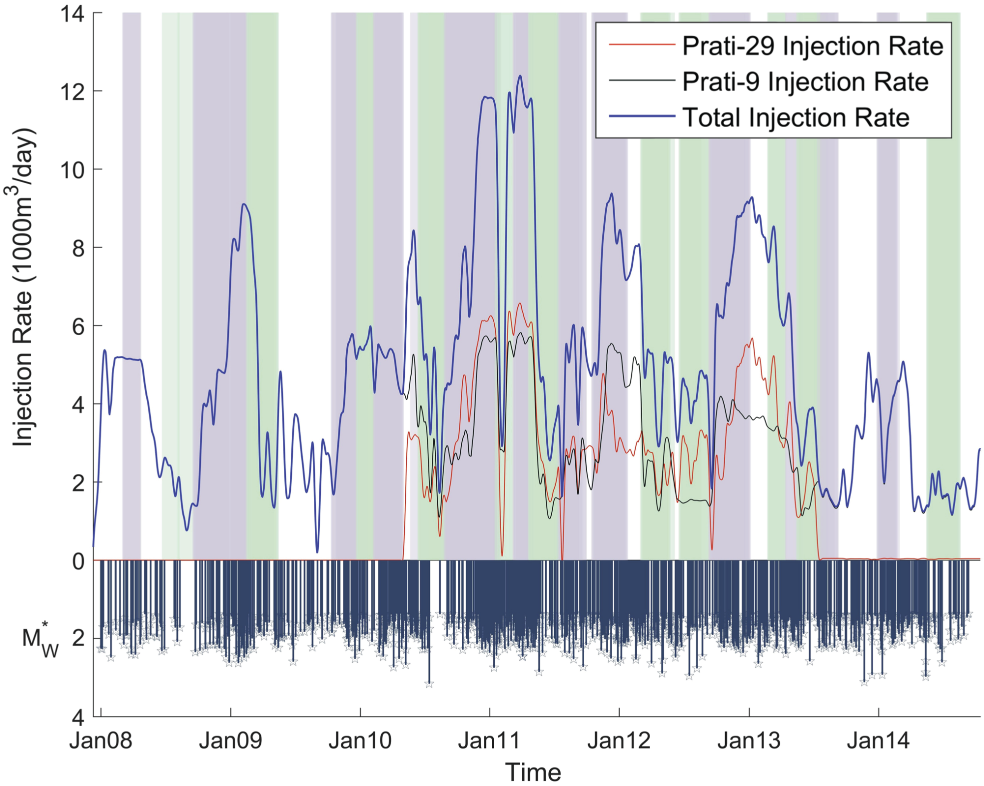


Fig. SI9. Daily total injection rates (blue curve) in relation to the occurrence of earthquakes (stem plot). The daily rates of fluid injected individually into wells Prati-9 and Prati-29 are indicated by black and red curves, respectively. The vertical bars indicate time periods of 50 days which have significantly increased (grey bars) or decreased (green bars) seismicity rates, in comparison with the preceding 50 days window. The time step applied in the analysis is 2 days, so the time windows are overlapping with each other (Fig. 2 from Leptokaropoulos et al., 2018a).

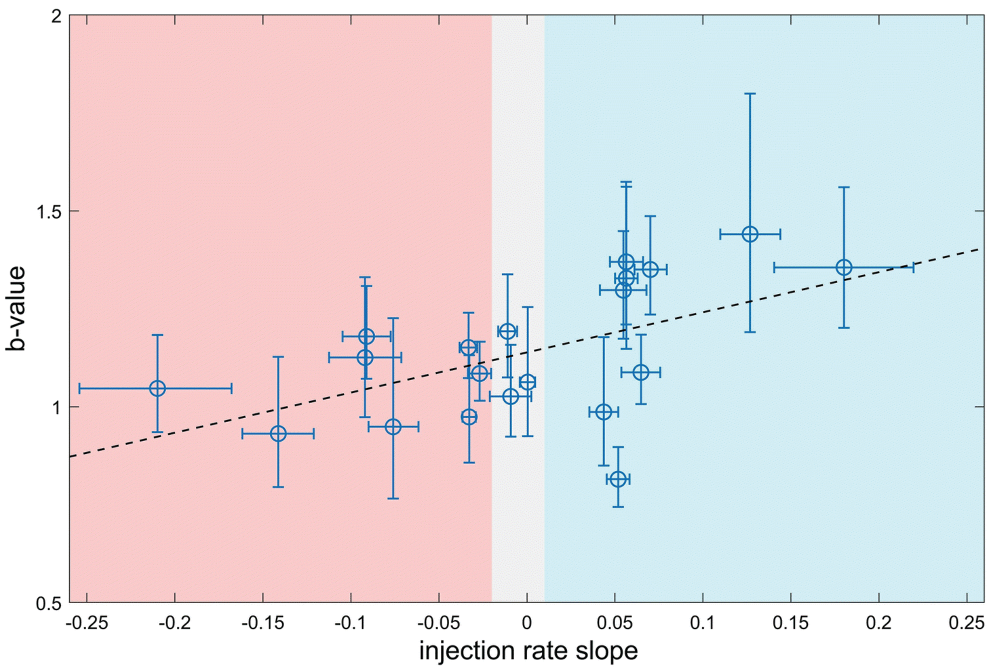


Fig. SI10. Estimation of b value for the 20 datasets described in Leptokaropoulos and Staszek (2018). Blue-shaded area corresponds to periods of increasing injection rate, red-shaded area corresponds to periods of decreasing injection rate, and grey-shaded area corresponds to periods of almost stable injection rate. The horizontal and vertical error bars indicate one bootstrap standard deviation (σ) of the injection rates' slopes and b values, respectively. The slope of the least-square linear regression curve, denoted by the dashed line, is ~ 1 (Fig. 2 from Leptokaropoulos and Staszek, 2018).

Magnitude distribution properties in noise-contaminated synthetic data comprising a complete and an incomplete part, when this distribution is controlled by the Gutenberg-Richter law were studied. The efficiency of the maximum likelihood estimator introduced by Aki (1965) was estimated using synthetic datasets exhibiting diverse but well-defined properties. The completeness magnitude, MC, was also estimated by means of several different techniques (maximum curvature, the goodness of fit test, b-value stability and modified goodness of fit test). The deviation of the b-value estimation from its real value is quantified by Monte Carlo simulations as a function of catalogue features and data properties such as sample size, magnitude uncertainties distribution, round-off interval of reported magnitude values and magnitude range. Analysis showed that the noise introduced to the data generally leads to a systematic overestimation of magnitudes close to and above MC. This fact causes an increase in the average number of events above MC, which in turn leads to an apparent decrease of the b-value. To summarize, the analysis performed shows that under the assumed conditions the following conclusions are drawn:

(1) The b-values tend to be underestimated when the noise of the character we have investigated is introduced to magnitude values. The degree of underestimation is proportional to the noise standard deviation (for Gaussian noise).

(2) Different methods for MC estimation lead to different results (MC and b-value), which are strongly influenced by sample size, noise properties, magnitude range and b-value itself.

(3) b-value analysis, especially for small datasets should be carried out together with M analysis. Relevant nomograms should be constructed and used.

(4) Even above a well-defined MC, a catalog is unlikely to be complete because of a bidirectional flow of data below and above MC. For Mmin>>MC, the actual number of events is overestimated by a factor depending primarily on the noise standard deviation (especially for N>800).

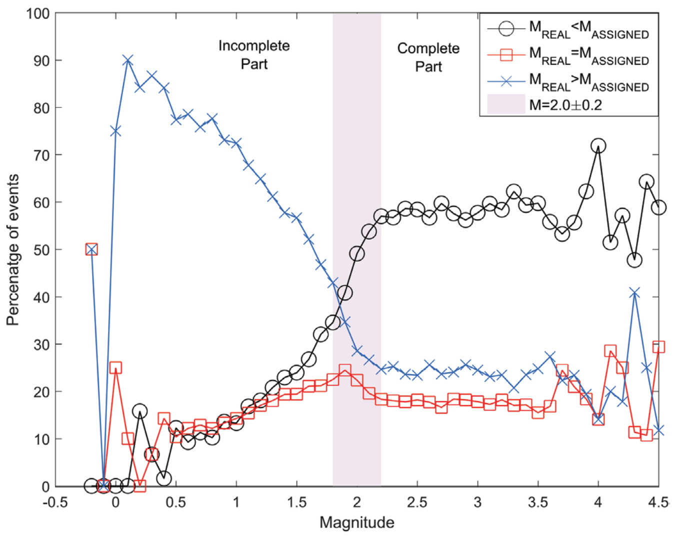


Fig. SI11. Percentage of events in the synthetic catalog A which have underestimated (blue crosses), overestimated (black circles) or correctly estimated (red squares) magnitudes when Gaussian noise (μM=0 and σM=0.2) is added, plotted against true (synthetic) magnitude. The shaded area indicates 0.2 units on both sides of M=2.0. Note the shift towards larger magnitudes (Fig. 9 from Leptokaropoulos et al., 2018b).

Incompatibility of anthropogenic seismicity with probabilistic models typically used in seismic hazard analysis: the case of Oklahoma earthquakes

| S. Lasocki, P. Urban

The exponential distribution model for magnitude arises from the Gutenberg-Richter magnitude-frequency relationship and the exponential model for interevent time is valid if the earthquake occurrences are governed by a homogeneous Poisson process. The Gutenberg-Richter rule for magnitudes and the Poisson process for earthquake occurrences are typically assumed in stationary earthquake hazard estimation although there are reports showing significant violations of these assumptions in both tectonic as well as anthropogenic seismicity cases. Anderson-Darling test was used to investigate the validity of these assumptions for injection induced earthquake data from Oklahoma (Oklahoma Geological Survey, www.ou.edu/content/ogs/research/earthquakes/catalogs.html). The epicentres of analysed events form two distinct spatial clusters, the one, A, in a north-western part of the study area and the second one, B, in a south-eastern part. The hypothesis that the magnitudes follow exponential distribution is rejected for the whole dataset and for cluster B. The hypothesis that the interevent times follow exponential distribution is rejected for the whole dataset and both spatial clusters. The side hypothesis that the occurrence process is an inhomogeneous Poisson process where interevent times follow a Weibull distribution, is also rejected for all three datasets. Neither an exponential distribution of magnitude nor a Poisson distribution of event rate can be used to assess the stationary seismic hazard due to the anthropogenic seismicity from Oklahoma. For the seismicity cases like in Oklahoma, therefore a new method to approximate event rate distribution, based on the estimation of interevent time distribution and computer simulation of event occurrences from this distribution estimate, is proposed. Regarding magnitude, it is proposed to replace the Gutenberg-Richter relation-led model with nonparametric estimates of the distribution functions. This approach is fully data-driven hence it reproduces correctly the distributions that underlay data. The differences between hazard estimates obtained with the use of the inappropriate probabilistic distributions: exponential for magnitude and Poisson for event rate, and attained from the proposed approach are significant. Results indicate that in anthropogenic seismicity cases hazards assessments should be preceded by tests of conformity of the distribution models, which are to be used, with observations. When the tests turn down any of these models, the approach introduced here should be applied.

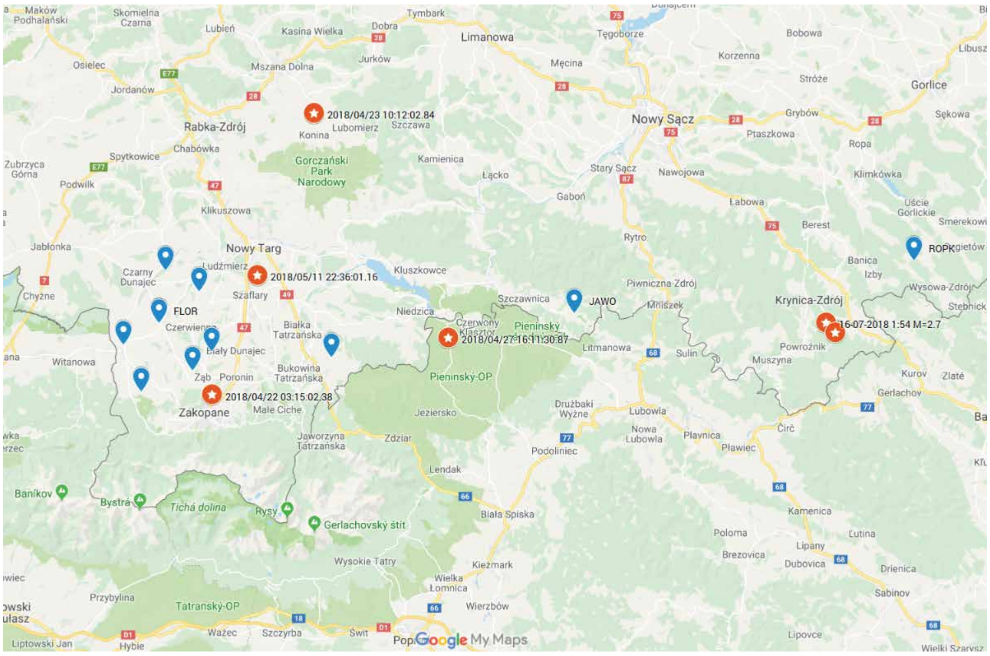


Fig. SI12. Location of six tectonic earthquakes (orange color) with the location of 10 stations (blue) in Podhale and Krynica regions.

Natural seismicity of Poland research was focused on monitoring the activity. After analysing 38 440 hours of continuous recordings and rejection of induced phenomena, six tectonic earthquakes were noticed; four in Podhale and two in the Krynica region. The largest earthquake was ML 3.1. Location of events confirms the Podhale, Pieniny and Krynica region as main tectonic seismicity zones in Poland. List of events with their occurrence time, location and magnitude is given in the table below. Figure NS1 shows the location of six tectonic earthquakes and location of 10 short-term mobile stations in Podhale and Krynica regions.

Region	Date and Time	Lat	Lon	Magnitude
Podhale	2018/04/22 03:15:02.38	49.3186	19.9621	0.5
Podhale	2018/04/23 10:12:02.84	49.6245	20.1322	1.7
Podhale	2018/04/27 16:11:30.87	49.3806	20.3559	3.1
Podhale	2018/05/11 22:36:01.16	49.4488	20.0383	1.0
Krynica	2018/07/15 21:19:44.74	49.3321	21.0260	2.9
Krynica	2018/07/16 01:54:05:67	49.3967	20.9862	2.7

Dynamic triggering of shallow slip on forearc faults | M. Sobiesiak

It is a long standing discussion whether tectonic faults can be triggered to move by earthquakes in the local, regional or global distance range. In the above listed publication, crustal faults in the forearc of the Northern Chilean convergent plate margin using different instrumental components of the IPOC (Integrated Plate Boundary Observatory in N-Chile) were studied. The observations document dynamic triggering on the surveyed faults which can be attributed to triggering by the passage of surface waves from far field earthquakes and by the passage of body waves from seismic events in the near field. With these observations, a magnitude – distance relationship of slip triggering was derived. This observed surface displacement does not occur by continuous creep but through discrete displacement events.

The Iquique Local Network and PicArray | M. Sobiesiak

The Iquique Local Network (ILN) consisted of 14 broad band and 6 additional short period seismological stations around the city of Iquique in Northern Chile. As one instrumental component of the IPOC (Integrated Plate Boundary Observatory in N-Chile), its purpose was to enhance the regional permanent IPOC network to aim at a better resolution for small magnitude events on the crustal faults of the subduction zone forearc as well as on the interface between the downgoing Nazca Plate and the overriding South American Plate. It was installed in this region according to the identification of possible seismogenic structures through gravity field surveys. At a later stage, several stations were newly installed to form an array around the village of Pica in order to monitor seismic events on a deeper part of the subduction interface for studying the interactions between seismogenic zone and the deeper subduction seismicity.

Initialization and development of anthropogenic seismic processes induced by artificial surface reservoirs | G. Lizurek, J. Wiszniowski, B. Plesiewicz, K. Leptokaropoulos

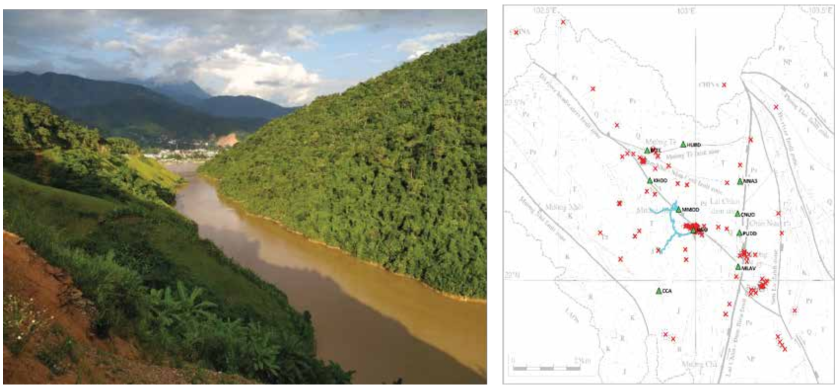


Fig. SI13. River Da which waters are backed up with Lai Chau dam (left, photo: G. Lizurek). Location of tectonic events (red crosses) recorded in the Lai Chau region in the period from October 2014 to June 2015 (right).

The aim of the project is to study the anthropogenic seismicity induced by the filling of water reservoirs (Lai Chau and Song Tranh2) and the assessment of the risks related to this activity. Within the framework of the project close cooperation with Institute of Geophysics Vietnamese Academy of Science and Technology (IGP VAST) is foreseen. In Vietnam, seismological measurements had started before the reservoir in Lai Chau was filled up. It allows exploration of the natural seismicity, which exists in the area of the future dam, and then determination the development of anthropogenic seismic activity associated with the impoundment of water in the reservoir. Measurements are conducted by a dense seismic network consisting of 10 seismic stations located within 20 km from the reservoir. This area is characterized by tectonic seismic activity, therefore there is a high probability to collect appropriate material to study the anthropogenic seismic activity. In 2018 it allowed exploration of the natural seismicity, which exists in the area of the future dam. Location of seismic events several months prior to the reservoir impoundment were calculated with use of the existing seismic network, which finally reached 10 stations in the reservoir vicinity. Events were mainly located near the dam along the Da river headwaters fault (fig. SI13). However, only 4 stations were available for all the period before impoundment. Despite the network limitations completeness of seismic catalogue b-value and its temporal behaviour were determined and can be used as a baseline for further analysis of seismicity in this area. The capability of the local network for moment tensor inversion was also determined with use of synthetic data tests. Test results provided the requirements for the station number according to azimuthal coverage of the network to obtain the reliable full moment tensor (MT) solution. Further measurements are continued in the region of Song Tranh 2, where joint Vietnamese-Polish seismic network recorded more than 5000 seismic events. The improving of the location of events and more accurate determination of the focal mechanisms are the main goals for this region research. Analysis of the magnitude distribution was performed. They covered the multimodality and bump tests for the clusters of seismicity recognized earlier as well as for the whole seismic catalogue available for Song Tranh2. The results show that all analysed datasets magnitude distribution follow an exponential distribution. However, two main clusters are characterised with the low probability of unimodal distribution.

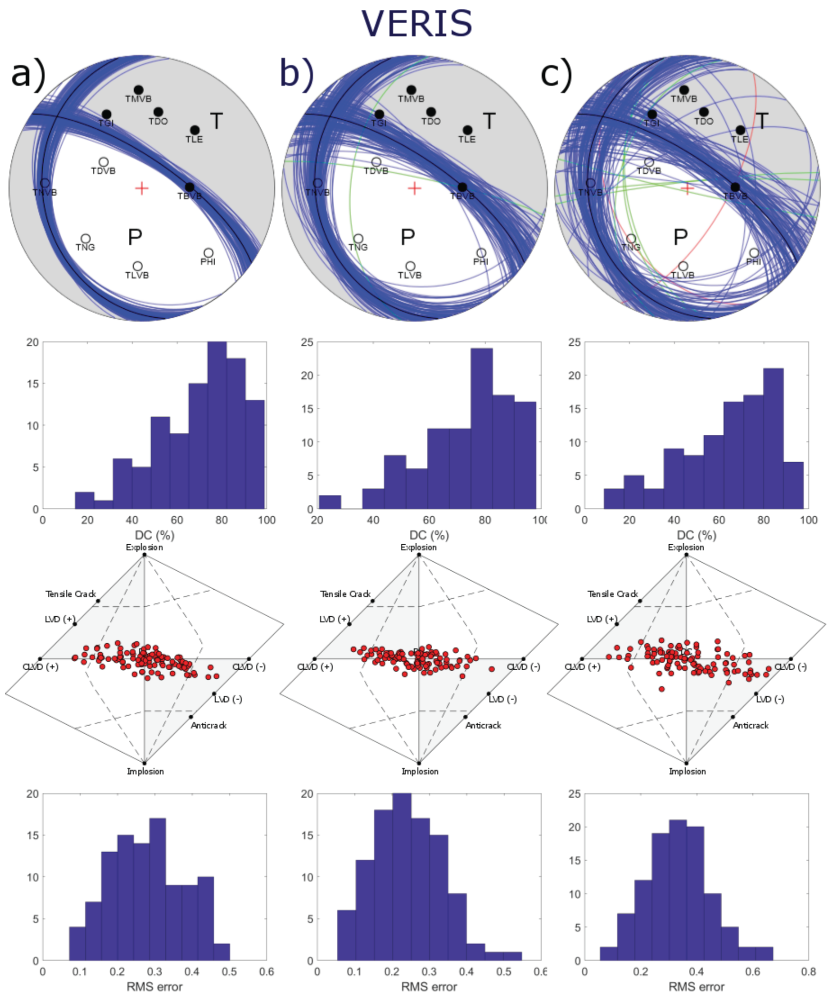


Fig. SI13. Full MT solutions obtained in resampling bootstrap test for VERIS: a) up to 20%, b) up to 40% and c) up to 60% noise contamination.

Another part of this research was aimed at testing the influence of noise on moment tensor inversion results. The sensitivity of the amplitude of P-wave first-motion moment tensor inversion method on noise and focal coverage setups was tested. Three different fault types: normal, thrust and strike-slip geometries of pure shear faulting were used to generate synthetic amplitudes. Then the amplitudes were contaminated with various amount of noise and inversion was performed for eight different focal coverage setups. Test results showed the noise being the main factor of the spurious non-DC components in MT solutions and the nodal planes determination. The best and the worst performing focal coverage setups were identified. Finally, the case study of a seismic network designed for monitoring of seismicity related to Song Tranh2 reservoir seismicity in Central Vietnam was performed. The investigated network performed well in the noise influence tests proving its robustness in MT inversion when the noise level is not higher than 40% of the initial displacement amplitude (Fig. WR2).

Physical properties of seismic sources in connection with regional tectonics | W. Białoń, G. Lizurek

Within this part of research related to reservoir triggered seismicity works upon Czorsztyn lake seismic activity was performed. Czorsztyn lake located in extremely complex geo-technical condition, between border zone of Inner and Outer Carpathians separated by Pieniny Klippen Belt. Before Czorsztyn 2D seismic survey, knowledge of tectonic boundaries and velocities was very limited. The seismic survey confirmed assumptions of flower type faults system and provided first 3D velocity model for this area. Location and moment tensor are crucial in the investigation of the origins of seismogenic process related with industrial operations. Therefore the relocation of the events and validation of the moment tensor solutions for the SENTINELS network were conducted with use of 3D velocity model (fig. SI14).

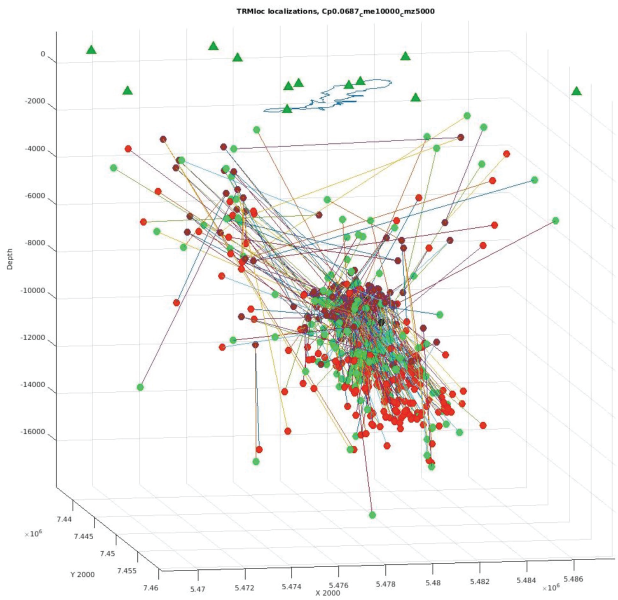


Fig. SI14. North-South cross-section of Czorsztyn lake area with relocated events. Violet dots marking localization form LocSat, green one TRMloc Rml, and red one TRMloc Rav, dark green triangles show station localizations. The line between violet-green and violet-red dots are marking a change in localization. Localization in XY2000 coordinates system.

The validation of the mechanism was conducted with the use of the synthetic tests based on the 1D velocity model derived from the 3D velocity model, taking into account its lateral velocity anisotropy. It was based on the synthetic amplitudes generated with assumed normal and strike-slip faulting similar to the obtained solutions. The validation proved that the focal mechanisms are reliable even in a sparse focal coverage and noise not exceeding 40% of the P-wave amplitude. Most of the events are normal or strike-slip with nodal planes striking NW-SE or NE-SW (fig. SI14).

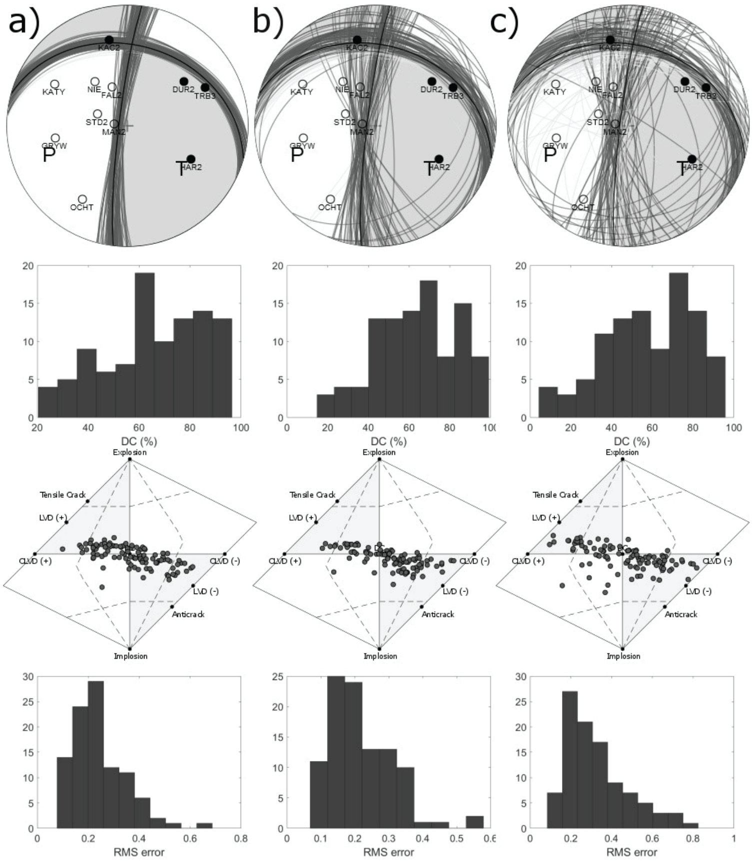


Fig. SI15. Results of the bootstrap noise influence tests of strike-slip fault solutions. From the left noise contamination up to 20%, 40% and 60%.

SERA | M. Sobiesiak, K. Leptokaropoulos, S. Lasocki, P. Sałek

Research activity within the framework of SERA was conducted within the following tasks: WP23 JRA1: Physics of the earthquake initiation.

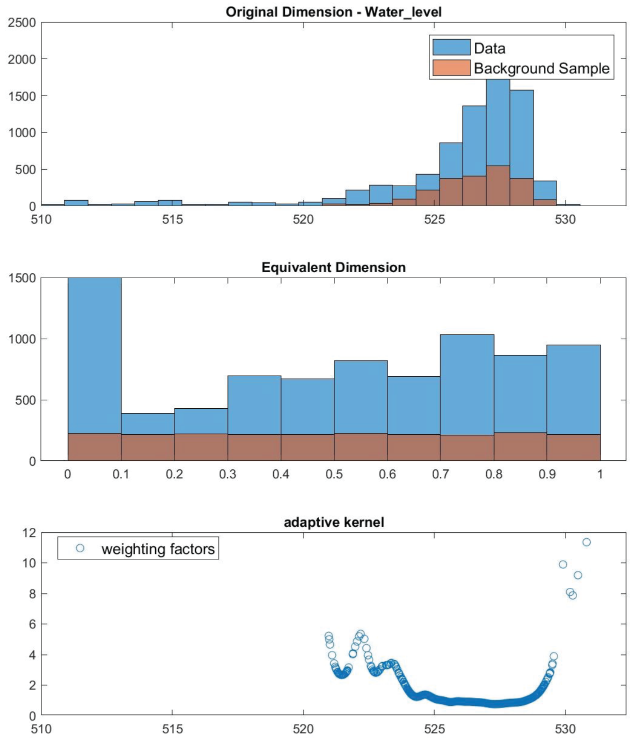


Fig. SI16. Water level changes of the Czorsztyn water reservoir. Top frame: Water level (m) histograms for the entire sample (blue, 1996-2018) and for the selected background sample (brown, 1998-2004). Middle frame: The respective entire and background sample after transformation to equivalent dimensions (ranging within [0,1]). Bottom frame. The corresponding weighting factors of the adaptive kernel.

Observations about the development of seismicity in space and time are crucial in terms of understanding the process of earthquake initiation. One possibility to gain such information is the application of statistical methods to seismicity catalogues to i.e. study seismicity rate changes or the complexity of the magnitude-frequency relation over space and time. The contribution of IG PAS to this issue comprises two toolboxes for the investigation of statistical parameters of seismic catalogues to apply to induced as well as tectonic seismicity. Namely, these are Toolbox for clustering – transformation to equivalent dimensions, Toolbox for magnitude complexity (including the Anderson-Darling test of exponentiation and test for multi-modality). At the moment the implementation of the toolboxes on the IS-EPOS Platform for Anthropogenic Hazard is prepared and is foreseen to be completed in 2019. Figure ES1 shows an example of the transformation to equivalent dimensions of water-level variation in Czorsztyn water reservoir. This image has been realized with Toolbox 1 (clustering and transformation to equivalent dimensions). As seismic catalogues are essential for the above-mentioned studies, the completeness in magnitude ranges and timely availability are important aspects of the quality of any results. Therefore, we are testing the possibility of automated phase detection and location of seismic events for induced seismicity. As a first testing environment, the data sets of Rudna Copper Mine have been chosen to test the performance of the BTBB program (BackTrack BB) which is executing multi-frequency array detection and location of seismic sources. One important feature with this program is the characteristic function (CF) to do the detection of seismic wave first arrivals and which can be defined by the user depending on i.e. frequency content and signal to noise ratio of the wavefield. Three disastrous earthquakes concerning Rudna Mine have been chosen to build a 4 weeks data set around the main shock event respectively in order to account for potential fore- and aftershocks: ML 4.2, 19th of March 2013, Mw 3.4, 29th of November 2016, Mw 3.7, 15th of September 2018. Figure SI17 shows the calculation of the location of the Mw 3.7, 15th of September 2018 event with the probabilistic approach of BTBB software.

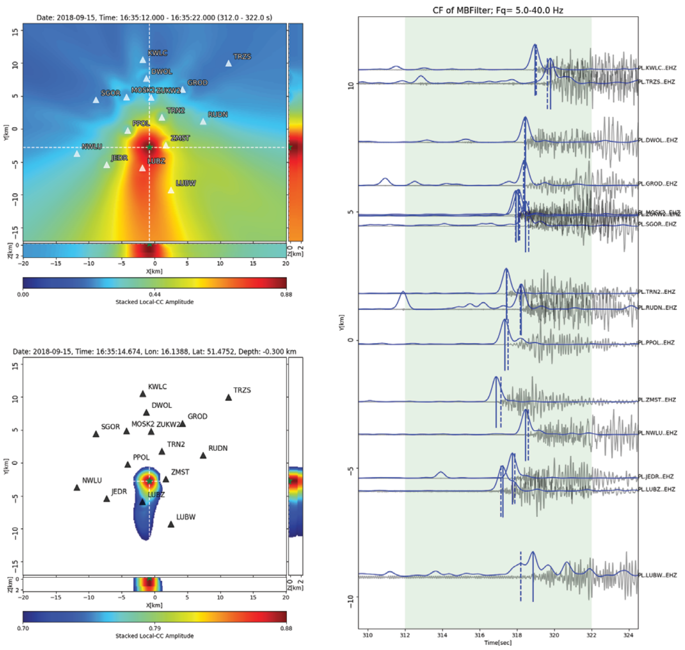


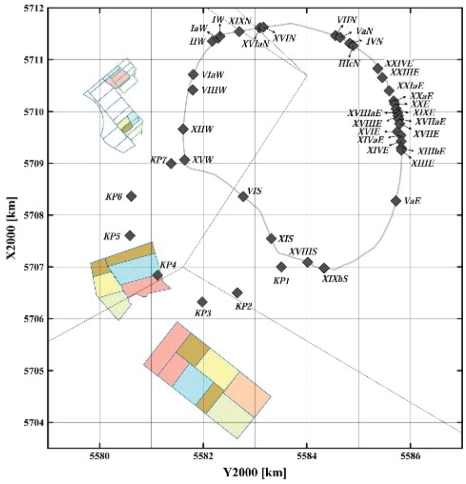
Fig. SI17. P-wave phase detection and location procedure for the Mw 3.7 earthquake of 15th of September 2018 in Rudna Mine. The color coding is due to the probabilistic approach of the locating procedure showing the distribution of the stacked seismogram amplitudes. On the right side, the seismograms at the different stations are shown in grey color. The blue graphs represent the characteristic function for each respective trace.

WP24 JRA2: Characterizing the activity rates of induced and natural earthquakes.

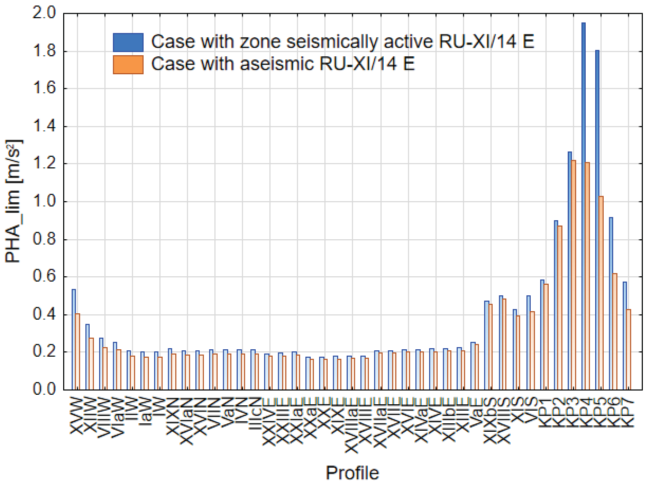
According to the increasing amount of high-quality seismological data and catalogues, the work package aims at an equivalent modernizing of tools for hazard assessment. In addition, evidence of complex magnitude distribution leads to the non-parametric kernel estimation of magnitude probability distribution functions. IG PAS is contributing to this aim with the third toolbox for hazard assessment in induced seismicity environments incorporating time dependency of the hazard process resulting from the temporal variation in production parameters, as well as a variety of parametric and non-parametric magnitude distribution models. This toolbox is already implemented on the IS-EPOS Platform for Anthropogenic Hazard and thus is available to the SERA community. The tool consists of several components which are: Estimation of source parameters in time-varying production parameters geometry, Time-dependent hazard in mining front surroundings, Time-dependent hazard in the selected area.

Prediction of impact of tremors and surface deformations induced by mining in sections G23 O/ZG Rudna and LU XI O/ZG Lubin on OUOW "Żelazny Most" considering its extension | S. Lasocki, B. Orlecka-Sikora

This project was carried out in the years 2017-2018 as part of the scientific research work of the Institute of Geophysics PAS in the framework of the contract No. KGHM-ZH-U-0162-2017 between KGHM Polska Miedź S.A. Hydrotechnical Division, Rudna. The project consisted of two stages. Stage 1 "Continuous Deformations" was produced by a subcontracted team composed from the AGH University of Science and Technology under the activity of the Stanisław Staszic Scientific Association in Krakow. It concerned a prognosis of surface deformations caused by the mining exploitation of a copper ore deposit performed and planned by the Rudna mine and Lubin mine within the range of impact of this exploitation on the Żelazny Most tailings storage facility (TSF) and its planned development-i.e. on the Southern Extension. It was shown that the expected values of deformation rates caused by mining exploitation by the Rudna mine in the area of the western dam of the Żelazny Most TSF should not exceed the permissible values. Similarly, the exploitation in Lubin mine will not cause any significant surface deformations exceeding the permissible values for the dam which will be surrounding the Southern Extension. The second project stage, "Dynamic Impacts" was worked out by the team from the Department of Seismology, Institute of Geophysics PAS, with a help of an expert on rock mechanics from Faculty of Geoengineering, Mining, and Geology, Wrocław University of Technology. In this stage limiting values of the horizontal and vertical components of dynamic impacts on OUOW "Żelazny Most", resulting from the exploitation plans within section G-23 O/ZG Rudna and LU-XI O/ZG Lubin, were predicted. The prediction was carried out by means of the probabilistic seismic hazard analysis in mines on an intermediate scale. Both the geological and mining conditions of the planned exploitation panels, as well as the works' programs in particular parts of these panels, were taken into account. The strongest impacts on the current OUOW earth dams is expected to be due to the future exploitation within section G-23 O/ZG Rudna. The largest limiting values estimates reached 1 m/s2 for the horizontal component of ground acceleration in the frequency band up to 10 Hz and 0.5 m/s2 for the vertical component. The strongest impact on the embankment of the Southern Extension is expected to be due to the exploitation within the section G-8 and G-6 O/ZG Lubin. Depending on which of the two possible ways the seismic process will proceed, it may be expected either up to 1.2 m/s2 for the horizontal component and 0.9 m/s2 for the vertical component or up to 1.95 m/s2 for the horizontal component and 1.4 m/s2 for the vertical component.



The arrangement of points at which limiting impacts have been predicted



Predicted limiting values of peak horizontal acceleration, PHA [m/s2], as a result of the expected seismic activity induced by mining works in sections G23, O/ZG Rudna and G-6 and G-8, O/ZG Lubin. Brown columns - Variant I: - the zone L1, O/ZG Lubin will be aseismic. Blue columns - Variant II: - the zone L1, O/ZG Lubin will be seismically active.

Fig. SI18. Results of the PHA analysis.

Horizontal-to-vertical spectral ratio variability in the presence of | D. Olszewska

This work is an example of using the HVSR method. This method is one of the most well-known techniques used in engineering seismology for recognition of site effect. The permafrost and its active layer exhibit characteristics and morphological features common to the polar areas. The low population density of these regions does not detract from the importance of permafrost studies, as they are relevant to permafrost engineering and to environmental research such as studies on increased methane emissions. Due to the high resistivity contrast between frozen and thawed geological media, direct current (DC) resistivity methods are frequently used in permafrost studies, and the employment of Electrical Resistivity Tomography (ERT) is currently standard practice. Also common in permafrost geophysics is the use of seismic methods, which are suitable for studying the permafrost table as it shows a high contrast in shear wave velocity (Vs). Of these methods, the horizontal-to-vertical spectral ratio (HVSR) was chosen for the purpose of this study. This project applies a methodology that uses seismic noise to calculate horizontal-to-vertical ratio curves (H/V curves). Seismic noise is a complex phenomenon as it is a combination of both natural and artificial signals. However, the statistical features of seismic noise are essentially time-independent. Furthermore, HVSR is also nearly time-independent in terms of both the frequency and amplitude of H/V peaks. This study aims to investigate the reliability of the HVSR method in the presence of permafrost. In addition, it assesses whether the HVSR method can be used to estimate the thickness of the active layer of the permafrost. For the purposes of the H/V ratio investigation, use was made of a data set compiled at the seismic station near the Polish Polar Station, Hornsund (station code: HSPB). The results of the analysis are presented with reference to air and ground temperatures and in comparison with electrical resistivity tomography measurements conducted nearby.

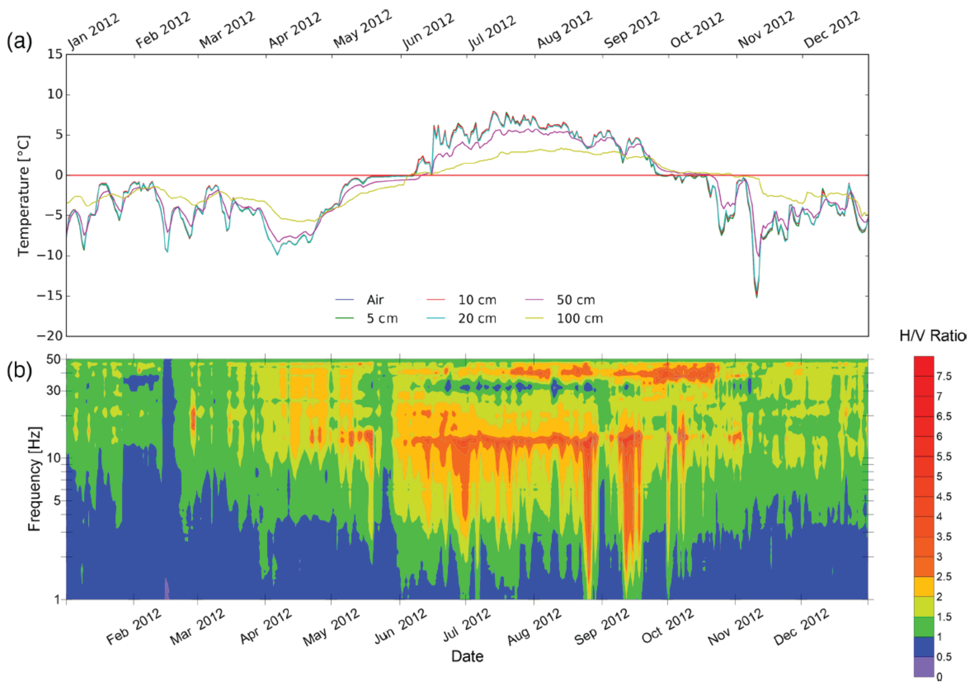


Fig. SI19. Mean daily temperatures of air and ground measured at 5, 10, 20, 50, 100 cm (a) versus variability of H/V value (b) in 2012.

The analysis was done using the seismic measurement from 2012 to 2015. The example of the result is shown on fig. ES4. The bottom panel of fig. ES4 shows the variability in HVSR curves during the course of 2012. Data samples were taken daily from 09:00 to 15:00. The whole year can be divided into three parts. The first part lasts from the beginning of the year until mid-May. In this period, the value of the H/V curve barely exceeds 2, the only exceptions being a few narrow peaks around 15 Hz. From June to November, an area of H/V curve values is visibly higher than the corresponding values observed at the beginning and the end of the year. There is a clearly visible local maximum at approximately 13 Hz, extending to lower frequencies. A significant drop in the H/V values at approximately 30–35 Hz appears in late June, fading out in September. Moreover, one more local maximum is evident at frequencies of approximately 40 Hz between late July and mid- October. The period from November until the end of the year is similar in terms of values to the beginning of the year. As a result, the variability in the HVSR curve can also be divided into winter and summer seasons. The H/V ratio fluctuations correlate well with the observed air and ground temperatures (Fig. SI19). A visible minimum can be observed at a frequency of approximately 30–35 Hz at the start of the thawing process. A maximum at an even higher frequency (40 Hz) becomes visible in mid-July. The fadeout of this maximum correlates well with a temperature drop to below 0 °C. The overall increase of the H/V value during the summer season may be connected to the above-mentioned temporary increase in human activity that occurs at this time. The results of this study showed fluctuations in the H/V ratio at the Arctic site over the course of a year. These variations correlate well with the increases in ground temperatures (above 0 °C). The first peak, observed at approximately 12 Hz on the H/V curves obtained, is more likely to have been caused by a deeper impedance contrast than by the depth of the permafrost table. This maximum is continuous throughout the summer season. During the rest of the year, it is non-continuous and its occurrence correlates with increased average wind velocity in the area. The second maximum occurs at around 35–45 Hz and is thought to be linked to an impedance contrast at the permafrost table. It is worth noting that this frequency range is beyond that which geoscientists and engineers generally consider when using the HVSR method. This second peak is not always present in data from previous years. The sampling frequency of the seismometer is 100 Hz, which gives a Nyquist frequency equal to 50 Hz. Furthermore, the frequency range of the seismometer is between 120 s and 50 Hz. All these features mean that the second peak is on the edge of a spectrum that can be recovered with hardware used at the HSPB seismic station. The HVSR curve inversion provided useful and expected results. No peaks are present in the curves during the winter season, which enables a wide range of velocity models to fit the curve. On the other hand, two peaks were obvious in the curves obtained during the summer season, and consequently, the inversion provides a velocity model where the range of possible combinations narrows near the surface and widens with depth. The depth at which a velocity increase occurs fits the depth of the boundary between the low and high-resistivity layers (inferred from the ERT results). The first increase in shear wave velocity is visible at 1.5–2 m in. This depth correlates well with ERT results, which show a low-resistivity layer 1.5–2 m thick. The low Vs and low resistivity that characterize the first layer correspond closely to in situ observations. They also reflect the geophysical characteristics of the permafrost active layer. The HVSR method is claimed to be stable over time. However, this study shows that under specific circumstances, such as in the presence of permafrost and in its active layer, the H/V ratio does change over time, and the changes correlate with the thawing of the ground. Due to the lower power of high frequencies during the winter, it was impossible to identify other features such as deeper impedance contrasts that may be present throughout the year.

A study of site effect using surface-downhole seismic data in a mining area

| D. Olszewska

The aim of this study is to examine the phenomenon of site effect using surface -downhole seismic data caused by mining tremors in the Upper Silesia Coal Basin (USCB). The USCB is located in southern Poland and as a consequence of underground mining operations about 1000 mining tremors occur annually with a local magnitude of ML≥1.5. The strongest event which occurred on 09.02.2010 reached ML=4.2 and the peak ground acceleration (PGA) observed was approximately – 2 m/s2. Induced events which can be treated as minor shallow earthquakes also have an impact on the surface. Thus, monitoring of ground motion is carried out and provided by the Central Mining Institute in this area – the Upper Silesian Seismological Network USSN (data are available as "episode USCB" on the IS-EPOS platform at https://tcs.ah-epos.eu/). The network for ground motion monitoring is equipped with 7 free-field surface triaxial accelerometers GeoSIG AC-63 and 2 downhole accelerometers GeoSIG AC-63DH located in 30 m deep boreholes. Thanks to that, 2 sites with surface and downhole ground motion measurements (Imielin and Miechowice) are available. The accelerations caused by seismic events during the time period Jan 2014 up to Jun 2017 were used in the analysis. The magnitude of the registered events varies from 2.3 up 4.1. The PGAs registered by surface stations were up to 0.37 m/s2. A mean shear velocity up to 30 m is equal to 423 m/s at the Imielin site and 352 m/s at the Miechowice site. These give the ground types B at the Imielin site and C at the Miechowice site – according to the European Standard 'Eurocode 8: Design of structures for earthquake resistance (Part1)' (Eurocode:8). The amplification factors in the time domain were calculated as a ratio of the surface and downhole PGA at Imielin and Miechowice stations. That factors were obtained for NS, EW and merged horizontal components and for the vertical one. The greatest amplification factor was obtained for the Miechowice site for the NS horizontal component (6.7). The Imielin amplification factors were around 2.1 - 2.4, only the value for the EW component was slightly greater (2.68). The greatest amplification factor was obtained for the Miechowice site for the NS horizontal component (6.7). In the next step of the analysis, the surface-downhole spectral ratios (SR) were calculated using data from Imielin and Miechowice stations. That is the transfer function (TF) between a depth of 30 m and the surface, which shows how components are amplified by this layer in the frequency domain. Calculations were done for NS, EW, and the merged horizontal component and the vertical one; likewise, a calculation of amplification factors was done. The shape of TF curves for Imielin and Miechowice differ in the number of local maximum and its frequencies. That result shows also the differences for NE-SW orientation. Therefore more detailed analysis should be performed in the future to check whether this effect is caused by anisotropy or other phenomena. The SR variability for the Imielin site is less than for the Miechowice site. That could be the effect of site characteristic or the number of analysed data (no of events registered by the Imielin site is 273 and the Miechowice only 57). Therefore this analysis should be repeated in the future when more usefully data from the Miechowice site will be available. HVSR was used for estimating the amplification for the Miechowice and Imielin sites. This method is based on surface measurements only. Thus, records from surface stations are used in this part of the analysis. Fig. SI20 compares the TF obtained from the above analysis and the HVSR curves. The merged horizontal components (surface and downhole) were used for this comparison – HHSR (Horizontal to Horizontal Spectral Ratio). As can be seen from that figure, there is satisfactory compatibility between the graphs for the Imielin site, compared to Miechowice site. The Imielin HVSR curve has also three main local maximums found in the same frequency as the HHSR curve. The amplitudes of the HVSR peaks is almost two times smaller than the HHSR peaks. Taking into account the Miechowice site, the HVSR and HHSR curves vary in the numbers of local maximums and their frequencies. From the graph below we can see that more comparable to the HVSR curve is the HHSR curve calculated for an epicentral distance above 10 km (dark blue line in fig. SI20).

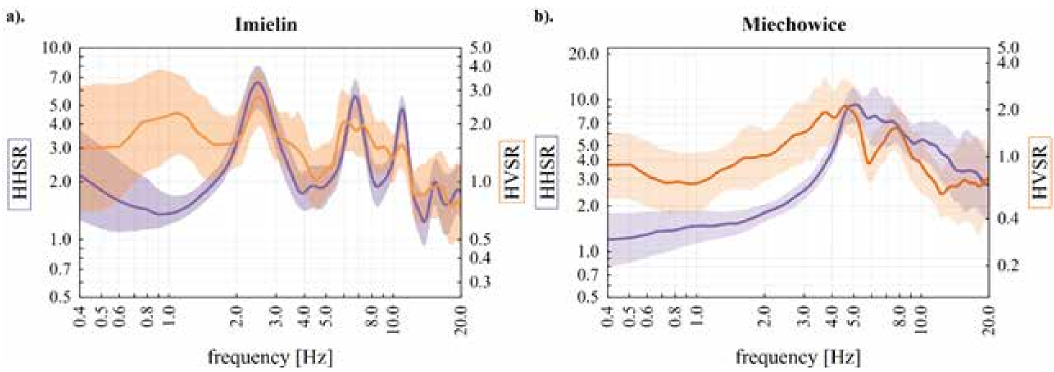


Fig. SI20. A HHSR and HVSR at Imielin (a) and Miechowice (b) stations.

In this work, the amplification factors were calculated for the Imielin and Miechowice sites. Thanks to a comparison of the obtained results and profiles of shear waves up to 30 m. characteristic of both sites were examined. The obtained result shows that the surface layer can play an important role in the amplification of ground motion. The geological structure and therefore a shear mean velocity up to 30m are correlated with the amplification factor. Transfer functions of both components were calculated using surface and downhole data. Amplification behaviour of surface waves by the surface layer may differ from the corresponding body wave amplification. In the case of induced seismicity, the body waves are mostly recorded – the epicentral distances are too small that surface waves could be observed. However, surface waves could also be observed, in the case of events with greater magnitudes, at a depth of up to 1 km and an epicentral distance to the stations greater than 3 km. The obtained result shows that the distance between the event and the station is important in the case of induced events. The amplification factor is significantly different for shorter distances than for longer ones. Additionally, the characteristics of transfer function calculated for registration caused for short distances differ from those that are longer. Nevertheless, additionally study are needed to confirm that the main reason for such a situation is the fact that for such short distances, surface waves are not registered. This phenomena could be also caused by incidence angle or back-azimuth. The HVSR curves were calculated and the results were compared with suitable transfer functions. These results show that the HVSR method could be used for estimating site effect in the case of induced seismicity.

Seminars and teaching

Seminars and lecture outside of the IG PAS

- Rudziński | *Complex mechanism of rockbursts observed on Polish Copper Mines.* | Invited lecture
  Oulu University | Oulu, Finland

- Lizurek | *Introduction to EPOS AH Platform* | Invited lecture
  Oulu University | Oulu, Finland

- Leptokaropoulos | *Properties of induced seismicity and its connection to fluid injection: The NW The Geysers geothermal field case study* | Seminar
  Aristotle University of Thessaloniki | Thessaloniki, Greece

Visiting scientists

- S. Dineva | Luleå University of Technology | Luleå, Sweden
- T. Ishida | Kyoto University | Kyoto, Japan
- J. Martinsson | LKAB | Malmberget, Sweden
- V. Tornman | LKAB/Luleå University of Technology | Kiruna/ Luleå, Sweden

Meeting, workshop conferences and symposia

European Seismological Commision | Valetta, Malta

Cielesta Sz., Orlecka-Sikora B. | *Seismic response and fracture growth due to fluid injection* | oral

Lizurek G., Wiszniowski J., Giang NV, Plesiewicz B., and Dinh Quoc Van. | *Moment tensor and stress inversion derived from anthropogenic seismicity in the Song Trahn 2 Reservoir, Vietnam* | oral

Olszewska D., Lizurek G., Mutke G., Kryński J., Rohm W., Araszkiewicz A., Barański A. | *Multidisciplinary Upper Silesian Episode as a new holistic approach in building research infrastructure* | poster

Blanke A., G. Lizurek, G. Kwiatek, P. Urban, B. Orlecka-Sikora, S. Lasocki, J.-R. Grasso, A. Karimov, M. Schaming, A. Fremand, J. Schmittbuhl, P. Bigarre, J.-L. Kinscher, A. Garcia, G. Saccorotti, P. Roselli, J. Nevalainen, E. Kozlovskaya, S. Toon, J. Pringle, J. Kocot, M. Sterzel, T. Szepieniec. | *Integration of anthropogenic seismicity data within the EPOS Implementation Phase (EPOS-IP) to encourage interdisciplinary research and collaboration* | poster

Haslinger Florian, Bailo Daniele, Cippoloni Carlo, Danciu Laurentiu, Aurelien Dupont, Elger Kirsten, Grellet Sylvain, Häner Rainer, Heaven Rachel, Hoffmann Thomas, Lange Otto, Litwin Prestes Mateus, Lizurek Grzegorz, Locati Mario, Lorenz Henning | *What are You talking about? Towards harmonizing and formalizing vocabularies within seismology and beyond* | oral

Paradisopoulou, P., C. Gkarlaouni, G. Spyrou, A. Panou, A. Adamaki, and K. Leptokaropoulos | *Impact of friction coefficient and fault parameters variation on Coulomb stress change analysis* | poster

European Geosciences Union | Wien, Austria

Sobiesiak M., S. Lasocki, B. Orlecka-Sikora, K. Leptokaropoulos, J. Kocot. and P. Urban | *Developments on the IS-EPOS Platform for Analyzing Anthropogenic Hazard* | oral

Sobiesiak M., K. Leptokaropoulos | *IS-EPOS: Development, Current Status and Future Challenges, Demonstration of the IS-EPOS platform at the EPOS booth* | oral

Victor P., O. Oncken, M. Sobiesiak, M. Kemter | *Remote triggering of forearc faulting – surface displacement along the Atacama Fault System monitored with the IPOC Creepmeter Array (N-Chile)* | poster

Lasocki, S., Urban, P | *Incompatibility of anthropogenic seismicity with probabilistic models typically used in seismic hazard analysis: the case of Oklahoma earthquakes* | oral

Adamaki, A., K. Leptokaropoulos, C. Gkarlaouni, and P. Paradisopoulou | *The impact of magnitude errors on basic catalogue properties investigated numerically with synthetic magnitude catalogues* | poster

Orlecka-Sikora, B., Lasocki, S. | *Seismic response and fracture growth due to fluid injection* | oral

Seminar of The Institute of Mine Seismology | Johannesburg, South Africa

Dineva S., Rudziński Ł., Mihaylov D., Lund B. | *Source Parameters of Seismic Events in Underground Mines from Regional Data and In-mine Seismic Systems: Examples from Swedish and Polish mines* | oral

SHEER final meeting | Kraków, Poland

Cielesta Sz. | *WP3 - Monitoring of environmental effects of shale gas operations - lessons learned from Wysin study* | oral

Lizurek G., Orlecka-Sikora B. | *SHEER database, SHEER Final meeting* | oral

Leptokaropoulos, K., S. Lasocki and B. Orlecka-Sikora | *Some advances in the assessments of hazards related to injection-induced seismicity, obtained in SHEER project* | oral

7th EAGE Workshop on Passive Seismic | Kraków, Poland

Cielesta, S., S. Lasoski, K. Leptokaropoulos, and S. Cesca | *The SHEER approach to shale gas exploration and exploitation associated risks* | poster

Leptokaropoulos, K., and A. Adamaki | *Uncertainty of b-value estimation in connection with magnitude distribution properties of small data sets* | oral

Orlecka-Sikora, B. | *Step-change in Tackling Grand Challenges of Seismic Hazard Associated with Exploitation of Geo-resources* | oral

65th IG-PAS Anniversary | Warszawa, Poland

Leptokaropoulos, K. et al. | *Leadership of the design, development and management of integration of research and infrastructures of anthropogenic seismicity in Europe and beyond* | oral

COST Action TIDES Workshop on: "Induced Seismicity: from the monitoring of non-stationary processes to the definition of performance-based mitigation strategies" | Bologna, Italy

Orlecka-Sikora, B., M. Staszek, S. Lasocki, K. Leptokaropoulos, G. Kwiatek, and S. Cielesta | *Static stress drop of induced earthquakes in seismic hazard assessment, Induced Seismicity: from monitoring of non-stationary processes to definition of performance-based mitigation strategies* | oral

Leptokaropoulos, K., and the IS-EPOS and EPOS-IP teams | *IS-EPOS: Development, current status and future challenges, Induced Seismicity: from monitoring of non-stationary processes to definition of performance-based mitigation strategies* | oral

Lasocki S. | *Seismicity and its relation with industrial factors, studied with the use of equivalent dimension approach. Assessments of fluid migration pathways buildup* | oral

SERA JRA1/ JR2 Joint Workshop | Kraków, Poland

Leptokaropoulos, K., M. Sobiesiak, and S. Lasocki | *Introduction to Clustering Toolbox and Magnitude Complexity Toolbox* | oral

Leptokaropoulos, K. | *Hands on Clustering Toolbox and Complexity Toolbox – on-line demonstration* | oral

Lasocki S. | *Influence of injection rate on ordering of induced seismic sources* | oral

Workshop: "Development of criteria for temporary closing/re-opening of seismically active mines due to seismic risk" | Luleå, Sweden

Leptokaropoulos, K., S. Lasocki and S. Dineva | *Characteristics of Kiruna mine seismicity (Block 34) in space-time-size domain and its relation to blasting activities* | oral

Kozłowska M. | *Model for estimating the spatio-temporal behavior of seismic activity after strong seismic events (Kiruna mine)* | oral

I konferencja projektu EPOS-PL „EPOS-System Obserwacji Płyty Europejskiej" | Jachranka, Poland

Grzegorz Lizurek | *Od integracji infrastruktury badawczej i danych pomiarowych do publikacji artykułu naukowego na przykładzie badań sejsmiczności wywoływanej eksploatacją zbiornika wodnego Song Tranh w Wietnamie* | oral

Orlecka-Sikora, B. | *Step-change in Tackling Grand Challenges of Seismic Hazard Associated with Exploitation of Geo-resources - Thematic Core Service Anthropogenic Hazards* | oral

GIS w nauce | Warszawa, Poland

Tymków, P., Guźniczak, Ł., Karpina, M., Kocot, J., Szepieniec, T., Sterzel, M., Urban, P., Kura, K. | *Prezentacja wybranych danych przestrzennych i produktów projektu EPOS – System Obserwacji Płyty Europejskiej w środowisku GIS 3D* | oral

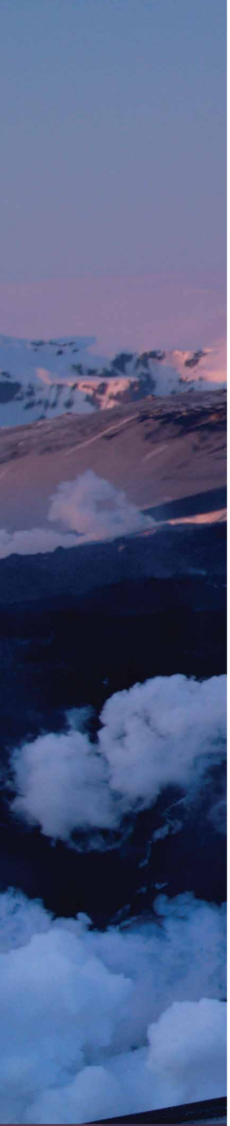
Science 4 Clean Energy, 1st Annual Consortium Meeting | Reykjavik, Iceland

Lasocki S. | *Studies of influence of injection rate on ordering of induced seismic sources, WP6 Implementation of Novel Technologies, Task 6.5 Assessing rapid fluid transport probability and tracking fluid pathways in the rockmass* | oral

Lasocki S. | *S4CE Database on IS-EPOS Platform, WP9 Dissemination, Exploitation and Innovation, Task 9.7 S4CE Database on IS-EPOS Platform* | oral

SHEER, Final Review Meeting | Brussels, Belgium

Lasocki S. | *WP3 On-site monitoring* | oral



Publications

Monika Sobiesiak, 2018, Dynamic triggering of shallow slip on forearc faults constrained by monitoring surface displacement with the IPOC Creepmeter Array; EARTH AND PLANETARY SCIENCE LETTERS

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