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GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN CSIC GEO3BCN Geosciences Barcelona

Scientific Council of the Institute of Geophysics
Polish Academy of Sciences

64 Ksiecia Janusa St.
01-452 Warsaw, Poland
Phone +48 22 6915 950
office@igf.edu.pl

**PhD Thesis review, assessment:**

Candidate: Brij Bhushan Singh
Title: **High-resolution velocity model building and advanced depth imaging in hardrock environment**
Supervisors: Prof. Dr. Michal Malinowski
Dr. Andrzej Górszczyk

In order to asses the candidate's capacity to develop independent research its important to emphasize the relevance of the topic. The current EU efforts towards the Net zero requires strong push for the development of renewable energy sources which is not viable without an increase in exploitation of natural resources and in particular of minerals. Therefore, having clear images of the subsurface is imperative. Conventional successful geophysical methods used to see beneath a mine site include: potential field and electromagnetic methods. These are helpful in order to delineate potential mineralized zones at shallow depths. However, 2D and 3D Seismic reflection imaging is the only surface method that can provide highly defined images of deep underground geological structures as it has been proven by the hydrocarbon exploration and exploitation industry. Seismic imaging has greater penetration with sufficient resolution, compared with other geophysical methods and can, therefore, better complement drilling and exploration programs. However, as is evidenced in several studies, the overall performance of seismic methods is highly site- and geology-dependent. The present trend in exploration and exploitation of mineral resources at great depth is leading to an increase in the use of seismic methods for targeting deep-seated mineral deposits and for deep mine planning. Seismic methods can provide high-resolution images of the geologic structures hosting mineral deposits and, in a few cases, can even be used for the direct detection of mineral deposits at depths greater than 1 km. The relatively slow establishment of seismic imaging techniques in aiding the discovery in the mining sector is strongly dependent on the assessments of imaging challenges some of which are addressed within this PhD. Memoir and, research carried out by the candidate B. Singh.

The application of reflection seismic in mineral exploration is maturing and a number of on land surface seismic surveys have been acquired by academia in collaboration with mining enterprises, such as the cases analyzed in this thesis. The data sets acquired by these efforts present a number of critical challenges, which have been identified and properly addressed by the candidate's research work. Factors like: low-impedance contrast between mineralization and host rock, geological complexity, high degree of heterogeneity that results in strong scattering of seismic energy, low signal-to-noise ratio (SNR), irregular shot and receiver geometries are some of the key challenges associated with the application of seismics in a hardrock (crystalline) subsurface environments. These are some of the identi-

c/ LLuís Solé Sabarís s/n
08028 Barcelona, Spain
Phone: +34-934095410
Fax: + 34-934110012

fied problematic issues discussed and, which are overcome by the candidate's proposed imaging/processing solution.

The thesis major question is that due to the complexity and heterogeneity characteristic of the media at mine sites, conventional seismic time imaging workflows in seismic data processing is not sufficient for successful high resolution imaging of the subsurface. Therefore, more sophisticated, elaborate depth imaging schemes are required. In these cases imaging difficulties can be further enhanced. For example: irregular acquisition geometry and sparse subsurface coverage due to logistical issues; environmental or human generated acoustic noise due to surface and mine exploitation activities. The candidate has demonstrated his knowledge of the topic by identifying the imaging challenges and developing alternative processing schemes to overcome this critical issue in 2D, as well as, in 3D data sets.

The candidate through out the PhD memoir demonstrates he has acquired extensive knowledge on subsurface geologic model building, technical issues and seismic data processing skills. The memoir documents: his understanding of the problem and, intellectual capacity to integrate the available knowledge and data to reach a reliable solution. He is able to integrate data coming from different sources including: petrophysics (logs, borehole, rocks physical properties, etc.), potential field geophysics (gravity, electromanetics, ...), structural geology (surface geology maps, cross sections, etc).

The problem behind the candidate's research is to overcome the imaging difficulties that characterize conventional time-domain imaging approaches applied to reflection seismic data acquired in the hardrock environments. DMO followed by PoSTM fails to delineate the geologically complex targets due to the issues mentioned above (target complexity, steep dips, low impedance contrast, low SNR, sub-optimal illumination due to the terrain-imposed constraints resulting in crooked-line 2D or irregular and/or sparse 3D seismic surveys). Then, the key research hypothesis behind the scientific investigation is that these drawbacks (of time imaging schemes) can be overcome by depth imaging approaches. The candidate's first step is to determine the flaws in time imaging workflows. Therefore he analyzes 2D and 3D seismic data sets acquired over two different active mine sites. The Kylylahti poly-metallic deposit and, the Ludvika iron-ore mineralization are the two areas which the author uses to assess the imaging challenges.

The candidate compares the quality of the time-domain imaging with the depth imaging using sparse 3D seismic data from Kylylahti poly-metallic deposit. Then he explores the benefits of using: a specialized version of Kirchhoff Pre-Stack Depth migration (KpreSDM) as well as coherence based Fresnel volume migration (CBFVM). Furthermore, the candidate also devotes an effort in evaluating the pros. and cons. of ray-based imaging (KpreSDM, CBFVM) versus wave-equation based schemes such as Reverse Time Migration (RTM). As a result of this research exercise, shifting from standard time-domain imaging to depth imaging requires a robust and detailed velocity model, thus a model building tool/scheme is needed to overcome the seismic imaging challenge.

A leading edge, innovative and, original idea developed in the thesis is to use advanced full-waveform inversion (FWI) schemes coupled with RTM to constrain a robust velocity model of the subsurface. FWI is a relatively time consuming and computationally expensive scheme, however it brings unprecedented resolution in elastic/anelastic parameter models

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08028 Barcelona, Spain
Phone: +34-934095410
Fax: + 34-934110012

as compared to ray-based methods. High quality data is required ideally with: enhanced low frequencies and including a number of recorded arrivals sampling the subsurface targets over a broad range of scattering angles. Usually, these conditions are hardly met by the seismic data acquired on land. The candidate is aware that: compared to marine datasets, seismic data acquired on land, is often limited to vertical component recording sensors, suffers from low SNR, strong elastic effects, large near-surface velocity contrasts, heterogeneous topography variations, among other issues. Thus, the proposed joint FWI-RTM velocity building scheme results in a better velocity model characterized by relatively high accuracy and improves the images. Therefore the innovative approach is helpful for mine planning, and specially relevant for resource estimations.

The research carried out by the candidate is summarized in three scientific contributions which have been published in international research journals included in the JCR. These are:

Singh B., Malinowski M., Hloušek F., Koivisto E., Heinonen S., Hellwig O., Buske S., Chamarczuk M. & Juurela, S., 2019, Sparse 3D Seismic Imaging in the Kylylahti Mine Area, Eastern Finland: Comparison of Time Versus Depth Approach, Minerals 9, doi: 10.3390/min9050305

Singh B. & Malinowski M., 2023, Seismic imaging of mineral exploration targets: evaluation of ray- vs. wave-equation-based pre-stack depth migrations for crooked 2D profiles, Minerals 13, doi: 10.3390/min13020264

Singh B., Malinowski M., Górszczyk A., Malehmir A., Buske S., Sito Ł. & Marsden P., 2022, 3D high-resolution seismic imaging of the iron oxide deposits in Ludvika (Sweden) using full-waveform inversion and reverse time migration, Solid Earth 13, doi: 10.5194/se-13-1065-2022

These contributions although they feature a relatively recent publication date, they have already been cited, which is indicative of the relevance of the candidate's developed research. Through the PhD memoir the candidate reveals that he is able to identify and formulate a research problem as well a devising a scheme to address it. Actually, the three contributions establish a well justified research flow.

In the first contribution, the candidate addressees the quality of the time-domain imaging and compares it with the depth imaging using sparse 3D seismic data from Kylylahti. He establishes and explores the benefits of using a specialized version of depth imaging, (CBFVM) over conventional KPreSDM. This clearly states the main lines of the research problem.

In the second contribution using 2D data from Kylylahti and velocity model built through FAT determines the benefits and drawbacks of ray-based imaging versus wave-equation-based imaging (RTM). Establishing the critical role that the velocity model plays in subsurface imaging schemes.

Finally, in the third contribution sparse 3D seismic data from Ludvika is used to build an integrated depth imaging workflow. The scheme consists of an acoustic FWI which constrains and resolves a velocity model and, a RTM module used to removing the limitations of ray-based PreSDM. This paper introduces the FWI as a velocity model building tool in a hardrock environment. The RTM is entrusted to verify the validity of the FWI model.

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In summary, the PhD. Memoir evidences the candidate's high level of theoretical knowledge and technical experience in the discipline. Furthermore, it reveals the candidate's ability to independently carry out scientific research and publish his findings. The fact that the contributions published in internationally recognized scientific journals and, that they have already been cited denotes the originality and value of the findings. Therefore, after carefully assessing the manuscript I have a very positive opinion of the research carried out and strongly support the admission of the candidate for public defense of his doctoral dissertation.

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Prof. Dr. Ramon Carbonell
CSIC-GEO3BCN, Geosciences Barcelona
Spanish National Research Council

c/ LLuís Solé Sabarís s/n
08028 Barcelona, Spain
Phone: +34-934095410
Fax: + 34-934110012