Editorial

Editorial for Special Issue "Seismic Methods in Mineral Exploration"

Gilles Bellefleur [1],*[ID]**, Michal Malinowski** [2][ID] **and Milovan Urosevic** [3]

1 Geological Survey of Canada, Natural Resources Canada, Ottawa, ON K1A 0E8, Canada
2 Institute of Geophysics, Polish Academy of Sciences, 01-452 Warszawa, Poland; michalm@igf.edu.pl
3 Faculty of Sciences and Engineering, Curtin University, Bentley WA 6102, Australia;
   M.Urosevic@curtin.edu.au
* Correspondence: gilles.bellefleur@canada.ca; Tel.: +1-613-793-0143

check for updates

In many parts of the world, exploration for mineral deposits is moving progressively but persistently to greater depths, relying on knowledge gained from previous exploration campaigns and on new exploration tools and techniques used to guide deep and costly boreholes to most suitable targets. As they maintain high resolution with depth, seismic methods are particularly effective at detecting and delineating deep geological units and structures. The effectiveness of this method is demonstrated by a number of recent case studies for a wide range of commodities from major mining camps across the globe (see Reference [1] and references therein). However, mineral prospecting using seismic methods is not straightforward and still requires improvements in all parts and aspects of the workflow. This Special Issue comprises seven papers demonstrating progress made in data acquisition and processing to produce accurate images of the subsurface, and interpretation and geological validation of seismic observations.

Benefits of state-of-the-art data acquisition and novel technology are demonstrated in two papers of the Special Issue. Naghizadeh et al. [2] demonstrate clear improvement in reflector detection and definition achieved during the acquisition and processing of deep seismic reflection profiles acquired in Canada by the Metal Earth project. Metal Earth is dedicated to understanding the processes responsible for the differential metal endowment in Archean greenstone provinces and uses seismic methods as one of the tools to identify key geological-geochemical-geophysical attributes of metal sources, transport pathways, and economic concentrations at the crust–mantle scale. Seismic improvements are demonstrated by a comparative analysis with earlier Lithoprobe surveys and are attributed to the increased bandwidth of the signal, better estimates of refraction and reflection velocities used in processing, and especially the pre-stack time migration of the data. Reidel et al. [3] present a case study of an underground vertical seismic profiling (VSP) experiment, which was designed to image a (semi-)massive sulfide deposit located in the Kylylahti polymetallic mine, Finland. They utilized and compared data measured with a conventional VSP system with three-component geophones and a novel fiber-optic distributed acoustic sensing (DAS) system. Both systems, deployed in boreholes located near the sulfide deposit, successfully recorded seismic reflections from the deposit and nearby geological contacts. In particular, they emphasize the potential benefit of using fiber-optic DAS systems, which provide reflection data with sufficient quality, with less logistical effort and a higher acquisition rate.

Seismic imaging commonly known as migration has a significant impact on results. Methods relying on depth imaging, because they can take into account significant lateral and vertical velocity variations, typically provide best results. However, depth imaging methods were used only recently for mineral exploration [4] because they require accurate velocity models that are particularly difficult to obtain with the low signal-to-noise ratio seismic data typical of mining environments.

The Special Issue comprises two papers further demonstrating the benefits of depth imaging for mineral exploration. The two papers show depth-imaging results on data acquired as part of the COGITO-MIN project, which aims at developing cost-effective geophysical imaging methods for mineral exploration. Singh et al. [5] compare and analyze results from time and depth imaging approaches, including a specialized Kirchhoff pre-stack depth migration, referred to as coherency-based Fresnel volume migration. The comparative study is performed with 3D seismic data acquired over the Kylylahti mine area, Finland. The 3D survey is characterized by an irregular shooting geometry and relatively large receiver intervals (50 m) resulting from the utilization of a receiver spread initially designed from passive seismic measurements and shot points from a 2D seismic survey, vertical seismic profiling (VSP), and randomly distributed shot points. The coherency-based Fresnel volume migration resulted in a cleaner image of steeply dipping reflections located at a shallow depth (< 1500 m). In comparison, standard time-domain processing and imaging failed to produce convincing image of the top ~1500 m of the subsurface, which was the primary interest of the survey. Heinonen et al. [6] show that an advanced pre-stack depth-imaging algorithm based on Fresnel volume migration (FVM) recovers meaningful and robust seismic images from 2D seismic data acquired with sparse shot points. This suggests that 2D seismic reflection profiling with sparse geometry can be used as a reconnaissance tool for mineral exploration in areas with limited access for active seismic surveys. Heinonen et al. [6] obtained these results by varying the number of shot points used in the depth migration algorithm on two approximately 6 km long seismic reflection profiles, acquired with 20 m source spacing at the polymetallic Kylylahti massive sulfide mine site, Finland. Steep reflectors in the shallow (<500 m) part of the seismic sections are imaged especially well in the FVM migration result and correlate with black schist interlayers with mica schist observed in the geological map.

Cichostępski et al. [7] present results of the inversion of prestack seismic data to evaluate the sulfur content within a carbonate reservoir. The strata-bound sulfur deposits occur at depths of about 300 m, with sulfur content reaching up to 30%. The sulfur-bearing strata and host rocks were imaged on five 2D high-resolution shallow seismic profiles processed to preserve relative amplitude relationships. Cichostępski et al. [7] used a simultaneous inversion procedure to recover porosity changes and sulfur content, and demonstrate that sulfur content is dependent on the carbonate reservoir's porosity.

Several deposit-types with major economic importance are inherently associated with the large volume of rocks infiltrated by hydrothermal fluids that, with precipitation and trapping processes, lead to the formation of deposits. Identification and recognition of such hydrothermal alteration provides important evidence that an area is favorable for the occurrence of deposits and can guide exploration in areas with the highest discovery potential. Thus, understanding and characterizing the signature of hydrothermal alteration on seismic data is of primary importance for exploration. Schetselaar et al. [8] used an integrated analysis of seismic rock properties, lithogeochemical data, and mineral compositional data, estimated via scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS), to provide insights into the effects of hydrothermal alteration on seismic reflectivity in the footwall of the Lalor volcanogenic massive sulfide (VMS) deposit, Canada. Footwall alteration of the Lalor VMS deposit is associated with an enhanced seismic reflectivity that can be tracked laterally, and at depth, on a 3D seismic volume, and is caused by the high abundance of garnet, anthophyllite, and, particularly, cordierite in rocks with mafic protolith. These minerals are constituents of amphibolite facies assemblages that are diagnostic of metamorphosed and intensely-altered footwall of volcanogenic massive sulphide ore lenses. Junno et al. [9] use self-organizing map (SOM) analysis to predict missing seismic velocity values from other available borehole data at the Kevitsa Ni-Cu-PGE deposit, Finland. SOM is used to predict missing seismic velocities from other geophysical, geochemical, geological, and geotechnical data to support the interpretation of a series of reflections observed beneath the Kevitsa resource area. Predicted reflectivity logs show that some contacts between olivine pyroxenite/olivine websterite-dominant host rocks of disseminated sulfide mineralization and altered olivine pyroxenite variants (metaperidotite) are reflective. This indicates that alteration can potentially cause the significant reflectivity within the Kevitsa intrusion.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Malehmir, A.; Durrheim, R.; Bellefleur, G.; Urosevic, M.; Juhlin, C.; White, D.J.; Milkereit, B.; Campbell, G. Seismic methods in mineral exploration and mine planning: A general overview of past and present case histories and a look into the future. *Geophysics* **2012**, *77*, WC173–WC190. [CrossRef]

2. Naghizadeh, M.; Snyder, D.; Cheraghi, S.; Foster, S.; Cilensek, S.; Floreani, E.; Mackie, J. Acquisition and Processing of Wider Bandwidth Seismic Data in Crystalline Crust: Progress with the Metal Earth Project. *Minerals* **2019**, *9*, 145. [CrossRef]

3. Riedel, M.; Cosma, C.; Enescu, N.; Koivisto, E.; Komminaho, K.; Vaittinen, K.; Malinowski, M. Underground Vertical Seismic Profiling with Conventional and Fiber-Optic Systems for Exploration in the Kylylahti Polymetallic Mine, Eastern Finland. *Minerals* **2018**, *8*, 538. [CrossRef]

4. Urosevic, M.; Bona, A.; Ziramov, S.; Pevzner, R.; Kepic, A.; Egorov, A.; Kinkela, J.; Pridmore, D.; Dwyer, J. Seismic for Mineral Resources—A Mainstream Method of the Future. In Proceedings of the Exploration' 17 Seismic Methods & Exploration Workshop, Toronto, ON, Canada, 21–25 October 2017.

5. Singh, B.; Malinowski, M.; Hloušek, F.; Koivisto, E.; Heinonen, S.; Hellwig, O.; Buske, S.; Charmarczuk, M.; Juurela, S. Sparse 3D Seismic Imaging in the Kylylahti Mine Area, Eastern Finland: Comparison of Time vs Depth Approach. *Minerals* **2019**, *9*, 305. [CrossRef]

6. Heinonen, S.; Malinowski, M.; Hloušek, F.; Gislason, G.; Buske, S.; Koivisto, E.; Wojdyla, M. Cost-Effective Seismic Exploration: 2D Reflection Imaging at the Kylylahti Sulfide Deposit, Finland. *Minerals* **2019**, *9*, 263. [CrossRef]

7. Cichostępski, K.; Dec, J.; Kwietniak, A. Simultaneous Inversion of Shallow Seismic Data for Imaging of Sulfurized Carbonates. *Minerals* **2019**, *9*, 203. [CrossRef]

8. Schetselaar, E.; Bellefleur, G.; Hunt, P. Elucidating the Effects of Hydrothermal Alteration on Seismic Reflectivity in the Footwall of the Lalor Volcanogenic Massive Sulfide Deposit, Snow Lake, Manitoba, Canada. *Minerals* **2019**, *9*, 384. [CrossRef]

9. Junno, N.; Koivisto, E.; Kukkonen, I.; Malehmir, A.; Montonen, M. Predicting Missing Seismic Velocity Values Using Self-Organizing Maps to Aid the Interpretation of Seismic Reflection Data from the Kevitsa Ni-Cu-PGE Deposit in Northern Finland. *Minerals* **2019**, *9*, 529. [CrossRef]