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INSTYTUT GEOFIZYKI PAN
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Brij Singh Ph.D. thesis evaluation report

By

Dr. Gilles Bellefleur, Geological Survey of Canada

1) Assessment of the candidate's general theoretical knowledge in the discipline and the ability to independently carry out scientific research.

Mineral deposits often occur in challenging geological settings characterized by complex structures due to polyphase deformation and steep dips. The reflection seismic method, commonly used for oil and gas, has been adapted for mineral exploration. However, issues like low signal-to-noise ratios, irregular data acquisition, and complex geology challenge traditional seismic imaging methods. This thesis tackles the difficult problem of seismic imaging in the depth domain in mining environments. The candidate presents and compares results obtained from various seismic imaging techniques using real seismic data acquired over different mineral targets in Finland and Sweden. Each method is presented with pertinent information, allowing the reader to understand the principles, the key theoretical aspects, and challenges and limitations. This is done gradually, starting with simpler methods (time-domain), and ending with the more complex FWI/RTM. There is a particular emphasis on refining velocity models for accurate imaging, with techniques like first arrival traveltime tomography (FAT) and full waveform inversion (FWI). After reading the thesis, it becomes apparent that the candidate has an in-depth understanding of seismic imaging theory in time and depth domains and has also gained significant practical knowledge on conditions most appropriate for applying each method. This knowledge is well-summarized in the imaging workflow based on the results obtained in the thesis and illustrated in Figure 3.1. The application of advanced depth imaging methods to field data also requires a good understanding of complications inherent to the environment and the impacts they may have on any imaging methods. To this end, the candidate has demonstrated that he fully understands the complexity of mining environments and the limitations of the various imaging methods in such environments. Furthermore, the candidate's knowledge goes beyond seismic imaging and comprises other aspects of the reflection seismic workflow (data acquisition and processing, physical rock properties and interpretation). Imaging is crucial, but it is only a part of the workflow that can only be adequately performed by considering the main objectives of a survey and considering how the data was acquired and processed. All aspects of the seismic workflow were considered and discussed at various levels in the thesis. For example, the candidate selected and applied key data processing steps before applying the imaging methods and provided interpretation/validation for geologically important reflections at the two mining sites (Kylylahti and Ludvika). Based on the above, the candidate has demonstrated that he possesses the theoretical and practical knowledge required to carry out high-level research in the field of reflection seismology applied to mining exploration. The three publications in peer-reviewed scientific journals, of which the candidate is the first author, are also strong indicators of his ability to conduct independent research. These publications, the dissertation and the presentations made by the candidate provide ample evidence of the candidate's research skills, critical thinking and ability to initiate and complete research projects.

2) The justification that the solution of the problem in the doctoral dissertation is original.

The main hypothesis tested in the thesis is the following: "An advanced depth-domain imaging approach can be used to delineate geologically complex targets in mineral exploration, even when the 2D and 3D seismic data are irregular." As stated by the candidate, this hypothesis was validated decades ago in oil and gas exploration; however, it still needs to be demonstrated for seismic data acquired in mining environments. The methodology chosen by the candidate to test this hypothesis is the application and comparison of results from several imaging methods (NMO-DMO-post-stack migration, Kirchhoff depth migration, FVM/CM migration, and RTM combined with FWI) at two mining sites located in Finland and Sweden. Whereas comparing results from different methods is not new, the number of methods used and tested is thorough, comprehensive, and beyond previous comparative works conducted in mining environments. This enabled the useful synthesis of an imaging workflow for Hardrock in Figure 3.1. This original contribution entirely relies on the imaging experiments conducted by the candidate with Hardrock seismic data.

Another novel aspect of this work is the emphasis on the velocity model building with FAT and FWI, particularly comparing imaging results obtained from velocity models obtained with both techniques. Building velocity models is crucial to high-quality imaging but challenging in Hardrock environments due to short and discontinuous reflections that prevent the use of reflection tomography and the minimal velocity increase with depth, limiting FAT's applicability to relatively shallow depths. As a result, velocity model building in mining environments has relied primarily on approaches based on geologically simplistic assumptions, especially at greater depths. Here, the candidate has demonstrated that FWI can be used with Hardrock seismic data to obtain velocity models with improved accuracy, producing better-focused images with RTM. The paper on FWI/RTM applied to the Ludvika mines is a fine research work with novel content in Hardrock seismics. It provides one of the first successful applications of FWI/RTM to a 3D seismic survey acquired in a mining environment. It is worth mentioning that the candidate went beyond a simple qualitative comparison of seismic sections and looked at alternative ways to assess the performance of FAT and FWI results (source wavelet estimation, data fitting comparison) and RTM results (Surface Offset Gathers). The candidate provided a solid and original demonstration of the potential benefits of using FWI/RTM at the Ludvika mining site.

3) Positive or negative opinion regarding the candidate's admission to the public defence of the doctoral dissertation.

The thesis contains many strong points but also (as always) some weaknesses or parts that could have been improved by adding information. The main strengths and weaknesses of the thesis are summarized below.

Strength of the thesis:

-Comprehensive and thorough comparison of imaging methods for Hardrock environments.

-Results are from field seismic data at real mining sites (Kylylahti, Finland; Ludvika, Sweden) – the most effective way to demonstrate the usefulness and limitations of each method.

-Strong focus on velocity model building.

-One of the first applications of FWI/RTM to 3D seismic data at a mining site (certainly the most comprehensive).

-Performance assessment of FAT and FWI results with source wavelet estimation and data fitting comparison, and assessment of RTM results with Surface Offset Gathers.

-Effort to validate results with boreholes/geology information where possible.

-Outstanding paper on FWI/RTM at Ludvika mines.

-Synthesis of seismic imaging workflow for Hardrock environments based on results presented in the thesis.

-thesis well-presented and well-written.

Weaknesses and areas of improvement:

-Physical rock properties are covered succinctly (sufficient information is provided, but a bit more would have been better to understand all potential causes of reflections).

-Qualitative assessment of the results can be subjective.

-Only a limited number of reflections per section presented in the thesis are interpreted and/or validated with known geology. One personal observation from the results presented in this thesis is that getting improved images with advanced methods does not necessarily simplify the interpretation of the data. Ultimately, a reader can only wonder what all the un-interpreted reflections correspond to geologically.

- Some depth images are cluttered with many short and discontinuous reflections, so much so that one can wonder if key geological features could be unequivocally identified based on seismic data alone (again, interpretation is difficult).

- No clear guidelines on how to handle statics with the various imaging methods tested in the thesis. The candidate missed an opportunity to synthesize and summarize the handling of static corrections for the various imaging approaches based on the experiment conducted in the thesis.

In my view, most weaknesses are inherent to seismic data acquired in mining environments and are not detrimental to the excellent work on seismic imaging presented in the thesis. Thus, I recommend moving forward with the public defence of the doctoral dissertation.

Dr. Gilles Bellefleur
Research Scientist
Geological Survey of Canada