A summary of research activities

1. Name, Surname

Michał Malinowski

2. Education

2000 – MSc, Eng. in exploration geophysics, Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology in Cracow

2006 – PhD in Earth Sciences, thesis entitled „2D and 3D modeling of the Earth crust in southern Poland based on integrated reflection and refraction methods", Institute of Geophysics PAS in Warsaw

3. Employment

2001-2006 Research Assistant, Deep Seismic Sounding Lab, Institute of Geophysics PAS in Warsaw

from 2006 – Assistant Professor, Department of the Lithospheric Research, Institute of Geophysics PAS in Warsaw

4. Scientific achievement submitted for evaluation of the Committee:

a) title of the achievement,

Advanced methods of processing and modeling of seismic data for imaging complex geological structures and resources exploration

b) (author/s, title/s, year, publisher),

[1] D. White, D. Secord, **M. Malinowski**, 2012, 3D seismic imaging of volcanogenic massive sulfide deposits in the Flin Flon mining camp, Canada: Part 1 - Seismic results, *Geophysics,* 77, WC47-WC58.

[2] **M. Malinowski,** E. Schetselaar, D. White, 2012, 3D seismic imaging of volcanogenic massive sulfide deposits in the Flin Flon mining camp, Canada: Part 2 - Forward modeling, *Geophysics*, WC81-WC93.

[3] D. White & **M. Malinowski**, 2012, Interpretation of 2D seismic profiles in complex geological terrains: Examples from the Flin Flon Mining Camp, Canada, *Geophysics,* 77, WC37-WC46.

[4] **M. Malinowski** & D. White, 2011, Converted wave seismic imaging in the Flin Flon mining camp, Canada, *Journal of Applied Geophysics*, 75, 719-730.

[5] **M. Malinowski**, S. Operto, A. Ribodetti, 2011, High-resolution seismic attenuation imaging from wide-aperture onshore data by visco-acoustic frequency-domain full-waveform inversion, *Geophys. J. Int.*, 186, 1179-1204.

[6] **M. Malinowski**, 2009, Structure of the crust/mantle transition beneath the Variscan foreland in SW Poland from coincident wide-angle and near-vertical reflection data, Tectonophysics, 471, 260-271.

[7] **M. Malinowski** & S. Operto, 2008, Quantitative imaging of the Permo-Mesozoic complex and its basement by frequency domain full-waveform inversion of wide-aperture seismic data from the Polish Basin, *Geophysical Prospecting*, 56(6), 805-825.

c) description of the scientific achievement

Introduction

Before PhD thesis my research was mostly confined to modeling and interpretation of wide-angle reflection/refraction (WARR) deep seismic soundings. As I have pointed out in my PhD thesis, my research interests have been evolving toward methodology of modeling and processing seismic data, especially integrating seismic refraction and reflection methods on experimental scales between crustal and industrial exploration. Regarding this, it is worth to mention establishing collaboration with the research team led by dr. S. Operto from France, developing innovative full-waveform inversion methodology. Two papers ([5] and [7]) and number of conference presentations (e.g. extended abstracts like Malinowski & Operto, 2006; Malinowski et al. 2007b; Malinowski et al. 2009; Malinowski et al. 2011ab) arise from this collaboration. I consider paper [5] as my major scientific achievement so far. Paper [6] describes my trials to implement reflection seismic techniques to WARR data.

Trying to search for innovative and unconventional solutions in seismic exploration, I took Visiting Fellow (post-doc) position at the Geological Survey of Canada in Ottawa. I was involved in processing and interpretation of a unique dataset acquired in the Flin Flon mining camp (Manitoba, Canada). It was acquired within the federal government Targetted Geoscience Initiative-3 programme, aiming at ore deposit exploration through integrative approach of various earth science disciplines. I have been continuing my work in this project upon my return to Poland, since I have received a HOMING scholarship from Foundation for Polish Science. My research was among pioneering work within so called hardrock seismic exploration. Four out of the submitted papers are related to this research topic (papers [1] to [4]). Three of them were published in a special issue of "Geophysics" devoted to "*Seismic methods in mineral exploration and mine planning*". Two more papers (not listed here) are accepted for publication in a special issue of "Economic Geology". Several conference presentations were delivered based on this research (e.g. following extended abstracts: Malinowski et al. 2008; White et al., 2008; Malinowski & White, 2009, Malinowski et al. 2010, White & Malinowski, 2011; Malinowski et al. 2012).

In recent years there has been an increasing interest in better imaging of the sub-surface for locating nuclear waste deposit sites, monitoring CO_2 sequestration, assessing natural hazards and characterize geothermal and oil and gas reservoirs. In particular, due to the decline in global oil and gas reserves, the oil and gas industry is seeking targets in deep, geologically complex structures. Exploration in such areas requires new methodologies, therefore search for novel and unconventional approaches in modeling and processing seismic data form common basis for the presented achievement entitled "***Advanced methods of processing and modeling of seismic data for imaging complex geological structures and resources exploration".*** This research has direct implications for exploration both for mineral and hydrocarbon resources. The areas of application are different. Papers [1]-[4] pertain to Canada, papers [5]-[7] are related to the area of Poland.

Papers [1]-[4]

Searching for new ore deposits (mostly base metals) using geophysical methods seems a little strange from the Polish perspective, however it is one of the most important challenges for European science. Due to the development of IT technologies there is an enormous demand for raw materials, especially rare earth metals. Europe is strongly depended on the providers from outside the continent. It is becoming a hot-topic, which could be exemplified by a 2011 European Geoscience Union General Assembly where a panel discussion was held „*How will Europe face the raw materials crisis*?". During the same conference, a special session entitled „*Mineral systems: from geological, geochemical and geophysical data to metallogenic systems simulation*" was organized as well as there was a *keynote lecture* of the German "*Geotechnologien*" organization entitled „*Development of Technologies for the Efficient Exploration, Exploitation and Usage of Mineralogical and Metallic Resources*" delivered.

The above mentioned Geological Survey of Canada programme called *Targeted Geoscience Initiative-3*, in which I was involved as a post-doc, has been considered as a great success. The project team was awarded by the Natural Resources Canada in *2011 (Earth Sciences Sector Team Recognition Award)* and in *2012 (Departmental Achievement Award*). Project's results were also highly-ranked internationally and some collaboration with European institutions was established (University of Uppsala, University of Helsinki).

Papers [1] and [2] complement each other. Paper [1] describes results of a 3D seismic survey performed in the Flin Flon mining camp (Manitoba, Canada) for volcanogenic massive sulfides (VMS) exploration. Imaging of the VMS deposits is a big challenge for seismic methods. It is related to the fact that the ore lenses are hosted in different volcanic rock types ranging from rhyolites to basalts, that are characterized by high P-wave seismic velocities (Vp=6000-7000 m/s) and a large degree of heterogeneity/scattering. High degree of deformation, steep dips (45-60^o) and deposit thickness of maximum 20-30 m add up to those challenges. 3D seismic survey (17 m^2) described in paper [1] is the world's first in terms of 3-C seismic acquisition for mineral exploration. It was accomplished in a very rough environment. It was partially located in the active town as well as active mine and smelter operations. In addition, a mix of different sources (dynamite, Vibroseis, air-gun) was used, which makes processing especially challenging. Despite those challenges, a good imaging of the existing ore deposits (Calinan and „777" ore zones) was achieved. A number of potential target zones was also detected (this issue was studied by White et al. 2012, accepted for publication in *Economic Geology*). In case of the more shallow ore zone (Calinan), a clear diffraction signature was observed in the DMO-processed volume. In case of the deeper "777" ore zone, a clear diffraction response is missing. It could be partially attributed to environmental issues (active town and a lake), as well as the change in lithology (rhyolite vs basalt as host rock) and ore composition (pyrhottite vs pyrite-rich ore). Differences in imaging of those two ore zones have led to the research presented in paper [2]. One of the most important findings of this paper is the detection of the polarity change in the response of the Calinan ore lens, which occurs immediately in a place where the ore changes from the intact one to mined-out and back-filled one. The impedance contrast of the intact ore and the ore back-filled with a tailings-pond paste is of the same order – only the sign is different. It demonstrates the potential of 3D seismic in ore exploration.

Paper [2] follows paper [1]. Several issues raised in paper [1] are being explored in paper [2] through the use of seismic forward modeling. It is probably the first use of massive seismic modeling for interpreting 3D seismic survey related to mining exploration. The biggest challenge encountered was related to model building. This model was based on so called *geological knowledge cube* (Schetselaar i in., 2010; 2012), in which surface geological mapping, borehole data, 2D and 3D seismic horizons were integrated using geostatistical and 3D GIS methods. It was necessary to transform this model composed of geological surfaces to a volumetric, regular-grid model for seismic modeling. There is a detailed description how to transform surface-based model into volumetric one. A phase-screen metod (Wild et al. 2000) was employed for seismic modeling. It is significantly faster as compared to e.g. finite-difference method. Therefore, it was possible to simulate the whole 3D survey in a pre-stack mode. Synthetic seismic data were subjected to processing, similarly to the real data. In order to explain differences in imaging of the Calinan and "777" ore zones, both the changes in host rock and ore composition were considered. Both factors were proven essential for explaining the differences in observed seismic responses. Some important conclusions were derived through the analysis of the migration process. A post-stack migration of noisy DMO data effectively focus seismic energy and improves S/N ratio. In case of the synthetic data nearly identical results were obtained using pre-stack and post-stack migration. Examples presented in paper [1] favour post-stack migration. It could be explained as being due to the highly irregular survey geometry, typical for hardrock seismic. Finally, seismic modeling could be used for direct ore targeting. Assuming sufficient validity of the model, all the anomalies that are present in the real data and which are not predicted by the model, could constitute potential exploration targets.

Paper [3] demonstrates how 2D crooked line data could be used for spatial location of the imaged structures. In case of *hardrock seismic exploration* 2D seismic data are acquired in a geological medium which is intrinsically 3D in nature. Therefore, most of the reflections observed in 2D sections are related to the *out-of-plane* energy. There are some methods which allow to exploit 3D information from *crooked line geometries* (e.g. *cross-dip analysis*). Here, a 3D *post-stack* migration of 2D data is used. It is a very unconventional approach since 2D data are characterized by a lack of enough *cross-dip* component. The 3D migration process distributes energy from a specific reflection observed on the 2D stacked section over a surface in 3D that is consistent with the observed two-way reflection traveltimes. This 3D surface does not correspond to a 3D reflector (i.e., geologic horizon), but its intersection with the (unknown) imaging plane defines a trace along the reflector in 3D. Thus, the spatial coincidence of this 3D surface with geologic contacts from drillholes can be assessed directly as a means of evaluating the contact as the source of the observed reflections. The input data were taken from the 2D processing results of three selected profiles from the Flin Flon camp (Malinowski et al., 2008). 3D migration of the 2D data was accomplished using the following steps: A 3D volume was constructed with 5 ×5 m bins containing zero amplitude traces. A rectangular 3D volume extending 900 m to either side of the 2D seismic profile was designed to accommodate crossline migration of reflections for moderate crossline dips to depths of up to ~1500 m. The original 2D DMO stack was decimated from the original 2.5 m bins to 5 m bins to match the bin dimensions of the 3D seismic volume. The resultant traces were used to populate the 3D volume at CDP locations corresponding to the 2D binning line. This construction process results in a sparsely occupied 3D volume having nonzero amplitude traces only within those 3D bins which are spatially coincident with the corresponding 2D CMP bin locations. Subsequently, a constant-velocity phase-shift migration was applied to those data. Selected inline and crossline sections from 3D volumes were compared against the borehole data and geological contacts. In case of deviated boreholes and dipping layers such a approach allows to match observed reflectivity in 2D with borehole data. One of the presented examples considers imaging of the ore lenses that are located few hundred meters west of the nominal 2D profile line. Those ore lenses dip toward south-east (towards the profile line). The only possibility to image those lenses is to consider out-of-the-plane events. Looking at the inline section from 3D migration located 250-300 m west of the imaging plane, a very good correlation of the observed reflectivity with the projection of the ore lenses is obtained. It confirms the inference that indeed this 2D line imaged existing ore bodies. Another important aspect of applying 3D migration method is related to mis-ties analysis of crossing profiles. 2D migration leads to the reflection events which dips are not equal to the true ones, if those reflection events originate at layers with strong out-of-the-plane component. In such a case, a significant mis-tie at crossing point of 2D lines is expected. Analyzing 3D migration volumes from crossing profiles, it is possible to find a location at which migrated events fit together. It allows to determine a true orientation of the reflection event. It is worth to stress that such a methodology could be employed in other settings, where significant out-of-the-plane energy expected (e.g. exploration in the Polish Carpathians).

Paper [4] deals with converted P-S wave processing performed for selected 2D profiles from the Flin Flon camp. Seismic data acquired within the TGI-3 project are unique in a sense that 3-C recordings were used with a broadband MEMS-type sensors. Apart of the work of Snyder et al. (2009) it is the only known application of converted wave processing in surface seismics related to mineral exploration. First, a feasibility study using synthetic finite-difference modeling was performed to proof the ability of obtaining detectable responses from P-to-S converted energy considering measured S-wave velocity contrasts, which are much lower than for the P-wave case. Ore deposits of a sufficient size and predominantly pyrite composition should produce a relatively large P-S reflection coefficient. Other lithological contacts, like rhyolite/basalt, produce weak P-S response, although it could be changed where an alteration zone is encountered. An important conclusion of the modeling part pertains to the possibility of using vertical component data for P-S processing. It is demonstrated that the P-S energy observed on the vertical component is highly contaminated with a P-P energy and therefore converted wave processing applied to this component only is not effective. A customized processing was applied to selected three 2D profiles. Processing approach ws adopted to steep dips and strong heterogeneity. In such an environment, the classic approach using data binning in *asymptotic common-reflection point* (ACRP) gathers break down. According to Den Rooijen (1991), transformation of the data to ACRP domain, could be obtained through the application of the *dip-moveout* (DMO) operator. Therefore, converted-wave DMO was applied to the data sorted into classical CMP gathers. A crucial point in P-S wave processing is the determination of the S-wave statics. Snyder et al. (2009) procedure was adopted in which the statics is determined by the hand-statics picked on the common-receiver stack of the radial-component data (after P-P statics and LMO correction). As an alternative to the DMO-post-stack migration route, pre-stack migration was employed. In some cases, pre-stack type migration was superior to the more standard approach. The comparison between P-P and P-S sections is not straightforward. In principle, P-S reflectivity is weaker than the P-P one, which can be partially attributted to a lower S/N ratio of the horizontal component data. Steep dips seem to be better imaged in P-P data and their apparent dips are different in both wave-modes sections. It is explained through different sensitivities of both P-P and P-S data to illumination angles or differences in subsurface sampling (CDPs vs common-conversion points). Despite the differences, some of the P-S reflectivity could be correlated with the events in the P-P sections. It allows to determine approximate Vp/Vs ratios – an important rock-type indicator. Obtained Vp/Vs ratios are in a good agrement with the inferred lithologies, e.g. Vp/Vs = 1.55-1.69 for felsic rocks, Vp/Vs = 1.7-1.9 for mafic rocks. It is worth to stress that the same methodology for processing converted wave data originating in complex geology could be applied in other regions, like in the Polish Carpathians.

Papers [5]-[7]

During the SUDETES 2003 WARR project (Grad et al. 2003), a special seismic experiment called GRUNDY 2003 was organized (Śliwiński i in., 2006; Malinowski i in., 2007a). It aimed at the recognition of the sub-Zechstein strata through the use of wide-angle low-frequency seismics. An unique experimental design provided data that were well-suited for the application of the full-waveform inversion method (FWI) (low-frequency, long-offset).

Since the pioneering work of Tarantola (1984), an advanced velocity model building tool, i.e. full-waveform inversion/tomography is being developed. FWT combines transmission-like imaging with migration-like imaging in single algorithm. It offers Earth's imaging with an unprecedented enhancement in resolution as compared to ray-based methods (like travel time tomography) (Virieux & Operto, 2009).

This method remains still underexplored and it has not become a standard imaging tool yet. The reasons are twofold. First, current implementations of the FWT are demanding in terms of the input data, which should contain sufficiently low frequencies and wide-apertures (i.e. short and long offsets). Secondly, the potential of the FWT has been mostly demonstrated on synthetic datasets. Only a few real-data applications have been reported so far, however it is increasing from year to year (see e.g. a spectacular 3D example by Sirgue et al. 2010). Until 2008, there were a few published real-data FWI examples (e.g. Ravaut et al., 2004; Operto et al., 2006; Bleibinhaus et al., 2007). In this regard, paper [7] fits to this pioneering era of FWI development. Currently, FWI is evolving towards the multiparameter inversion in order to exploit as much information as possible from the recorded wavefield. Paper [5] is an excellent illustration of such an approach.

Papers [5] and [7] tackle the applicability of the FWI method to the GRUNDY 2003 experiment data. Both papers arise from the collaboration started in 2005 with the French SEISCOPE team led by dr. S. Operto and prof. J. Virieux. It is one of the leading-edge academic team related to FWI development.

Paper [7] is an extension of an expanded abstract presented during EAGE conference in 2006 (Malinowski & Operto, 2006). It was published by invitation to participate in a special issue of "Geophysical Prospecting", devoted to FWI method. It is the first case, when the FWI method is used in Poland and a first world-wide example of applying FWI to an offshore data with offsets up to 50 km, recorded in the deep sedimentary basin (namely Polish Basin). FWI was implemented in the acoustic approximation, using frequency domain modeling. Data preprocessing followed Ravaut et al. (2004) and amplitude normalization. Inverted data window was kept narrow, including first-arrivals and wide-angle reflections close to the first-breaks. Inversion was performed sequentially for frequencies ranging from 4 to 16 Hz in 1 Hz intervals. Lower frequency limit was chosen based on natural frequency of the geophones used in the GRUNDY 2003 experiment (4.5 Hz). Analysis of the frequency panels indicate little coherent energy below this frequency. Presented implementation of the FWI is the combination of the *early-arrival* FWI (Sheng et al. 2006) and the *efficient* FWI (*sensu* Brenders & Pratt, 2007). A high-resolution P-wave velocity model was obtained from the FWI. It constitutes a material for interpretation on its own. Differences between final model from FWI and the starting model from first-arrival tomography (perturbational model) resemble a low-pass filetered version of depth-migrated seismic section, emphasising structural details of the model. FWI model was verified through demonstrating the data fit (both in frequency and time domains) and comparison with the exisiting geological and borehole (VSP) data. Structural interpretation of the FWI model is consistent with the classical CDP processing applied to the same profile. Horizons picked based on the FWI model were further verified by the a posteriori ray-tracing modeling. It was essential for the horizons selected below the Zechstein. The interpreted base of Permian and upper Paleozoic seem to confirm Malinowski et al. (2007a) inferences regarding the existence of an Carboniferous foredeep. This paper clearly demonstrates how seismic interpretation could be enhanced through the use of a high-resolution velocity model, especially, when conventional seismic faces imaging problems (imaging below Zechstein cover).

Paper [5] is a continuation of the research Publisher in paper [7] and it forms a summary of the long-term research on the applicability of the multiparameter FWI, in particular its ability to recover seismic attenuation (Q parameter) as an important diagnostic factor for lithology and fluid saturation discrimination. Initial results were shown during the *European Association of Geoscientists and Engineers* (EAGE) conference in 2007 (Malinowski et al. 2007b) and during a special EAGE workshop devoted to attenuation (Malinowski et al. 2009). Those results were also shown (Malinowski i in. 2011b) during the annual meeting of the *Society of Exploration Geophysicists* (SEG) during the workshop entitled *Full Waveform Inversion: Beyond the Phase of Direct Acoustic Arrivals*. It is worth to stress that those results were noticed by the oil&gas industry by soliciting the author to submit a proposal for Eni Award 2013 in the „*New Frontiers of Hydrocarbons (Upstream)*" category.

The trials to recover seismic Q refer mostly to cross-hole data (Pratt et al. 2005). Only few surface seismic data examples are known (Hicks and Pratt, 2001; Smithyman, 2009). Mulder and Hak (2009) and Hak and Mulder (2010) questioned the ability of jointly reconstructing Vp & Q when narrow aperture data are used. Same authors (Hak and Mulder, 2011) conclude that such a inversion is possible, once a sufficient number of non-linear iterations is performed and a casual Q model is used. Those issues were addressed based on theoretical derivations and synthetic modeling using visco-acoustic FWI. Conclusions from the radiation pattern analysis (section 3.1) are as follows: when the Q is going to low values, data sensitivity to Q increases relatively to the sensitivity of the data to velocity. Sensitivity of the data to Q is diminishing for lower Q values. It means that inversion for Q for low frequencies and weakly-attenuating media could be unstable. Those inferences are confirmed by the *grid-search analysis* (section 3.2), for simple spherical Vp i Q inclusions. Analysis of the misfit function for different Vp and Q values (different from the true ones) provides insight into the sensitivity of the joint inversion for the errors in those parameters. For parameter Q, the misfit function is much more sensitive for Q values lower than the true value than for the Q value higher than the true one. It illustrates the fact, that the inversion for Q could be unstable for weakly-attenuation media. Sections 3.3 and 4. deal with the synthetic examples of deriving Vp and Q from FWI based on complex models. The most interesting results were obtained here for the realistic test with surface acquisition based on the GRUNDY 2003 experiment. Indeed, it confirms predictions of Hak and Mulder (2011) that it is possible to jointly recover Vp and Q when sufficient (40 in this case) number of iterations of non-linear inversion is performed. During the synthetic tests, the influence of the near-surface layer on the deeper inversion performance was analyzed. A thin (100-m) low velocity, attenuating layer was put atop the model. Despite the fact, that the starting model for inversion included this layer, the acoustic FWI overestimated Vp values in this layer and the overall Vp model was contaminated with artifacts. On the contrary, visco-acoustic FWI provided very good recovery of both Vp and Q, although the recovered Q model is smoother than the true one. In the next step, visco-acoustic FWI was applied to GRUNDY 2003 data. Data preprocessing was similar to the one presented in paper [5], with a significant distinction in terms of the amplitude handling. Frequency domain deconvolution (spectral whitening) was performed with the normalized operator, which means that the amplitude with offset changes are preserved. An unified workflow of imaging land data with FWI is presented. It consist of: (1) data preprocessing and starting model building; (2) actual FWI; (3) model assessment. One of the most important finding of this paper is the ability of obtain a reliable Vp model even in the acoustic approximation, when the attenuation (and other factors affecting amplitudes) effects are heuristically removed through normalization of the amplitudes. It is a conclusion that relates also to paper [7]. When amplitudes are properly preserved during processing and wide-aperture data are present, it is possible to jointly recover Vp and Q. An important diagnostic of the recovered models validity is the a posteriori source wavelet estimation. It is sensitive for errors both in Vp and Q. Source wavelet estimation performed in the starting model helps in determining starting Q model through matching the AVO trend of synthetic and real data. Finally, recovered Vp & Q models were verified by time-domain finite-difference modeling. There was an excellent fit of the simulated and real data observed, which in turn validates obtained results.

Final part of the paper is devoted to interpretation of the results. Together with the stratigraphic, other geological and well-log data, it was possible to interpret the Q model in terms of lithology/fluid content. High-attenuation zones were interpreted as the areas of high clay content or brine saturation, which is confirmed by well-logs.

This paper provides some new perspectives for the qualitative and quantitative seismic interpretation and it emphasizes the benefits of the multiparameter FWI applied to surface seismic data. In sedimentary basins like the Polish Basin, attenuation plays a major role in imaging conditions. Therefore the research presented here opens some perspectives for application of inverse-Q filtering techniques in routine processing of seismic reflection data for resolution enhancement.

Paper [6] is also based on the GRUNDY 2003 dataset, in particular on its unique acquisition scheme, during which, the data were recorded in the extended offset range (100-150 km) along SUDETES 2003 S01 profile. Thanks to a dense shooting system (30 shot points every 1.5 km on average) the recorded WARR data were processed using reflection seismic approach (CDP method). It is only rarely performed in case of WARR data. It is demonstrated how this kind of methodology of processing WARR data could enhance the interpretation complementing it with a reflectivity image. For a typical WARR survey with shot spacing of 30-50 km, applicability of such a methodology is strongly reduced.

Through the processing of the wide-angle reflections a good quality section was obtained revealing reflectivity in the lower crust and uppermost mantle. In addition, near-vertical incidence (NVI) data from the GRUNDY 2003 experiment were reprocessed focusing on the deeper part down to 20 s TWT. A new processing workflow was devised for this low-fold (max. of 30) data. Finally, a joint refraction/reflection tomography was performed along the SUDETES 2003 S01 profile using Moho reflected phases – both wide-angle PmP arrivals and the NVI data from the GRUNDY 2003 section. For final interpretation, all the methods were combined in a comprehensive earth model with both velocity and reflectivity image. It provides a detailed picture of the crust and upper mantle in the Foresudetic Monocline/Dolsk Fault area. Despite the methodological aspects, there is a discussion on the geodynamical implications of this research. It is made in conjunction with the earlier studies (e.g. POLONAISE'97 experiment). The findings of this paper seem to confirm the idea of Avalonian crust being thrusted over the lower crust of Baltica. This lower crust was in turn transformed into eclogite. Therefore, a vast area of the upper mantle of the Foresudetic block could be composed of eclogite. This is contrary to Grad et al. (2008), who interpreted upper mantle in the same area as being composed of dunite.

Conclusions

The set of seven papers presented here as my scientific achievements submitted for obtaining habilitation degree is related with working out a methodology of processing, modeling and interpretation of unconventional seismic data. Those data were acquired over different scales and different geological (e.g. *hardrock terrains*) and geographical settings. However, the challenge here remains the same: we would like to obtain the best possible image of the subsurface for better understanding how the earth systems are working. It is worth to mention that the methods I have developed or co-developed during my research are directly applicable to other areas and studies, e.g. interpretation of the deep regional reflection profile in SE Poland (see section 5), analysis of the data from the deep regional seismic programme called PolandSPAN or modeling the near-surface data acquired over a quick-clay landslide site in Sweden (see section 5). The range of applications from shallow to deep ones could be questioned, however I believe that equal challenges exists both in shallow and deep seismic data, despite the scale on which the imaging is performed. Based on this statement of my research interests, in May 2012, I established "Seismic Imaging Team" at my host Institute.

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5. Other scientific achievements

Interpretation of the large wide-angle reflection/refraction surveys

I took part in the experiment and interpretation team of the world's largest wide-angle reflection/refraction survey to date – CELEBRATION 2000, that covered the area of Central Europe and was organized in the collaboration of more than 20 institutions from Europe, USA and Canada. I derived and interpreted 2D and 3D crustal velocity models based on CELEBRATION 2000 data in complex geodynamic settings: transition from Precambrian to Paleozoic Europe (Malinowski et al. 2005) and in the Pannonian Basin. Malinowski et al. (2005) paper was awarded "Top-50" highly cited papers between 2005-

2010 in “Tectonophysics”. I was also analyzing surface waves recorded during CELEBRATION 2000 experiment for determining shallow Vs structure (Malinowski 2005).

Building a large 3D velocity model (500x500 km) of the crustal structure in SE Poland was a part of my PhD thesis (Malinowski 2006). It was further developed in two papers published in “Geophysical Journal International” (Malinowski et al. 2008;2009). As a member of CELEBRATION 2000 and SUDETES 2003 Working Groups, I'am a co-author of a few publications from the JCR list, including a *Geological Society of America* monograph (Grad et al. 2007). The following publications arise from those studies:

Papers:

M. Malinowski, Środa, P., Grad, M., Guterch, A. and CELEBRATION 2000 Working Group, 2009, Testing robust inversion strategies for three-dimensional Moho topography based on CELEBRATION 2000 data, *Geophys. J. Int.* 179, 1093–1104, doi: 10.1111/j.1365-246X.2009.04323.x

M. Malinowski, M. Grad, A. Guterch and CELEBRATION 2000 Working Group, 2008, Three-dimensional seismic modelling of the crustal structure between East European Craton and the Carpathian Mts. in SE Poland based on CELEBRATION 2000 data, *Geophys. J. Int.*, 173, 546-565.

M. Malinowski, A. Żelaźniewicz, M. Grad, A. Guterch, T. Janik and CELEBRATION Working Group, 2005, Seismic and geological structure of the crust in the transition from Baltica to Palaeozoic Europe in SE Poland - CELEBRATION 2000 experiment, profile CEL 02, *Tectonophysics* 401(1-2), 55-77.

M. Malinowski, 2005, Analysis of short-period Rayleigh waves recorded in the Bohemian Massif area during CELEBRATION 2000 experiment, *Studia Geophys. Geodet.* 49, 485-500.

Invited presentation:

M. Malinowski and CELEBRATION 2000 Working Group, 2004, 3D seismic modeling of crustal structure between East European Craton and the Carpathians Mts. in the SE Poland based on CELEBRATION 2000 data **(invited)**, 1st General Assembly of European Geosciences Union, Nice, France.

Interpretation of a low-frequency seismic survey in the Polish Basin using novel techniques

I was the principal investigator of the oil and gas industry-funded GRUNDY 2003 experiment. This unique experiment stands in between the scale of crustal and industrial seismic investigations and it offered a rare opportunity to test variety of methods: reflection processing, refraction/reflection travel time tomography, prestack-depth migration and finally – full-waveform inversion. Developing a suitable work-flow of interpreting this kind of data constitutes part of my PhD thesis. The following publications are based on GRUNDY 2003 data (except papers [5]-[7]):

Papers:

M. Malinowski, M. Grad, A. Guterch, E. Takacs, Z. Śliwiński, L. Antonowicz, E. Iwanowska, G. R. Keller, E. Hegedus, 2007, Effective sub-Zechstein salt imaging using low-frequency seismics - results of the GRUNDY 2003 experiment across the Variscan front in the Polish Basin, *Tectonophysics*, 439, 89-106.

Śliwiński, Z.; Antonowicz, L.; Iwanowska, E.; **Malinowski, M.**; Grad, M.; Guterch, A.; Keller, R.G.; Takács, E. & Working Group, 2006, Interpretacja zasięgu eksternidów waryscyjskich na eksperymentalnym profilu sejsmicznym GRUNDY 2003, *Przegląd Geolog.,* 1/2006, 45-51 (in Polish).

Extended abstracts:

M. Malinowski, 2005, Velocity macro-model estimation by wavefield continuation. Application to GRUNDY 2003 data. 67th EAGE Conference & Exhibition, Madrid.

10 more conference presentations (including AGU, EGU, EAGE) were delivered based on this research.

Processing and interpretation of deep seismic reflection data

The methods developed through my research are directly applicable in processing and interpretation of the deep seismic reflection data recently acquired in SE Poland over a 240-km long profile (called POLCRUST). Those data were acquired in a Academia-Industry partnership led by Institute of Geophysics PAS and funded both by the Ministry of Environment and Polish Oil and Gas Company. I was a key person involved in this project, being responsible for processing and interpretation of both deep reflection and refraction data. I was also responsible for preparing final reports. Several papers are being prepared right now for submission for highly-ranked journals (*Geophysical Research Letters, Geology, Tectonics*).

Monitoring of the quick-clay landslides using integrated geophysical techniques

Since Sept 2011 I'm taking part (together with my PhD student) in a research project coordinated by the Uppsala University devoted to *Integration of geophysical, hydrogeological and geotechnical methods to aid monitoring landslide in Nordic countries: A 4D approach for landslide risk assessment*. This project is sponsored by the *Society of Exploration Geophysics* within its *Geoscientist without Borders* programme. Within this project, a comprehensive suite of geophysical techniques was used, including 2D and 3D seismic data. It is a very good opportunity for testing advanced processing and modeling methods like full-waveform inversion and verify its method through the comparison with other methods. Initial results of the FWI are promising. Our research was presented during three conferences so far, attracting a lot of interest. The following publications are related to this study:

Papers:

A. Adamczyk, **M. Malinowski** & A. Malehmir, 2012, Application of first-arrival tomography to characterize a quick-clay landslide site in southwest Sweden, *Acta Geophysica* (minor revision required).

Extended Abstracts:

A. Adamczyk, **M. Malinowski** & A. Malehmir, 2012, Near-surface high-resolution velocity model building using full-waveform inversion: a case study from a quick-clay landslide site in southwest Sweden, SEG Research Workshop – Velocity Model Building in Complex Geology, Charleston (extended abstract).

A. Adamczyk, **M. Malinowski** i A. Malehmir, 2012, Application of Full-waveform Inversion to Characterize Quick-clay Landslide Site in Southwest Sweden, 74th EAGE Conference & Exhibition, Kopenhaga (extended abstract).