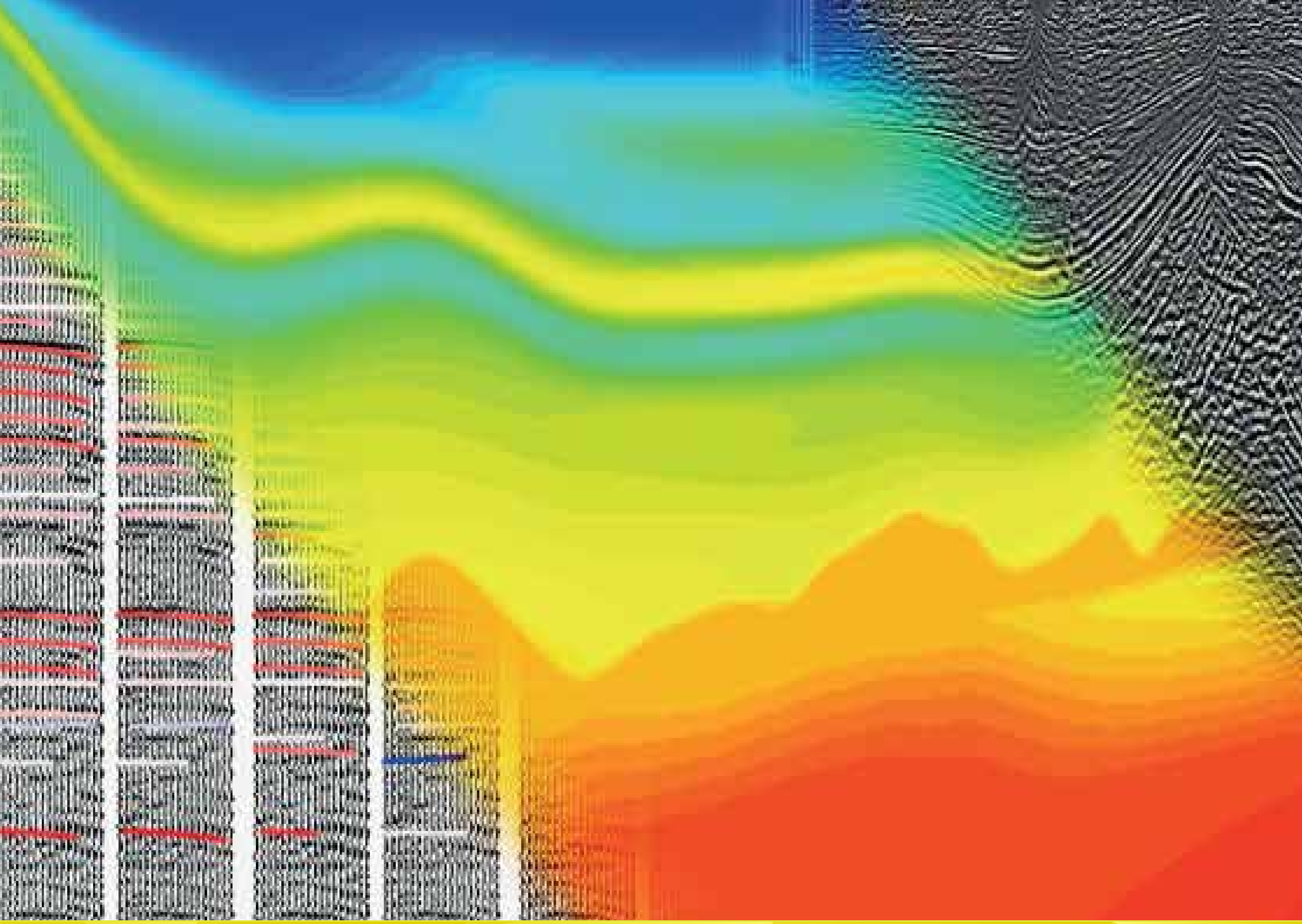

Department of the Geophysical Imaging

About

Department activities in 2018 were traditionally split between the two groups. The first one was focused on the geophysical imaging of geological structures in various scales; the second on the mathematical analysis of complex system in geophysics. The scale of applications ranged from near-surface to the deep crust. We have been working towards solving some fundamental research questions like the structure of the crust in NE Poland from reprocessing of the PolandSPAN regional profiles or structure of the crust within the Nankai Trough seismogenic zone in Japan, employing innovative methods like full-waveform inversion (FWI). We finalized seismic/borehole measurements in Hornsund (Sptisbergen) in a project devoted to studying the temporal changes of the permafrost layer. In another Arctic-related project, we successfully collected passive seismic data from the temporary seismic network operating on the Hans glacier (Hornsund). Near-surface seismic field measurement were also performed for solving geological problems at various locations (mostly in the Holy Cross Mts.), validating our methodology. Another area is related to more applied research within the broader scope of sustaining the raw material supply for Europe by supporting mineral exploration. This year we finished the COGITO-MIN project, in which together with partners from Finland, we have been developing active/passive seismic methods for mineral exploration using the data acquired in the Kylylahti area (Outukumpu mineral belt, Finland). This topic is further being developed in the framework of the EU-funded H2020 Research and Innovation Action project called "Smart Exploration", in which we aim to improve seismic imaging by the use of FWI. We also keep working on the methodology for characterization of the unconventional reservoirs (shale gas bearing), both using the active source seismic, as well as microseismic data. This year, a special section of the SEG "Interpretation" journal was published devoted to "Characterization of potential Lower Paleozoic shale resource play in Poland", in which we contributed with 4 papers. The "theoretical" group was working towards the construction of a universal model in the form of a stochastic cellular automaton integrating fundamental empirical laws describing statistical properties of earthquakes and enabling the study of the relationship between these laws. The biggest organizational achievement this year was the 18th edition of the biennial International Symposium on Deep Seismic Profiling of the Continents and their Margins (SEISMIX 2018), which was held in Kraków between 17-22 June.

Personel

Head of the Department
Michał Malinowski
Associate Professor

Mariusz Majdański
Associate Professor

Mariusz Białecki
Associate Professor

Andrzej Górszczyk
Assistant Professor

Marta Cyz
Research Assistant

Brij Singh
Geophysicist/Research Assistant

Jacek Trojanowski
Research Assistant

Research Project

- Linking deep and shallow geological processes in the transition from Precambrian to Palaeozoic platform in the southern Baltic Sea using new geophysical data.
  M.Malinowski | NCN | 2018 -2021
- Crustal structure of the East European Craton margin in northern Poland based on the new geophysical data.
  M.Malinowski | NCN | 2016 -2019
- Three dimensional model of the lithosphere in Poland with verification of seismic parameters of the wave field.
  M.Majdański | NCN | 2016 -2019
- Relationship of permafrost with geomorphology, geology and cryospheric components based on geophysical research of the Hans glacier forefield and its surroundings. Hornsund, Spitsbergen.
  M.Majdański | NCN | 2017 -2019
- Mechanistic explanation of a generation of (and deviations from) the universal curve of the Earthquake Recurrence Time Distribution by means of constructions of solvable stochastic cellular automata and their analytical description.
  M.Białecki | NCN | 2018 -2021
- COst-effective Geophysical Imaging Techniques for supporting ongoing MINeral exploration in Europe(COGITO-MIN).
  M.Malinowski | NCN | 2016 -2018
- Sustainable mineral resources by utilizing new Exploration technologies (SMART EXPLORATION).
  M.Malinowski | NCN | 2017 -2020
- Determining structure and physical properties of the crust in the Nankai Trough area (Japan) using multiparameter full-waveform inversion.
  A.Górszczyk | NCN | 2016 -2018

PhD Students

Michał Chamarczuk | Poland
supervisor: Michał Malinowski

Wojciech Gajek | Poland
supervisor: Michał Malinowski

Miłosz Mężyk | Poland
supervisor: Michał Malinowski

Quang Nguyen | Vietnam
supervisor: Michał Malinowski

Brij Singh | India
supervisor: Michał Malinowski

Artur Marciniak | Poland
supervisor: Mariusz Majdański

Bartosz Owoc | Poland
supervisor: Mariusz Majdański

Arpan Bagchi | India
supervisor: Mariusz Białecki

Silvana Magni | Italy
supervisor: Mariusz Białecki

Rishabh Sharma | India
supervisor: Mariusz Białecki

Instruments and facilities

- 40 x DATA-CUBE seismic recorders with 1C 4.5 Hz geophones
- 20x DATA-CUBE seismic recorders with 3C 4.5 Hz geophones
- Seismic source PEG-40 with carriage and timing system

Laboratory

- Facilities for seismic data processing, imaging, modelling and interpretation including local InfiniBand cluster, GPU Workstation and NAS data storage systems; Industry state-of-the art software, such as ProMAX, Globe Claritas, TSUNAMI, VISTA, OMNI3D, Petrel, Kingdom Suite, GOCAD, Hampson Russell + in-house and academic software

Research activity and results

Imaging East European Craton margin in Northern Poland using extended-correlation processing applied to regional reflection seismic profiles | M. Malinowski, M. Mężyk

In NE Poland, the Eastern European Craton (EEC) crust of the Fennoscandian affinity is concealed under a Phanerozoic platform cover and penetrated by the sparse deep research wells. Most of the inferences regarding its structure rely on geophysical data. Until recently, this area was covered only by the refraction/wide-angle reflection (WARR) profiles, which show a relatively simple crustal structure with a typical cratonic 3-layer crust. ION Geophysical PolandSPAN™ regional seismic program, acquired over the marginal part of the EEC in Poland, offered a unique opportunity to derive a detailed image of the deeper crust. Here, we apply extended correlation processing to a subset (~950 km) of the PolandSPAN™ dataset located in NE Poland, which enabled us to extend the nominal record length of the acquired data from 12 to 22 s (~60 km depth). Our new processing revealed reflectivity patterns, that we primarily associate with the Paleoproterozoic crust formation during the Svekofennian (Svekobaltic) orogeny and which are similar to what was observed along the BABEL and FIRE profiles in the Baltic Sea and Finland, respectively. We propose a mid- to lower-crustal lateral flow model to explain the occurrence of two sets of structures that can be collectively interpreted as kilometre-scale S-C′ shear zones. The structures define a penetrative deformation fabric pointing out to ductile extension of hot orogenic crust. Subsequent, localized reactivation of these structures provided conduits for subsequent emplacement of gabbroic magma that produced a Mesoproterozoic anorthosite-mangerite-charnockite-granite (AMCG) suite in NE Poland. Delamination of overthickened orogenic lithosphere may have accounted for magnatic underplating and fractionation into the AMCG plutons. We also found sub-Moho dipping mantle reflectivity, which we tentatively explain as a signature of the crustal accretion during the Svekofennian orogeny. Later tectonic phases (e.g. Ediacaran rifting, Caledonian orogeny) did not leave a clear signature in the deeper crust, however, some of the subhorizontal reflectors below the basement, observed in the vicinity of the AMCG Mazury complex, can be alternatively linked with lower Carboniferous magmatism.

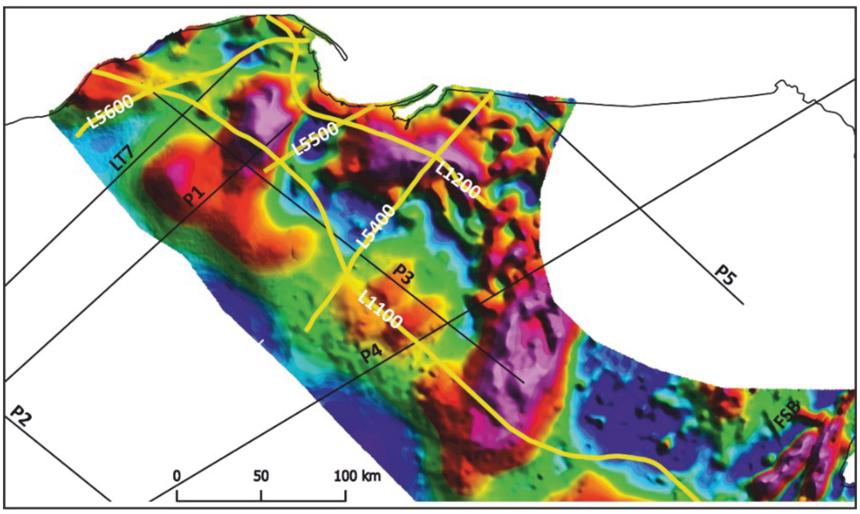

Figure 1: Location of the PolandSPAN™ seismic profiles on the background of a total magnetic field anomaly map of NE Poland (reduced to pole) (data compilation of S. Mazur).

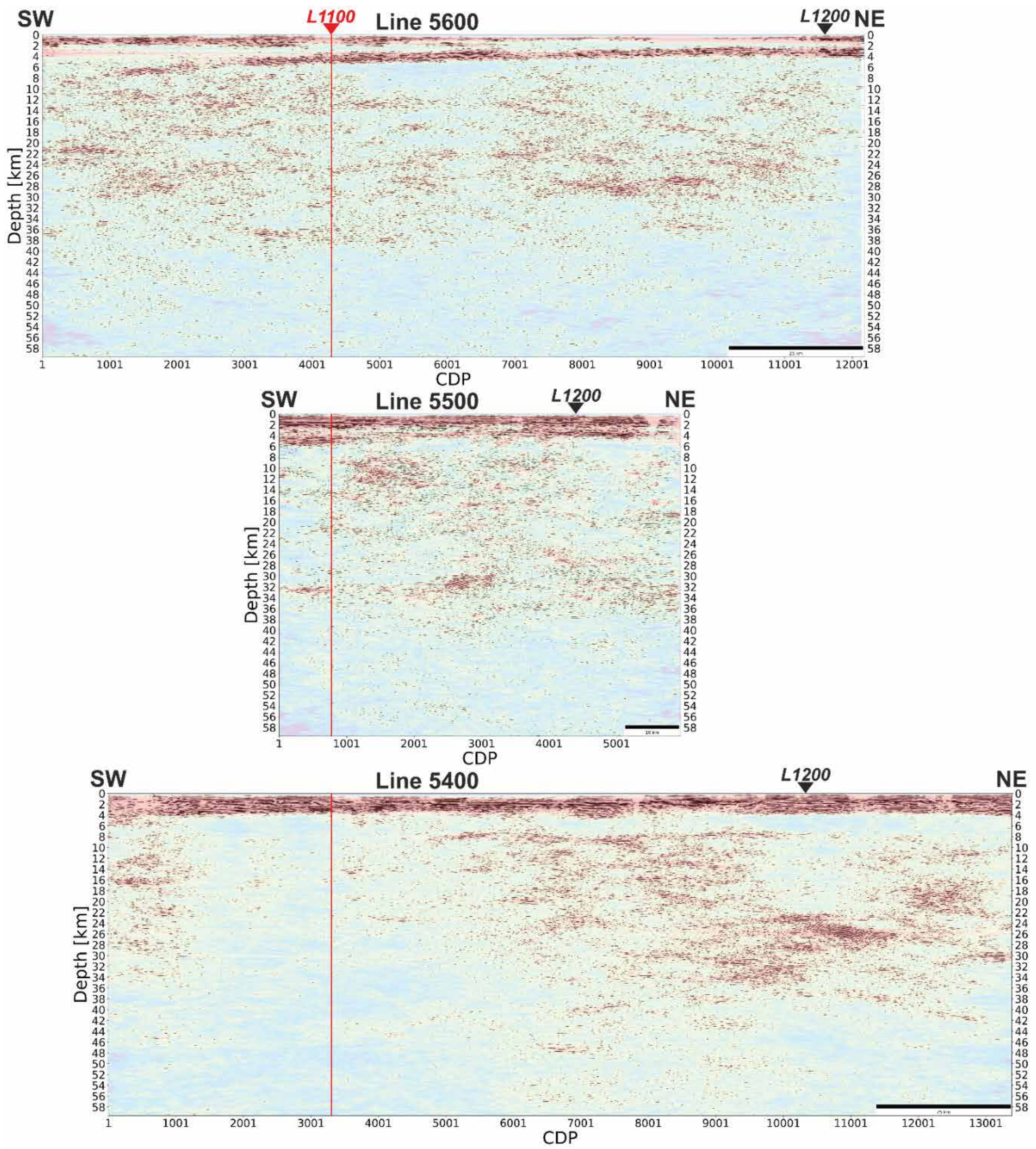

Figure 2: Final migrated depth-converted section along PolandSPAN™ profiles 5600, 5500 and 5400 (envelope and amplitude combined plot). Profiles are centered at the intersection with line 1100 (vertical red line).

Deriving COst-effective Geophysical Imaging Techniques for supporting ongoing MINeral exploration in Europe (COGITO-MIN) | M. Malinowski, M. Chamarczuk, B. Singh

In 2016, the COGITO-MIN project acquired new types of active and passive seismic data at the Kylylahti sulphide mine site in Eastern Finland (Fig. 1). Kylylahti is situated within the historical Outokumpu ore district that hosts polymetallic Cu Co Zn Ni Ag Au semimassive-to-massive sulphide deposits. Overall, the new experiments consisted of a 2D seismic survey, sparse active-source and passive 3D seismic surveys, as well a VSP survey partly utilizing novel fibre-optic Distributed Acoustic Sensing (DAS) technology. The experiments were designed with different stages of the exploration workflow in mind; from mapping of the ore host rocks at larger scale to high-resolution resource delineation.

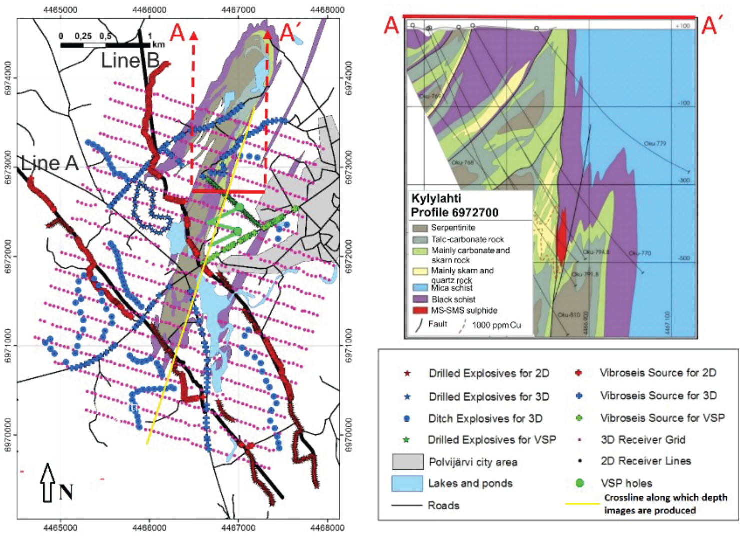

Figure 1 Acquisition geometry of the COGITO-MIN 3D seismic survey (left). A-A′ is cross-section through the Kylylahti deposit (right) (from Kontinen et al., 2006). Yellow li marks the crossline position intersec the ore zone, shown in Figure 3.

The COGITO-MIN 3D experiments (Fig. 1) included a passive seismic survey in which 1000 one-component wireless receivers recorded ambient noise for a month. The receivers were deployed in a 3.5 x 3 km grid, with 200 m line spacing and 50 m inline receiver interval. The aim was to test and develop a cost-effective method for mapping the continuity of the ore host rocks through the application of body-wave seismic interferometry (SI). In the COGITO-MIN project, Chamarczuk et al. (2017, 2018) have developed a new workflow (called MESI) for processing such data acquired in the crystalline rock terrain. This workflow involves detection of body-wave events, evaluating their locations, and selective stacking over stationary-phase areas for creating virtual shot gathers (Fig. 2). The 3D grid was also used for a sparse 3D active-source survey with an irregular distribution of Vibroseis and explosive sources. However, even with the sparse source distribution, the 3D survey has provided new details about the architecture of the Kylylahti area, in particular about the spatial extent of the Outokumpu assemblage rocks (Fig. 3). Both time and depth imaging was performed for 3D data, however time imaging failed to provide a clear image of the main structure of the steeply dipping Kylylahti formation, showing only sparse, discontinuous reflectors. Motivated by the earlier successful application of Kirchhoff pre-stack depth migration (PreSDM) to the COGITO-MIN 2D data (Heinonen et al., we decided to apply it also to the 3D data. Apart of the Kirchhoff PreSDM, we also used the coherency-based Fresnel Volume Migration (CBFVM) approach developed a TU Freiberg. It is well suited for sparse acquisition geometries because it reduces migration artefacts caused by insufficient coverage of the survey area.

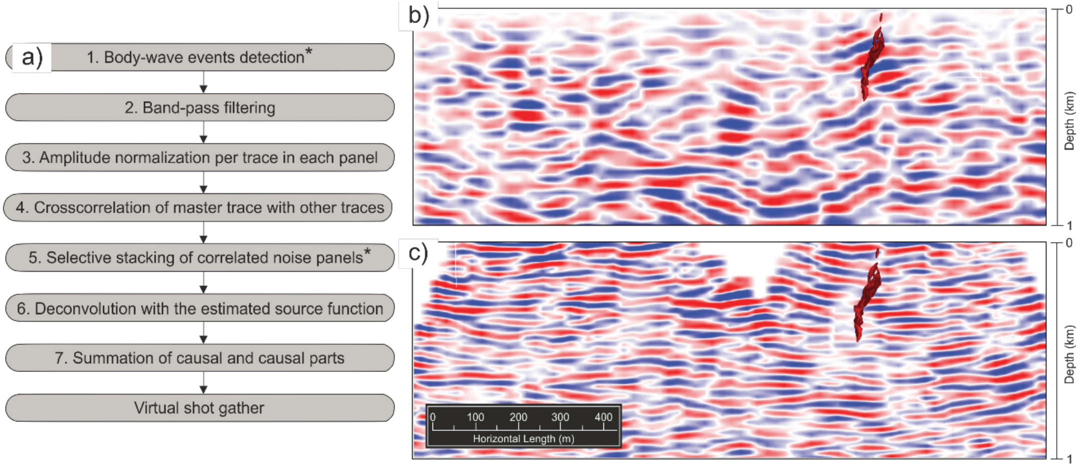

Figure 2 (a) The MESI processing workflow; (b) Example of an inline migrated seismic section obtained from the MESI-processed data compared to (c) the migrated co-located inline section from the active data. Projection of the massive sulphide ore lens is shown as a red shape.

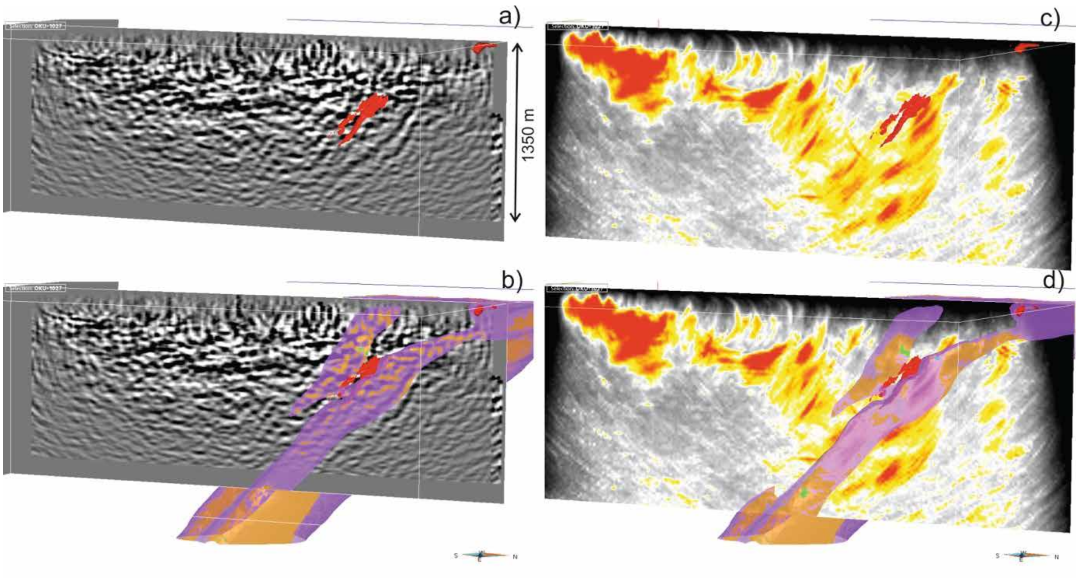

Figure 3 Comparison of standard Kirchhoff PreSDM (a,b) and CBFVM (c,d) along a crossline through the ore zone, which is marked by a red surface. The base of the Outukumpu assemblage is identical with the base of the Kylylahti formation, which is shown as a purple surface in (b) and (d).

Facing the 3D Crustal-Scale Imaging via Full-Waveform Inversion of the Ocean-Bottom Seismometer Data - Phase I: Building a 3D Synthetic Model of a Subduction Zone and Wavefield Modelling | A.Górszczyk

The current paradigm on how onshore, crustal-scale velocity models based on long-offset stationary-receiver surveys are built relies on 2D ray-based methods such as first-arrival traveltime tomography (FAT). This is mainly because such methods offer acceptable resolution for delineating the main crustal units while remaining affordable in terms of data acquisition and processing. As an alternative approach, full-waveform inversion (FWI) allows one to develop subsurface models at wavelength-scale resolution and has the potential to be utilized for multiparameter reconstructions. Moreover, it does not require the identification and picking of individual phases, since the ultimate goal of FWI is to automatically account for all types of arrivals.

On the other hand, our imaging relies on the 2D assumption which implies some important limitations: structures are imaged along vertical section with possible artifacts resulting from limited fold and illumination, 3D propagation effects, empirical 3D-to-2D amplitude and phase corrections etc. This raises the issue of designing next generation of 3D sea-bottom acquisitions for deep crustal investigations. In order to move towards high resolution 3D imaging of the whole crust and to broaden our knowledge about the structural factors that govern active geodynamical processes in various environments, we must first define the specifications of new-generation OBS surveys that are amenable to FWI at crustal scale. Among others, different key points are related to the acquisition geometry and logistic in particular in terms of sampling and spread, the computer implementation of FWI for large-scale optimization problems (parallelism, time versus frequency domain modeling engines, compressive sensing), the development of optimization strategies to mitigate the nonlinearity and ill-posdeness of the inverse problem etc.

To mitigate the mentioned issues we start with building of a realistic 3D marine crustal-scale model amenable to evaluate different acquisition geometries and processing techniques suitable for deep crustal imaging. The model has been inspired by the geologically complex structure of the Nankai subduction zone combined with the previous results of geophysical investigations of this area. It contains wide range of realistic features like strong bathymetry variations, oceanic ridges, subducted topography highs, low-velocity zones, velocity gradients, complex accretionary prism, large faults and thrusts with local damage-zones as well as shallow sedimentary basins. Additionally we incorporate different stochastic components to mimic more realistic wave propagation. We further obtain S-wave velocity and density models using polynomial functions derived from empirical relations between P-wave velocity and other physical parameters. These elastic models are consequently modified according to our assumptions about local heterogeneities in the model.

The model is cast in 3D cube which dimension is 30x170x105 km with 25 m grid interval. Such parameterization of the model leads to more than 34 billion degrees of freedom imposing challenge from the point of view of computational resources and the high performance computing implementations.

We believe that through the development of this synthetic model and the following visco-elastic dataset we have chance to better understand the determinants of the crustal-scale imaging via FWI of the OBS data and stimulate its popularization in the communities aiming on regional data acquisition and imaging.

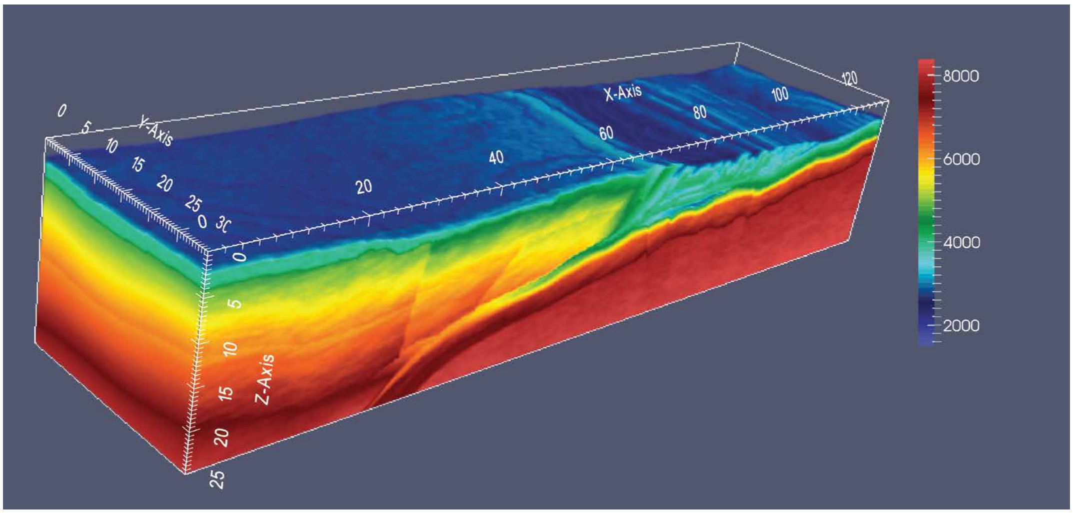

Figure 1. Perspective view on the part of 3D P-wave velocity model.

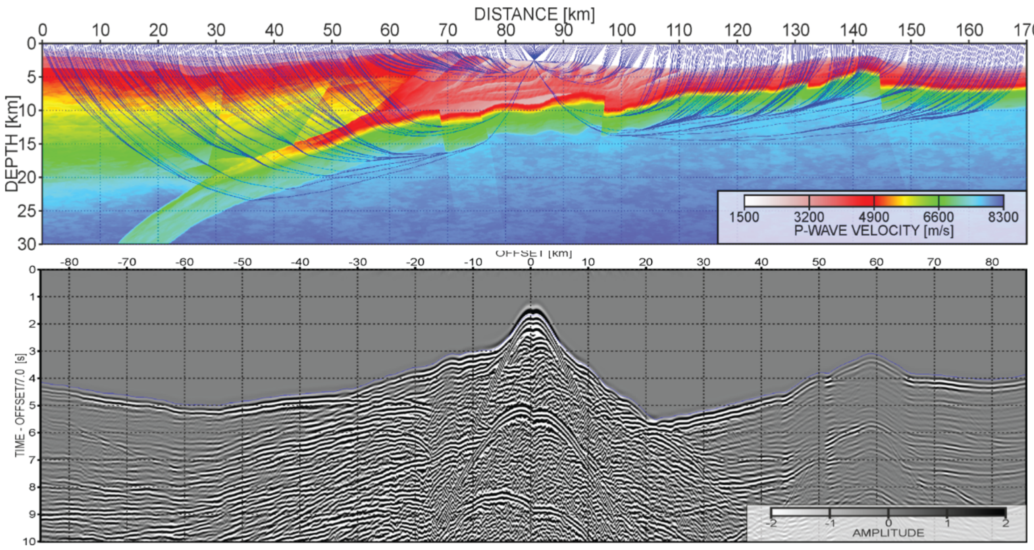

Figure 2. Ray-tracing (upper panel) and P-wave modeling (lower panel) performed along one of the inlines extracted from 3D cube. Note the complexity of the wavefield reflecting the rich structural information incorporated into the synthetic model.

Crustal-scale depth imaging via joint FWI of OBS data and PSDM of MCS data | A.Górszczyk

Pre-Stack Depth Migration (PSDM) imaging from Multi-Channel Seismic (MCS) reflection data at the scale of the whole crust is inherently difficult. This mainly results because the depth penetration of the seismic wavefield is controlled, firstly (i) by the acquisition design, like streamer length and air-gun source configuration, and secondly (ii) by the complexity of the crustal structure. Moreover, the limited length of the streamer makes the estimation of velocities from deep targets challenging due to the velocity-depth ambiguity. The problem is even more pronounced when processing 2D seismic data, due to the lack of multi-azimuthal coverage. Therefore, in order to broaden our knowledge about the deep crust from seismic methods, one can target the development of specific imaging workflow combining (i) first-arrival traveltime tomography and full-waveform inversion (FWI) of wide-angle/ long-offset data collected by Ocean Bottom Seismometers (OBS) for velocity model building and (ii) pre-stack depth migration of short-spread multichannel reflection data for reflectivity imaging, using the former velocity model as background model. We present an application of such workflow on seismic data collected by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Institut Francais de recherche pour l'exploitation de la mer (IFREMER) in the eastern Nankai Trough (Tokai area) during the 2000/2001 SFJ experiment. We show that the FWI model, although derived from OBS data, provides yet an acceptable background velocity field for the PSDM of the MCS data. Furthermore, from the initial PSDM, we first refine the FWI background velocity model by minimizing the residual moveouts (RMO) picked in the pre-stack migrated volume through slope tomography (ST), from which we generate a better focused migrated image. Such integration of different seismic data sets and imaging techniques led to optimal imaging results at different resolution levels. That is, the large-to-intermediate scale crustal units identified in the high-resolution FWI velocity model complement the short-scale reflectivity inferred from the MCS data to better constrain the structural factors controlling the geodynamics of the Nankai trough area.

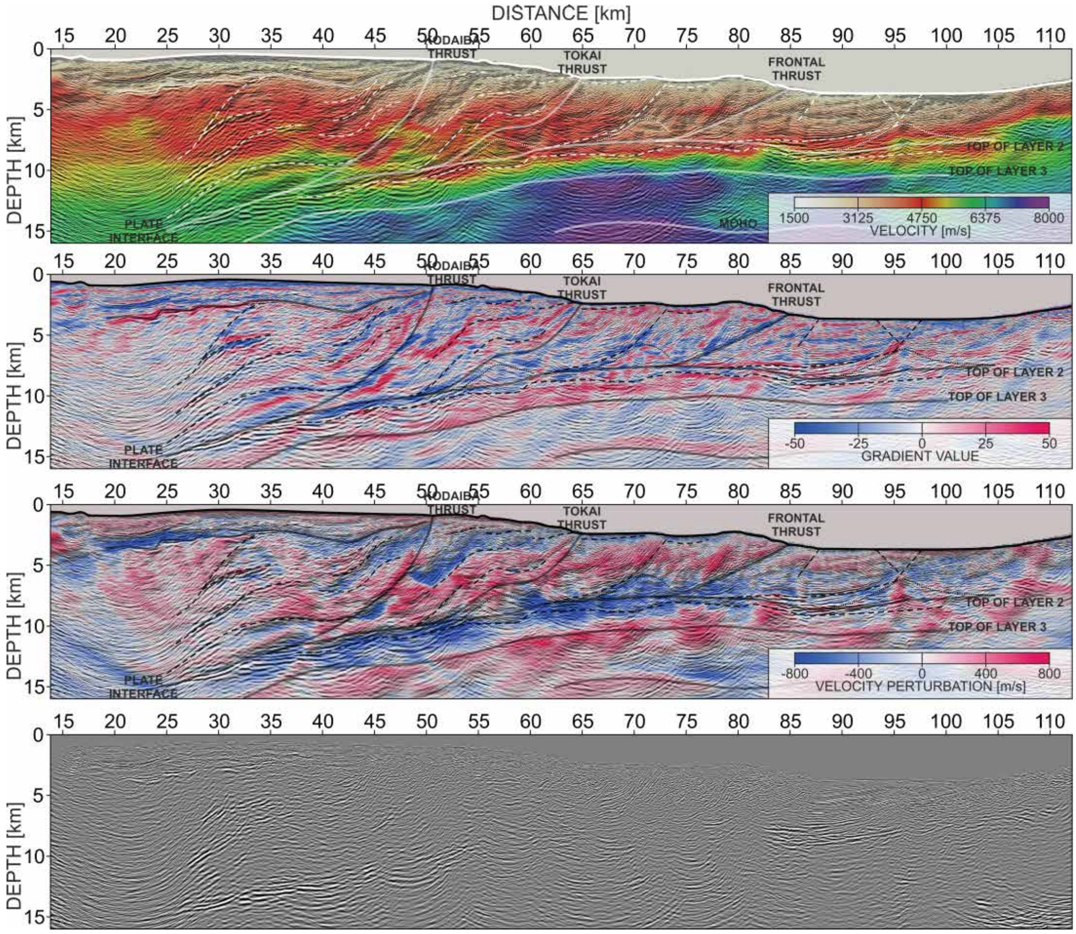

Figure 3. Results of crustal scale imaging derived from joint FWI of OBS data and PSDM of MCS data. From top to bottom paneLs present: (i) PSDM section superimposed on the absolute FWI velocity model; (ii)) PSDM section superimposed on the gradient of FWI velocity model; (iii)) PSDM section superimposed on the FWI velocity model after removing polynomial velocity trend; (iv) PSDM section. Note the detailed geological information coming from the velocity models which support the interpretation of the PSDM section.

Application of the stochastic inversion for shale reservoir characterization | M. Cyz, M. Malinowski

Seismic inversion is an important tool for subsurface modelling and characterization. It allows to obtain the spatial distribution of the elastic properties (e.g. density (ρ), P-wave (Vp) and S-wave (Vs) velocities) based on existing seismic reflection and well data. Seismic inversion methods can be divided into two categories: deterministic and geostatistical. Deterministic inversion is based on low frequency models and has limited bandwidth and result in smooth inverted models with low-resolution, but they manifest the general trends within the considered property. Geostatistical inversion simulates possible property models based on well data and a model describing the expected spatial continuity pattern of the property of interest. This allows to retrieve high-resolution inverted models and assess uncertainty of the predictions. However, these methods are computationally expensive, requires good quality data and proper well-to-seismic ties. Obtaining high-resolution models is especially important while dealing with the characterization of thin beds, what is mostly the case in the shale reservoirs.

Here, we apply geostatistical seismic Amplitude-versus-Angle (AVA) inversion (Azevedo et al., 2018) to characterize the unconventional Lower Palaeozoic shale reservoir from Baltic Basin, Northern Poland where the most interesting targets are of small thickness (up to 25 m) and deeply buried (ca. 3 km depth). This inversion method allows inverting pre-stack angle-domain seismic gathers simultaneously for elastic properties (ρ, Vp, Vs). The procedure uses direct stochastic simulation and co-simulation (DSS) as the model perturbation technique and a genetic algorithm as a global optimiser to ensure the convergence of the iterative procedure. The elastic properties are simulated and co-simulated sequentially from available well-log following a pre-defined spatial continuity pattern as expressed by a variogram model. The resulting models exhibit high-resolution and allow assessing uncertainty on the predictions. Elastic properties obtained from the geostatistical inversion are compared with the results of the more standard, deterministic simultaneous Amplitude-versus-Offset (AVO) inversion.

The application of a geostatistical inversion was successful and allowed for obtaining the high resolution results and delineation of the thin target formations (Figure 1A), what was not possible to reach with the deterministic inversion application (Figure 1B). The geostatistical inversion also properly reproduce the well-log data while with the deterministic inversion only the general trend over a bigger interval is observed (Figure 1C).

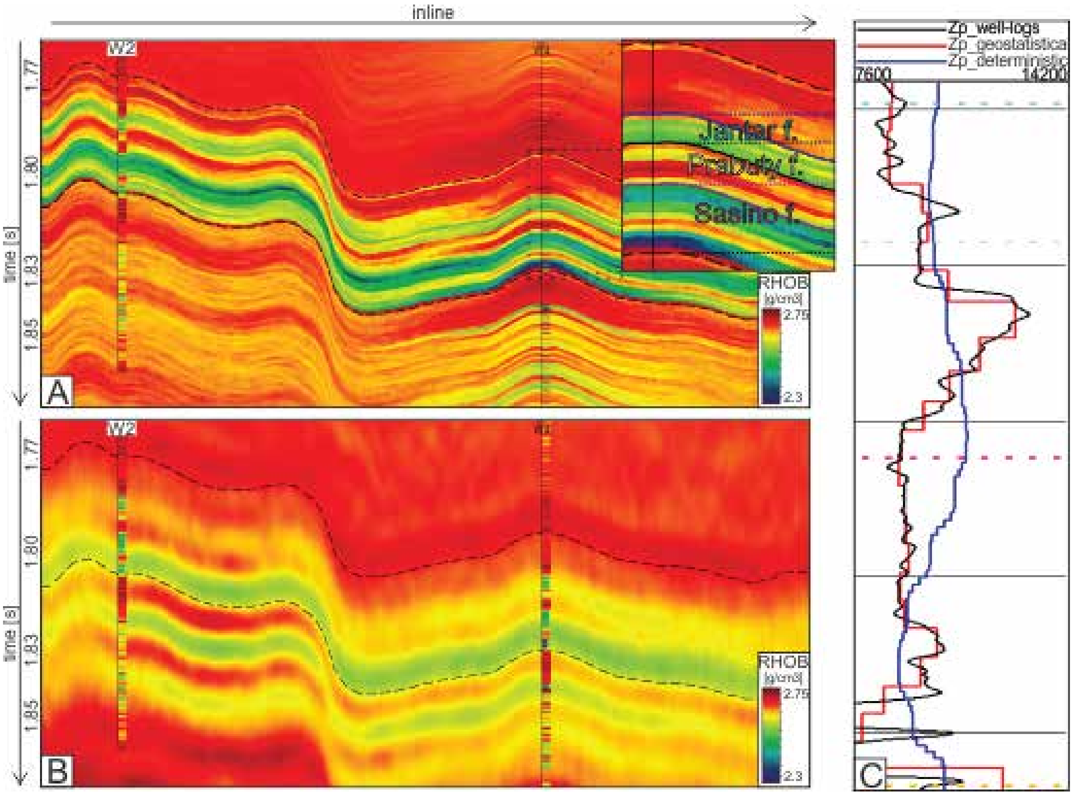

Figure 1. Vertical well sections through density model resulting from (A) geostatistical and (B) deterministic inversion. The dashed, black horizons mark the area of the main interest. Solid lines at a zoomed section marks the top horizons of a key formations. Models are overlaid with the actual well-log properties. (C) P-wave impedance (Zp) calculated from the results of the geostatistical inversion (red line) and deterministic inversion (blue line) versus actual well log Zp (black line).

Hans glacier seismic monitoring using a dedicated local network | W.Gajek

We have deployed a pilot 3-season long-term seismic network to monitor the dynamic activity of Hans glacier in Hornsund, Svalbard. The network was continuously gathering seismic data from September 2017 to April 2018, hence from the late summer throughout whole winter until the spring season. It consisted of 11 recorders commonly used in controlled-source seismology (DATA CUBES) equipped with 4.5 Hz three-component geophones and powered by battery packages. The stations were placed either directly on ice (2 stations) or rocky basement in the close vicinity of Hans glacier terminus, with some of them only a couple hundreds of meters from it.

Recorded data is rich and complex - it consist of more than half a year multi-station records at arctic environment. Recorded wave field consists of events of different characteristics. We can observe short-lasting events present in a broad range of high frequencies (above 20 Hz), short-lasting spiky events, and monochromatic low-frequency events. A phenomenon of repeating events with same mechanisms displaying high correlation of the waveforms have been found. Some of the events are strong enough to be registered on all of the stations. Recorded events display expected seasonal distribution based on the observations from permanent seismological station HSPB only, but much more data is now available. Next step will be to work towards locating the registered events and to study the correlation between their location and character.

We established collaboration with geophysicists from glaciology group at ETH Zurich working in alpine glacier environment.

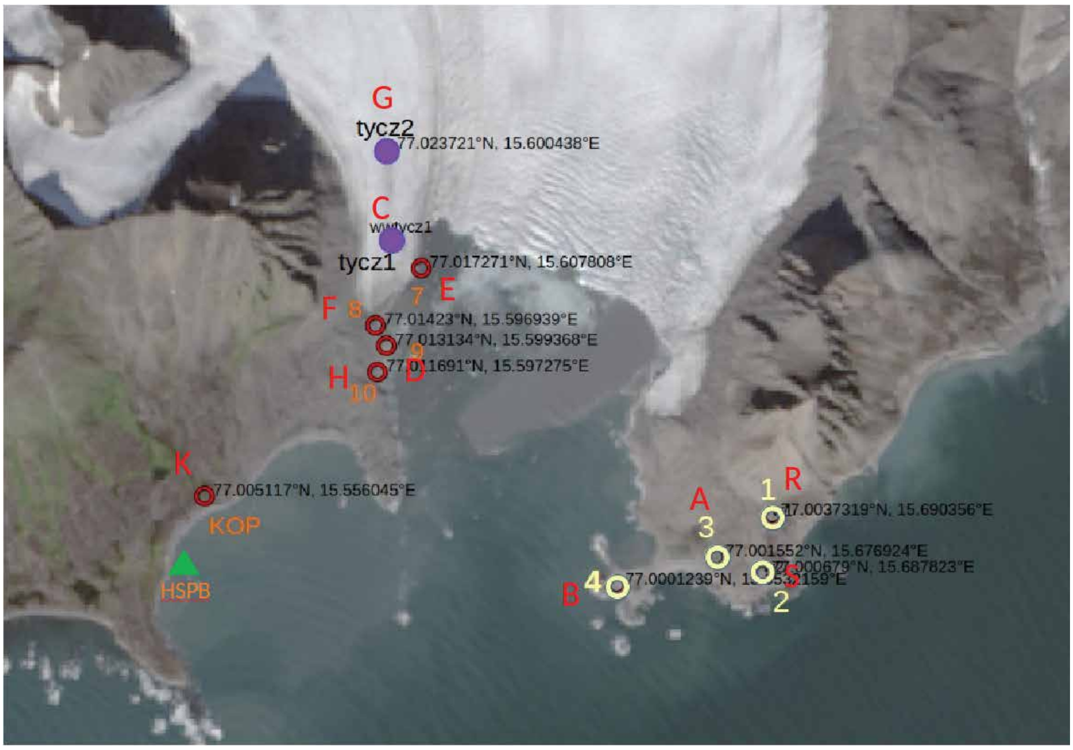

Figure 1: Locations of 11 temporarily deployed seismic stations and a HSPB permanent seismological station in the Hornsund fjord, Svalbard

Theory of the detection function for migration-based methods for the detection of microseismic events and optimized detection scheme | J. Trojanowski

A theoretical study was performed to describe a detection function which is used during the migration-based detection of microseismic events. A potential event is detected when a detection function exceeds some specified threshold value. However, the value of this threshold is usually selected manually; therefore, the detection process is subjective and lacks constraints on the probability of exceeding the threshold. In practice, any change in the detection algorithm results in a change in the distribution of the detection-function values. Consequently, the threshold value must be adjusted to have the same probability of exceedance as before. A general probabilistic theory of the detection-function was developed that is valid for any migration-based detection method. For the sake of transparency and the inter-changeability of the results, it is recommend to use the definition of a threshold in terms of the exceedance probability. To do so, it is necessary to define a probability distribution of the detection-function. There is also developed a general method for assessing the detectability of a given stacking method for the purpose of comparing different migration-based methods.

The optimization of the detection scheme was performed using real microseismic data provided by MicroSeismic Inc. The data were acquired by a surface array during one stage of hydraulic stimulation of shale rocks. Different ways of data conditioning were tested. It turned out that it was crucial for the performance of detection to reduce the influence of noisy traces on stacking process by, e.g., balancing or trace selection. Application of the two developed denoising methods further improves the detectability of microseismic events recorded with low signal-to-noise ratio. The number of detected microseismic events highly varied with changes to the processing sequence. The best achieved result was 210 (Fig. 1) detected events and the worst was 0. It shows that a careful and conscious choice of the processing steps is crucial to achieve a high detectability of microseismic events. It is particularly important for the surface microseismic monitoring which is often criticized for providing a low number of detected microseismic events comparing to the borehole monitoring.

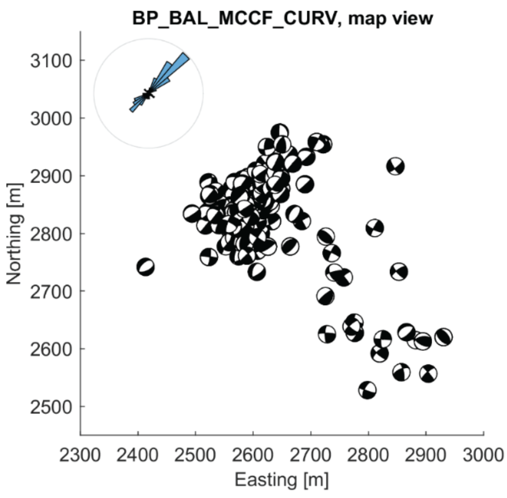

Figure 1. Horizontal locations and source mechanisms for 210 detected microseismic events. Symbols representing a double-couple part of the source mechanism solution are plotted at locations of respective events. The inset in the top plot is a rose diagram plot of strike azimuths for all events and the solution with the highest dip angle (more vertical plane).

Recognition of the varying permafrost conditions in the SW Svalbard by multiple geophysical methods | A.Marciniak, B.Owoc, M.Majdański

In the presented work, we applied multiple geophysical methods and tools, to recognize horizontal and vertical distribution as well as ongoing changes in the seasonally and perennially frozen ground. The study site, located near the Polish Polar Station in the Hornsund (Svalbard), is unique due to its location between sea-shore and mountainous ridges and close presence of the retreating Hans Glacier. Such an environment allows for conducting research encompassing various dynamical cryospheric, geological and other environmental processes. The monitoring of the ground temperature variations in the several boreholes, with detailed ERT, GPR and MASW modeling, allow for recognition and analyses of the active layer spatial variability and the permafrost changes in this area. The seismic recognition, based on the dense 2D seismic reflection and refraction methods (Fig.1), allows for the direct comparisons between observations conducted during the summer and winter seasons. Results obtained by those methods are directly targeted to visualize not only the active layer thickness but also the permafrost which until today is unknown in the area of Southern Spitsbergen. Additionally, the comparison of the data-set quality between two seasons allowed to select the best conditions for future data acquisition. The recognition of vertical and horizontal changes of the permafrost as well as the active layer depth provided unique information about the thermal ground conditions.

Obtained results, gives us the opportunity for explanation of seasonal changes which were observed, measured, and modeled. This information allows for better understanding of the geophysical processes responsible for the cryospheric and geological processes occurring in the study site, and further better estimation of the climate change impacts on the environment SW Spitsbergen.

Figure 1 Active seismic team during the field works in Hornsund in April 2018; seismic line composed by DATA-CUBE stations (left), seismic source PEG-40 mounted on sledges (right).

Near-surface structure of the Carpathian Foredeep Marginal Zone in the Roztocze Hills area | M. Majdański, B. Owoc

Shallow seismic survey was made along 1280 m profile in the marginal zone of the Carpathian Foredeep. Measurements performed with standalone wireless stations and especially designed accelerated weight drop system (Fig.1) resulted in high fold (up to 60), long offset seismic data. The acquisition has been designed to gather both high-resolution reflection and wideangle refraction data at long offsets. Seismic processing has been realised separately in two paths with focus on the shallow and deep structures. Data processing for the shallow part combines the travel time tomography and the wide angle reflection imaging. This difficult analysis shows that a careful manual front mute combined with correct statics leads to detailed recognition of structures between 30 and 200 m. For those depths, we recognised several SW dipping tectonic displacements and a main fault zone that probably is the main fault limiting the Roztocze Hills area, and at the same time constitutes the border of the Carpathian Forebulge. The deep interpretation clearly shows a NE dipping evaporate layer at a depth of about 500 700 m. We also show limitations of our survey that leads to unclear recognition of the first 30 m, concluding with the need of joint interpretation with other geophysical methods.

Figure 1 Seismic source PEG-40 adapted to new carriage system, that can be operated without a car. This system can operate in rough terrain like steep hills and dense forest.

Shallow seismic investigations yielded detailed images of the Carpathian Foredeep marginal zone (Fig.2). A large offset survey combined with modified accelerated weight drop source was specially designed to allow both high resolution reflection image and refraction tomography. Four strokes of the source give enough energy to observe refractions at all offsets up to 350 m, but also to recognize a deep structure down to 700 m. Two processing paths were used to enhance both shallow and deep structures, resulting in detailed image of the near-surface faults, but also a sharp deep reflection. The 5-m spacing used for both shots and receivers was not dense enough to clearly recognize the first 30 m. Additional information like ERT experiment or different seismic processing, e.g., MASW, and finally joint interpretation might be used to further verify this part of the structure. Still, a clear image of a main fault in the area was presented. This weight drop seismic profile was performed to recognize near-surface structures, that is why it was surprising to observe clear reflection at 700 m. For surveys of this type with limited number of stations we suggest to use different spacing for shots and receivers. For example deploying stations with 8 m spacing and shooting with 2 m spacing will result in similar fold, but would limits number of deployments, limiting number of repeated shots. Thanks to dense shooting it would be possible to recover shallower structures, but wider deployments would give important long offset refracted arrivals. In the end acquisition time should be similar with higher resolution results. To make it optimal it would be beneficial to perform test shooting and recognize the maximum offset of clear observations, and design the survey for specific environment.

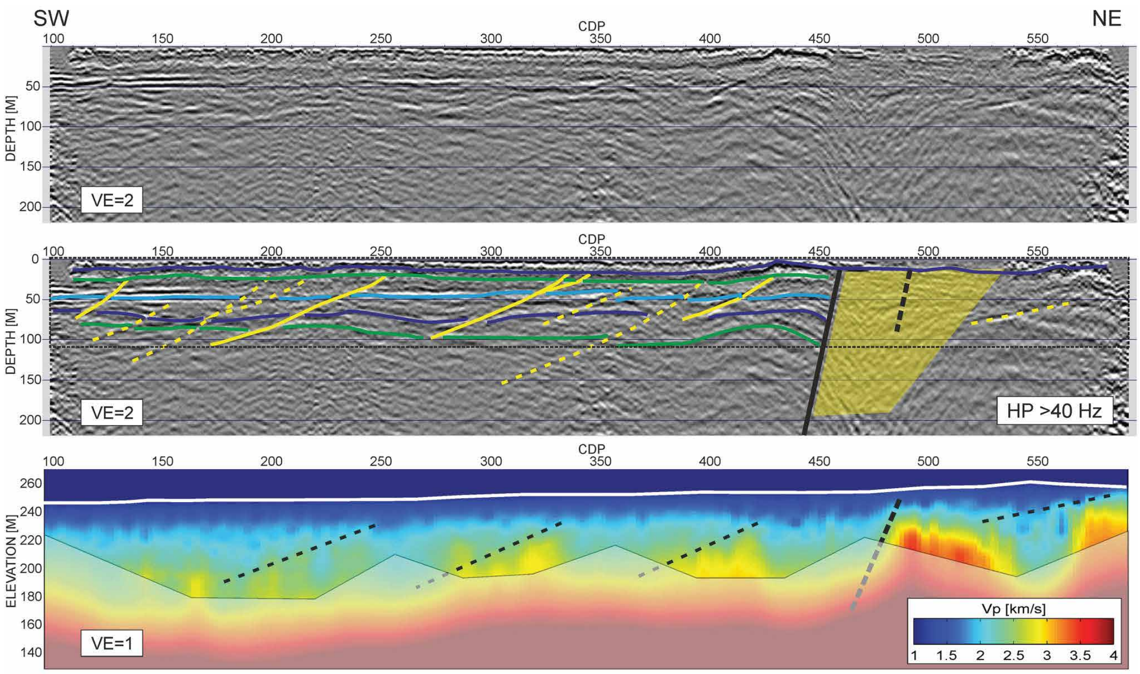

Figure 2 Shallow structure in the depth domain obtained with shallow reflections enhanced processing (top). The bottom panel shows several discontinuities in the flat reflections (marked with colour solid lines) that do not reach the surface. Those marked with solid yellow lines are confirmed with tomography. Yellow polygon marks the area of the low reflectivity that differs from surrounding structures, and corresponds to a zone of the strong velocity gradient in tomography.

Geo-engineering fieldwork summer school in Chęciny with imaging of the Quaternary fluvial system | M.Majdański, A.Marciniak, B.Owoc, M.Malinowski

In June 2018 a week-long fieldwork summer school has been organized in the cooperation with Department of Geology University of Warsaw. The school covers both theoretical lectures about reflection imaging, tomographic methods and surface wave method (MASW), and practical computer classes presenting Globe Claritas, Geopsy and JIVE3D software. Moreover, during an outdoor training, several geophysical measurements have been collected along three profiles. The most important one called Mosty 1 covers a quaternary sediment basin. Along the 800 metres profile, high-resolution reflection profiling has been shot using enhanced PEG-40 accelerated weight drop and 60 DATA-CUBE 1C 4.5Hz stations (Fig.1). This measurement has been supported with georadar profile and precise geodetical measurements.

Figure 1 Outdoor training at the profile Mosty 1. Assembling of enhanced PEG-40 seismic source.

All obtained data will be interpreted together. In 2018 an initial reflection image (Fig.2) has been prepared. Separately MASW analysis and a travel time tomography using JIVE3D and new Tomo3D codes has been conducted and will be finished in 2019.

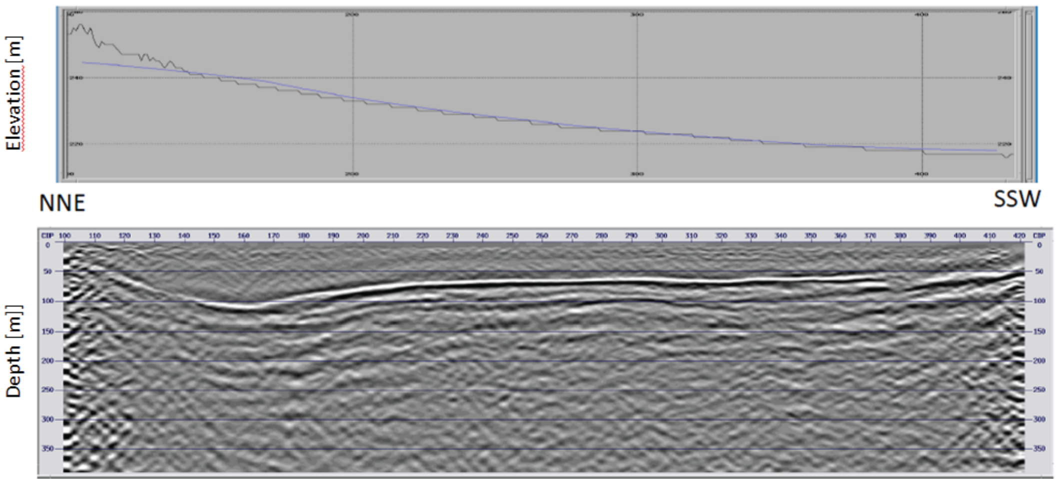

Figure 2 Precise elevation along profile (top); Initial reflection imaging after the depth conversion (bottom).

Deep Neural Network and Multi-pattern Based Algorithm for Picking First-arrival Traveltimes | M.Mężyk, M.Malinowski

Static corrections are amongst the most important steps in processing land seismic data. First-order statics solution is conventionally obtained by application of refraction statics based on first-arrival traveltime picks and the quality of such static solution is directly connected with the ability to pick reliable first-breaks. Picking can be difficult, especially with the low signal-to-noise Vibroseis data and very laborious (e.g. picking millions of seismic traces in large surveys). Modern seismic processing systems employ several methods of automatic first-break picking, based e.g. on STA/LTA method or artificial neural networks (ANN). There is however no universal method that will work on every dataset and still several passes of QC by an interpreter are required. In order to improve picking accuracy and reduce this QC time, we proposed an ANN-based approach whose core mechanism relies on pattern recognition techniques and signal-based methods of generating these patterns. The first-break picking is treated here as a binary classification problem that requires a model to differentiate first-break sample from all others samples. In order to provide a sufficient training dataset a STA/LTA method, an entropy-based method, and a variogram fractal-dimension method have been used. The approach appears robust and flexible in a way of adding new pattern generators that might contribute to even better performance.

In our study case, we exploited the high quality 2D Vibroseis data, that has already underwent the manual picking during the conventional seismic processing. These manually derived picks were retrieved and properly conditioned to serve as learning patterns. The model building process involved not only collecting the data, but also finding and understanding the relations between the most important features in the data to answer the questioned we asked.

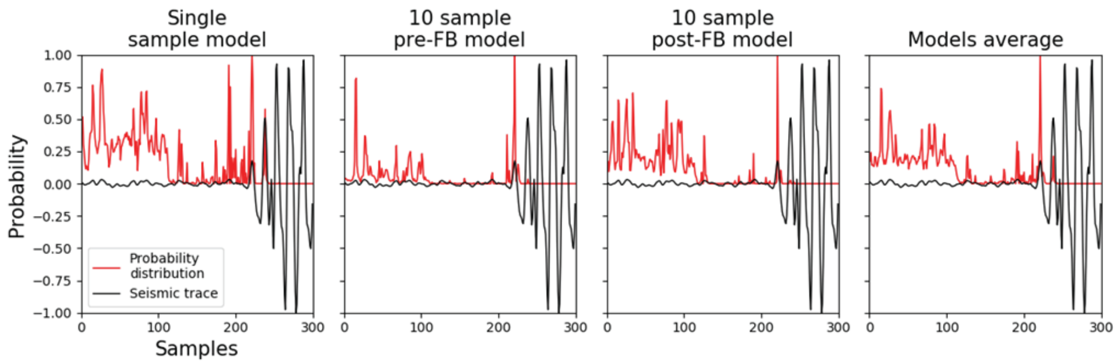

Figure 1. Arbitrary seismic trace juxtaposed with the various model predictions.

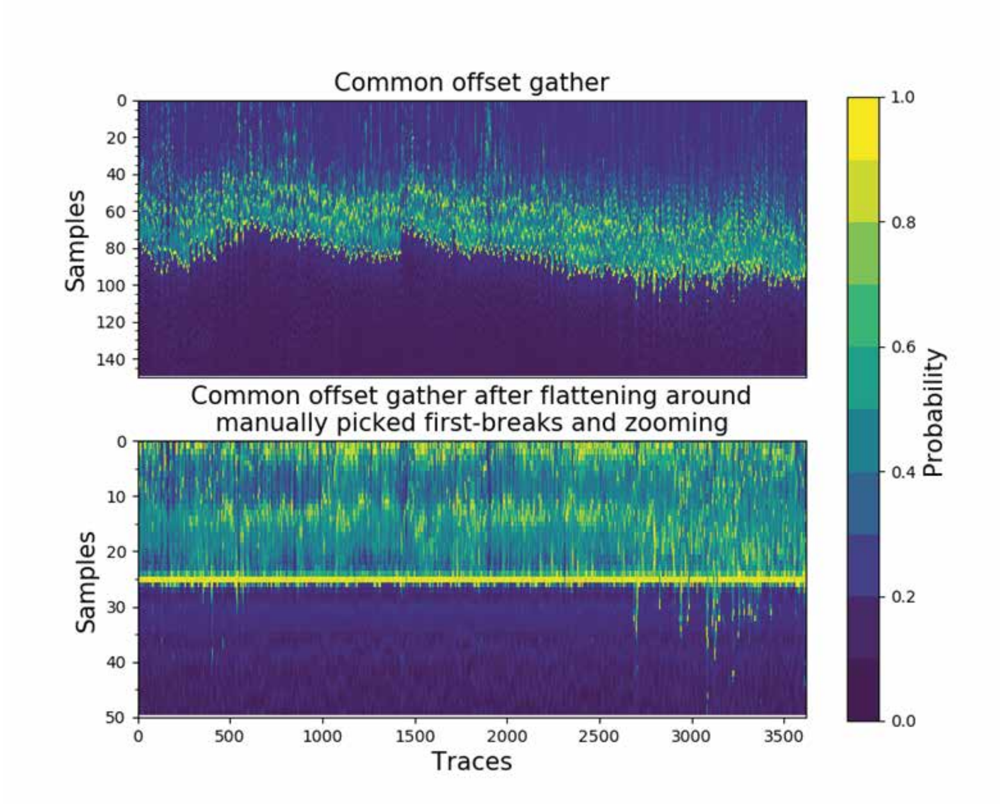

Figure 2. Common offset gather after first-break prediction (top)
and the same gather flattened around manually-picked first-break times (bottom).

Pattern-recognition algorithms, after being properly set up once, turns out to be useful method that tremendously reduce the need for human interaction in tedious processing steps as picking first-break times and their QC. It appears robust and flexible in a way of adding new pattern generators that might contribute to even better performance. The core of the method is based on straightforward idea provide a training data, create a model and predict an answer by linking first-break representations across different domains to output single probability value of positive event at analyzed sample. That means that the binary classification algorithm might be easily adapted to address different kind of problems, e.g., a noisy trace editing. Moreover, already trained models can be saved and reproduced for another dataset collected with similar acquisition parameters (e.g., in multi-line surveys) or on totally new seismic survey.

Characterization of potential Lower Paleozoic shale resource play in Poland | M.Malinowski, M.Cyz, W.Gajek, J.Trojanowski

The August 2018 issue of SEG "Interpretation" journal features a special section on the "Characterization of potential Lower Paleozoic shale resource play in Poland", in which our group published 4 papers summarizing the results of the NCBR-funded SHALEMECH project. M. Malinowski served as the Assistant Editor of this special section.

The Lower Paleozoic shale play in Poland comprises Ordovician to Silurian shales that were deposited within a vast sedimentary basin located above the southwestern edge of the East European Craton, which was later tectonically divided into three sub-basins: the Baltic, the Podlasie, and the Lublin Basins.The recent shale gas exploration boom in Poland resulted in acquisition of a large amount of new, good-quality data, but did not lead to a commercial production. While the current oil price plays a role, the original assumptions that Polish shales would be similar to North American shales proved to be untrue, with Polish shales being both deeper (below 2500 m) and older (Ordovician and Silurian rather than Carboniferous and Cretaceous). For this reason, the goal of this special section is to capture our learnings and knowledge about the geological setting and reservoir properties of the Lower Paleozoic shales to better understand the key factors that can lead to not only the reopening of the exploration possibilities in this play, but to provide broader understanding of shale plays in general. The papers in this special section focus on the Baltic Basin in Northern Poland (nine papers), with only one case study covering the Lublin Basin.

Cyz and Malinowski present an application of Amplitude versus Azimuth analysis (AVAz) for quantifying weak anisotropy (1-2%) in the thin-layers case of the Lower Paleozoic shales from the Baltic Basin. Obtained results match well available calibration data, e.g. XRMI image logs, cross-dipole sonic logs or microseismic shear-wave splitting inversion results.

Cyz et al. present a case study of brittleness prediction by integrating well and 3D seismic data using machine learning technique for the Lower Paleozoic shales in Baltic Basin. Prediction was successful and allowed for differentiation of ductile and brittle zones within thin shale formations with improved resolution while compared with original input seismic data. The important part of the success was the appropriate definition of the mineralogical brittleness index tailored to the local geological conditions.

Gajek et al. present results from borehole microseismic monitoring of a pilot hydraulic stimulation job in Poland. This case study elaborates on challenging anisotropic velocity model building and evaluates the stimulation effectiveness in the geomechanical context.

Gajek et al. utilize shear-wave splitting measurements derived from the borehole microseismic data to invert for anisotropic rock-physics model unrevealing strike and density of pre-existing fractures in the stimulated shale gas reservoir.

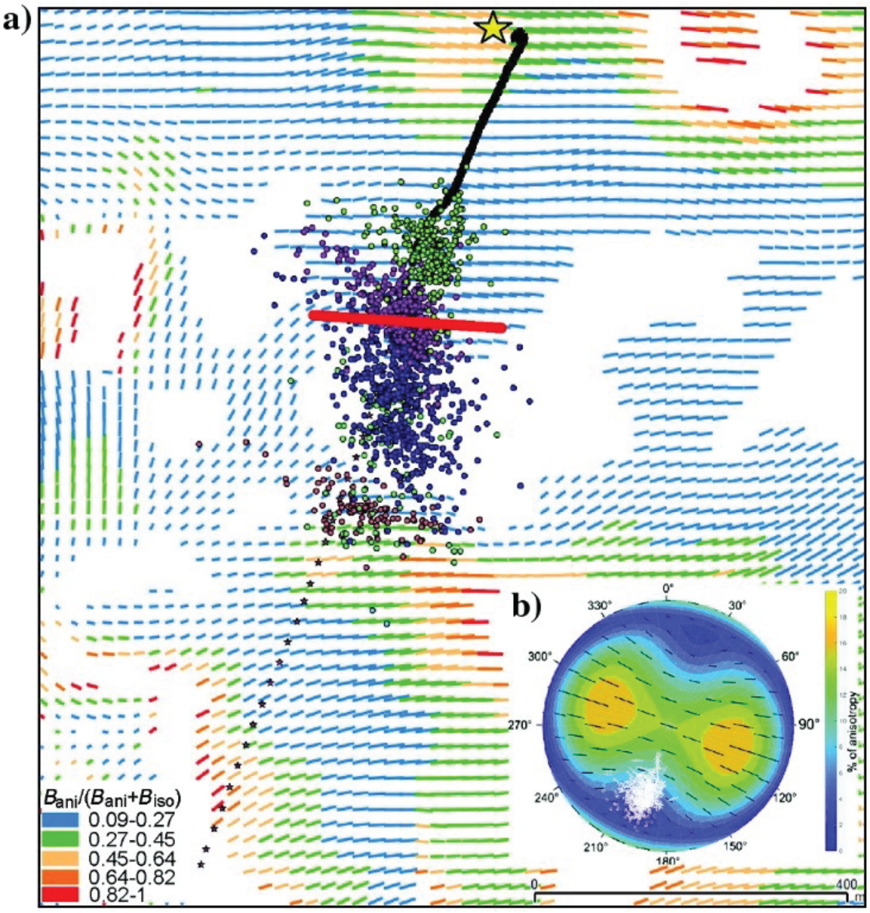

Figure 1 (a) Map of the AVAZ-derived azimuthal anisotropy orientation and magnitude for the stimulated Sasino Formation close to the horizontal well overlaid with microseismic event locations (Gajek et al., 2018a). The yellow star points out an observation well location. The red line marks the average anisotropy azimuth around the horizontal well (approximately 95°). (b) Fracture strike as determined from the SWS analysis (approximately 108°) (Gajek et al., 2018b).

Reconstructing Universal Statistical Properties of Earthquakes by Simple Stochastic Cellular Automata | M. Białecki, A. Bagchi

The subject of the research topic is investigation of constructions of a simple models in the form of a stochastic cellular automaton, that capture universal mechanisms for generating earthquakes and reconstruct fundamental empirical laws describing their statistical properties. Such models are constructed in order to study these laws and a relationship between them. In particular we work on reconstruction of inter-event time between occurrence of successive earthquakes. It is known, after Alvaro Corral's discovery in 2004, that the probability of waiting time for the next earthquake can be described by one universal distribution, as long as the time is expressed in units corresponding to the average seismicity of the region. The existence of such a universal formula, which does not depend neither on local geological and tectonic conditions, nor on how much the area is seismically active, strongly indicates the universal nature of the mechanism for a generation of the distribution of waiting times for earthquakes.

Investigated models are extensions of studied for almost ten years Random Domino Automaton, describing the slow accumulation of energy and its abrupt releases, controlled by specific probabilistic rules. For the construction and analysis of Random Domino Automaton models we use advanced physical concepts and mathematical methods, including: stochastic processes, graph theory, analytical combinatorics, difference equations, Markov processes as well as elements of theory of complex systems and statistical physics.

A novel version of Random Domino Automaton was defined on Bethe Lattice and respective set of equations describing statistically stationary state in mean-field like approximation was derived. In particular, this model was able to produce truncated inverse power distributions. For these distributions, the range of independent variables, for which power law holds, is limited without introducing artificially any 'ad hoc' value. These and other new findings extend our ability to model fundamental properties of earthquakes and other natural phenomena.

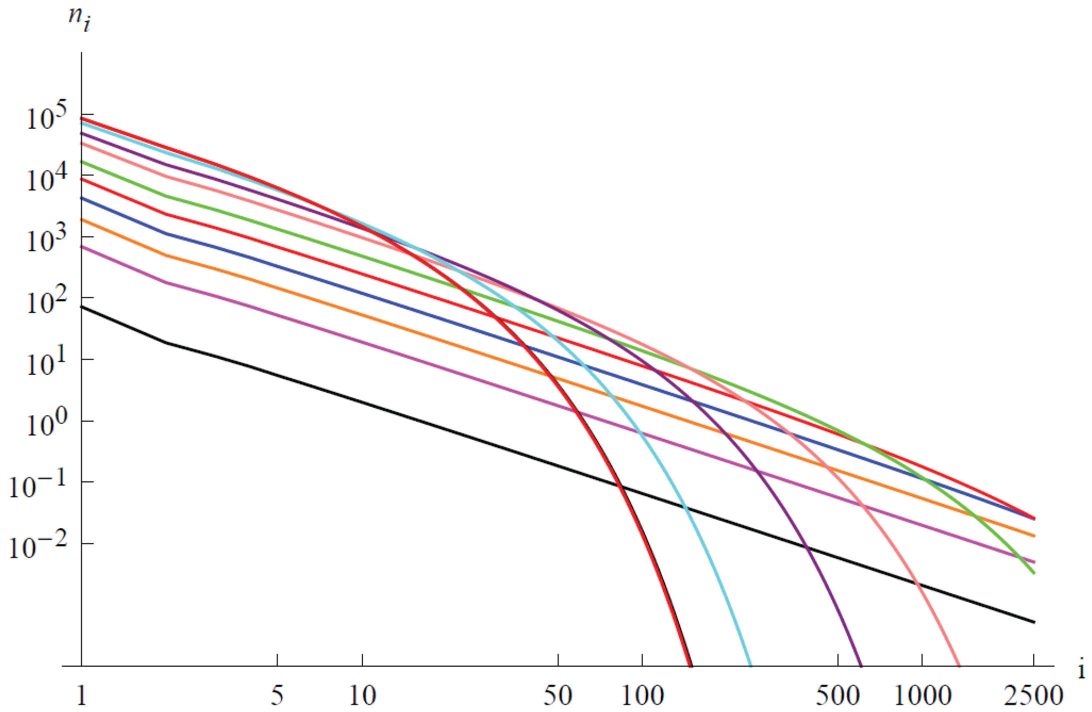

Figure 1. Distribution of avalanches calculated form equations of Random Domino Automaton on Bethe Lattice (with coordination number 3) for various parameters ranging from exponential limit (curved red line), through piece-wise inverse power distributions with exponential tail, up to inverse power distribution   the limit related to Self-Organized Criticality.

Seminars and teaching

Seminars and lecture outside of the IG PAS

- A.Bagchi | *Various undergrad courses* | Lecture
  Santipur College, Kalyani Univerity | Santipur, India

- M. Malinowski | *Geophysical methods in mineral exploration* | Invited lecture
  International Center for Geological Education | Chęciny, Poland

- M. Malinowski | *Introduction to seismic processing/imaging* | Invited lecture
  International Center for Geological Education | Chęciny, Poland

- M. Majdański | *Seismika szerokokątowa we współczesnej geofizyce* | Invited lecture
  International Center for Geological Education | Chęciny, Poland

Completed PhD thesis defense

- A. Adamczyk | *Application of full- waveform inversion to land datasets: how much does the acquisition matter?* | Supervisor: M. Malinowski

Visiting scientists

- Satish Singh | IPGP | Paris, France
- Ian Jones | ION Geophysical | London, UK
- Olaf Hellwig | TU Freiberg | Freiberg, Germany

Meeting, workshop conferences and symposia

CHAOS2018 conference | Rome, Italy
A. Bagchi | Solvable probabilistic cellular automaton on Bethe lattice with smooth transition between inverse-power and exponential distributions of avalanches | oral

32nd IUGG Conference on Mathematical Geophysics | Nizhny Novgorod, Russia
M. Białecki | A universal solvable model of slow accumulation of energy and its abrupt releases with smooth transitions from exponential to inverse-power distributions | oral

Symmetries and Integrability of Difference Equations SIDE 13 | Fukuoka, Japan
M. Białecki | Random Domino Automaton on Bethe lattice | poster

International Symposium on Deep Earth Exploration and practices DEEP-2018 | Beijing, China
M. Malinowski | Imaging East European Craton margin in Northern Poland using extended-correlation processing applied to regional seismic profiles | oral

M. Malinowski | Application of full-waveform inversion to crustal-scale velocity model building in complex subduction zone setting: Eastern Nankai Trough, Japan | oral

EGU General Assembly | Vienna, Austria
M. Mężyk | Imaging East European Craton margin in Northern Poland using extended-correlation processing applied to regional seismic profiles | poster

B. Owoc | The uncertainty in seismic traveltime tomography | poster

M. Majdański | Seismic image of the Carpathian Foredeep Marginal Zone | poster

A. Marciniak | Seismic Tomography and MASW analysis of the results of Spitsbergen seismic experiment   case study | poster

A. Górszczyk | Feasibility of crustal-scale imaging from 3D OBS data by Full Waveform Inversion. Phase I: building a 3D synthetic model of a subduction zone and wavefield modelling | oral

M. Chamarczuk | Towards adapting seismic interferometry to retrieve body-wave reflections for mineral exploration: the passive seismic experiment in the Kylylahti Cu-Au-Zn mine area, Finland | oral

18th International Symposium on Deep Seismic Profiling of the Continents and their Margins (SEISMIX 2018) | Kraków, Poland
M. Mężyk | Imaging East European Craton margin in Northern Poland using extended-correlation processing applied to regional seismic profiles | poster

B. Owoc | Estimation of the uncertainty in seismic tomography | poster

M. Majdański | Near-surface structure of the Carpathian Foredeep marginal zone in the Roztocze Hills area | poster

A. Górszczyk | Synthetic study on the crustal-scale imaging via FWI of the 3D OBS data   building a realistic benchmark model of a subduction zone | oral

M. Chamarczuk | Using large N arrays in mineral exploration: the passive seismic experiment in the Kylylahti Cu-Au-Zn mine area, Finland | oral

M. Cyz | Characterization of the Lower Paleozoic Shales in Northern Poland from the Analysis of Wide Azimuth Seismic Data | poster

LXXXVI Zjazd Naukowy Polskiego Towarzystwa Geologicznego | Łuków, Poland
M. Mężyk | Imaging East European Craton margin in Northern Poland using extended-correlation processing applied to regional seismic profiles | poster

80th EAGE Conference & Exhibition | Copenhagen, Denmark
M. Mężyk | Deep Neural Network and Multi-pattern Based Algorithm for Picking First-arrival Traveltimes | oral

13th SEGJ International Symposium | Tokyo, Japan
A. Górszczyk | Crustal-scale depth imaging via joint FWI of OBS data and PSDM of MCS data the eastern Nankai Trough seen in high resolution | oral (invited)

Near Surface Geoscience Conference & Exhibition 2018 | Porto, Portugal
B. Owoc | The Discussion of the Uncertainty in the Traveltime Seismic Tomography | poster

A. Marciniak | Uncertainty Based Multi-Step Seismic Analysis for the Near Surface Imaging | poster

EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining | Porto, Portugal
M. Chamarczuk | Seismic interferometry for mineral exploration: passive seismic experiment over Kylylahti mine area | oral

Workshop: Worldwide Mineral Exploration Challenges and Cost-Effective Geophysical Methods | Porto, Portugal
M. Chamarczuk | Seismic interferometry reflection imaging for mineral exploration using ambient noise recorded with large-N geophone array | poster

XXXVII Sympozjum Polarne „PolarChange - Global Change" | Poznań, Poland
A. Marciniak | Seismic Tomography and MASW analysis of the results of Spitsbergen seismic permafrost study | oral

W. Gajek | Latest results of seismic monitoring of Hans glacier, Svalbard | oral

7th EAGE Workshop on Passive Seismic | Kraków, Poland
W. Gajek | Downhole microseismic monitoring at a pilot hydraulic fracturing site in Poland | poster

ESC General Assembly | Valetta, Malta
W. Gajek | Feasibility of 3-season long glacier monitoring by temporal seismic networks at Hans glacier, Svalbard | oral

A. Górszczyk | Facing the 3D Crustal-Scale Imaging via Full-Waveform Inversion of the Ocean-Bottom Seismometer Data | oral

Publications

M. Mulińska, M. Cyz, M. Malinowski, 2018, Brittleness prediction for the Lower Paleozic shales in Northern Poland.

M. Malinowski, 2018, Deeply concealed half-graben at the SW margin of the East European Craton (SE Poland)—Evidence for Neoproterozoic rifting prior to the break-up of Rodinia.

M. Majdański, J. Grzyb, B. Owoc, 2018, Near-surface structure of the Carpathian Foredeep marginal zone in the Roztocze Hills area.

A. Bagchi, 2018, Notion of Random Domino Automaton revisited.

M. Malinowski, M. Lewandowski, 2018, On the nature of the Teisseyre-Tornquist Zone.

W. Gajek, M. Malinowski, 2018, Results of downhole microseismic monitoring at a pilot hydraulic fracturing site in Poland - Part 2: S-wave splitting analysis.

W. Gajek, J. Trojanowski, M. Malinowski, 2018, Results of the downhole microseismic monitoring at a pilot hydraulic fracturing site in Poland - Part 1: Event location and stimulation performance.

M. Cyz, M. Malinowski, 2018, Seismic azimuthal anisotropy study of the Lower Paleozoic shale play in Northern Poland.

J. Trojanowski, 2018, Theory of the detection function for migration-based methods for the detection of microseismic events.

M. Malinowski, 2018, Underground Vertical Seismic Profiling with Conventional and Fiber-Optic Systems for Exploration in the Kylylahti Polymetallic Mine, Eastern Finland.

Chapters

M. Malinowski, M. Cyz, 2018, Późnosylurskie-wczesnodewońskie deformacje tektoniczne na przedpolu pomorskiego odcinka orogenu kaledońskiego; LXXXVI Zjazd Naukowy Polskiego Towarzystwa Geologicznego

Extended abstracts

Väkevä, S., E. Koivisto, M. Chamarczuk, M. Malinowski and the COGITO-MIN Working Group, 2018, Passive Seismic Three-Component Interferometry Experiment at the Kylylahti Mine Site, Eastern Finland, EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining, Porto, 5 pp.

Koivisto, E., Malinowski, M., Heinonen, S., Cosma, C., Vaittinen, K, Wojdyla, M., Chamarczuk, M., Riedel, M., Kukkonen, I. and the COGITO-MIN Working Group, 2018, From regional seismics to high-resolution resource delineation: Example from the Outokumpu ore district, Eastern Finland, EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining, Porto, 5pp.

Riedel, M., Cosma, C., Enescu, N., Koivisto, E., Komminaho, K., Vaittinen, K., Malinowski, M., 2018, Distributed Acoustic Sensing versus conventional VSP imaging of the Kylylahti polymetallic deposit, EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining, Porto, 5 pp.

M. Chamarczuk, M. Malinowski, D. Draganov, E. Koivisto, S. Heinonen, S. Juurela and the COGITO-MIN Working Group, 2018, Seismic interferometry for mineral exploration: passive seismic experiment over Kylylahti mine area, Finland, EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining, Porto, 5 pp.

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Mężyk, M. & M. Malinowski, 2018, Deep Neural Network and Multi-pattern Based Algorithm for Picking First-arrival Traveltimes, In 80^{th} EAGE Conference and Exhibition, Copenhagen, 5pp.

Gajek, W., Trojanowski, J., & Malinowski, M., 2018, Downhole Microseismic Monitoring At A Pilot Hydraulic Fracturing Site In Poland. 7^{th} EAGE Workshop on Passive Seismic, Kraków, 5 pp.

S. Väkevä, E. Koivisto, G. Hillers, M. Chamarczuk and M. Malinowski, 2018, 3C Seismic Interferometry at the Polymetallic Kylylahti Deposit, Outokumpu District, Finland, LITHOSPHERE 2018 Symposium, 2 pp.

S.Heinonen, M. Malinowski, G. Gislason, F. Hlousek, S. Buske and E. Koivisto, 2018, COGITO-MIN seismic reflection profiling for mineral exploration in Polvijärvi, Finland, LITHOSPHERE 2018 Symposium, 4 pp.

E. Koivisto, M. Malinowski, S. Heinonen, M. Riedel, M. Chamarczuk, C. Cosma, K. Vaittinen, M. Wojdyła and the COGITO-MIN Working Group, 2018, Testing of seismic mineral exploration methods at different scales at the Kylylahti polymetallic mine site, Eastern Finland, LITHOSPHERE 2018 Symposium, 4 pp.

A. Górszczyk, S. Operto, L. Schenini, 2018, Crustal-scale depth imaging via FWI of the OBS data and PSDM of the MCS data a tour over the eastern Nankai Trough seen in high resolution, Proceedings of the 13^{th} SEGJ International Symposium, 5 pp.

Marciniak, A., Stan-Kłeczek, I., Idziak, A., & Majdański, M. 2018, Uncertainty Based Multi-Step Seismic Analysis for the Near Surface Imaging. In 24th European Meeting of Environmental and Engineering Geophysics, 5 pp.

Owoc, B., Górszczyk, A., & Majdański, M. 2018, The Discussion of the Uncertainty in the Traveltime Seismic Tomography. In 24th European Meeting of Environmental and Engineering Geophysics, 5 pp.