Introduction to the special issue on “Cost-effective and innovative mineral exploration solutions”

Malehmir, Alireza; Manzi, Musa; Draganov, Deyan; Weckmann, Ute; Auken, Esben

DOI
10.1111/1365-2478.12915

Publication date
2020

Document Version
Accepted author manuscript

Published in
Geophysical Prospecting

Citation (APA)
Malehmir, A., Manzi, M., Draganov, D., Weckmann, U., & Auken, E. (2020). Introduction to the special issue on “Cost-effective and innovative mineral exploration solutions”. *Geophysical Prospecting*, *68*(1), 3-6. https://doi.org/10.1111/1365-2478.12915

Introduction to the special issue on “Cost-effective and innovative mineral exploration solutions”

Alireza Malehmir[1,*], Musa Manzi[2], Deyan Draganov[3], Ute Weckmann[4] and Esben Auken[5]

1: Department of Earth Sciences, Uppsala University, Uppsala, Sweden
2: University of the Witwatersrand, School of Geosciences, Johannesburg, South Africa
3: Department of Geoscience and Engineering, TU Delft, The Netherlands
4: GFZ German Research Centre for Geosciences Potsdam, Germany
5: Department of Earth Sciences, Aarhus University, Aarhus, Denmark

**corresponding author:* alireza.malehmir@geo.uu.se,

ORCIDs:
Alireza Malehmir https://orcid.org/0000-0003-1241-2988
Musa Manzi: https://orcid.org/0000-0002-1654-5211
Deyan Draganov https://orcid.org/0000-0001-8606-1178

The mineral exploration industry is again in a boom to provide new resources of critical raw materials as well as base and precious metals. This is evident from the globally increased expenditure reported for 2018 (International Mining, 2018). Global demand towards green technologies requires sustainable flow of primary raw materials into the so-called whole value-chain. Without exploring in new areas (greenfields), the chance of finding giant deposits or providing fresh resources to the market and sustaining the value-chain loop would be minimal. However, it is convenient in the short-term to explore in brownfield areas and near mines to make use of existing infrastructures and to avoid new environmental footprints. In such circumstances, the mineral exploration industry is further challenged to not only provide high-quality and high-resolution deep-targeting solutions but also to do it in a cost- and environmentally effective way. This is particularly significant in the EU and in regions with thick cover requiring new and much more sensitive exploration technologies for direct deposit targeting and geological characterization. In addressing these, there are several research and innovation initiatives worldwide trying to tackle some of these challenges like, to list a few, Smart Exploration in the EU, Metal Earth in Canada. There are also a number of CRC (cooperative research centre) projects in Australia as well as in Africa where favorable geology exists but exploration is challenged to find new “tier 1” deposits at depth (+ 500 m).

This Special Issue of Geophysical Prospecting contains 18 papers and is coordinated by a number of experts involved in the Smart Exploration project (Malehmir et al., 2019). Eight of the included articles are from the project itself, and highlight the progress being made in this topic with a particular focus on legacy data and the value and potential such data have for deep targeting and high-resolution imaging. The Special Issue, through showcases, reports the remarkable progress being made in overcoming the perceived high exploration cost for mineral exploration particularly for deeper targets.

In the following, we provide a brief introduction to the papers included in this Special Issue. The included articles are divided into three main categories: legacy and exploration data, innovative solutions, and state-of-the-art equipment. Interested readers are also encouraged to check the three earlier special volumes on similar topics by Eaton, Milkereit and Salisbury (2003 and the references therein), Malehmir et al. (2012 and the references therein) and Buske, Bellefleur and Malehmir (2015 and the references therein).

LEGACY AND EXPLORATION DATA

Markovic *et al.* combine two sets of seismic data acquired over an iron-oxide mineralization in the Ludvika mines of Sweden using different setups and equipment. Through a novel approach, employing curvelet-denoising methods, they attenuate surface waves, which are dominant in the data. The processing work images a set of reflections associated with the mineralization and new ones that have potential to be from additional mineralized bodies. In particular, it is illustrated that the seismic data not only are capable of confirming the presence of mineralization at depths greater than 800 m, only known by historical boreholes, but also suggest potential resources deeper than this depth in the depth extension of the known ones.

Bräunig *et al.* employ focusing prestack depth-imaging techniques to obtain a clear and well-resolved image of the iron-oxide mineralization down to over 1000 m depth. In order to image the internal structure of the mineralization and decipher the surrounding structures, they applied the concept of reflection image spectroscopy to the data, allowing the imaging of wavelength-specific characteristics within the reflective body. As a result, conjugate-crossing faults around the mineralization could directly be imaged in a low-frequency band while the internal structure was obtained within the high-frequency bands.

Donoso *et al.* present the reprocessing of 2D legacy seismic data, acquired in 1996, from the Neves-Corvo mine site in the Iberian Pyrite Belt in southern Portugal, with the motivation to inquire whether the early European mineral-exploration datasets had a potential for seismic imaging that was overlooked. As a result, the world-class Lombador massive sulphide and other smaller deposits were imaged with improved continuity and resolution; furthermore, a number of shallow and steeply dipping reflections were imaged, which were not seen before. The importance of this dataset is that this survey could likely have been the first study in Europe that demonstrated the capability of directly imaging massive sulphide deposits using the seismic method. The study highlights the value of legacy seismic data and the importance of taking advantage of state-of-the-art data-processing algorithms in hard-rock environments.

Cheraghi *et al.* present Metal Earth seismic imaging investigations in Swayze area, located in the western zone of Abitibi greenstone belt, Canada. Two 2D high-resolution seismic surveys, Swayze north and Swayze south, each one about 10 km, are acquired as crooked surveys. The seismic imaging in Swayze includes two main scenarios for the processing. The first scenario is considered to design 2D straight-line processing and the second is to process crooked surveys as 3D swath geometry. Both scenarios address challenges to image complex subsurface architecture in crystalline rocks of the Abitibi greenstone belt. An interpreted fault/deformation zone imaged in the Swayze north survey would be a target for metal endowment.

Junno *et al.* present results from Self-Organizing Map (SOM) analysis, an unsupervised artificial neural-network method, of borehole data from the Kevitsa disseminated Ni-Cu-PGE sulphide deposit in Northern Finland. They aim to investigate the cause of observed reflectivity within a spatially restricted zone associated with the Kevitsa deposit within 3D seismic reflection data acquired in Kevitsa in 2010. Earlier, it was suggested that the laterally continuous and spatially restricted reflections originate from contacts between tops and bottoms of smaller-scale, internally differentiated magmatic layers that control the extent of the economic mineralization in Kevitsa. However, this interpretation was not unequivocally supported by the borehole data, and, in particular, the effect of alteration on the reflectivity properties remained an open question. In Junno et al., the SOM borehole-data analysis results are examined together with theoretical modelling of the effect of mineralization and alteration on the reflectivity properties of Kevitsa rock types (based on average modal compositions of the rock types). Based on the results, the reflectivity is most plausibly attributed to alteration, and may also be linked to the presence of sulphide minerals.

Kieu and Kepic present a novel method of improving the interpretability of seismic data for mineral exploration by constraining and integrating prior information into model-based, post-stack seismic-impedance inversion via the fuzzy c-means (FCM) clustering technique. Application of FCM guided inversion to a challenging magnetotelluric/seismic dataset from the Carlin Gold District, USA provided a useful acoustic impedance model without the usual supporting log data, and a cluster map for interpretation and exploration. Using FCM guided inversion of magnetotelluric (MT) data to create a starting model for acoustic-impedance inversion of the seismic data allowed the MT data to provide information to support the seismic inversion process, which is normally provided by borehole logs. A fundamental advantage of using FCM in geophysical inversion is that it can create a model based upon multiple geophysical data sets that may be interpreted by non-specialists in geophysical/seismic data analysis. This is demonstrated by comparison with diamond-drilling core assay that low values of acoustic-impedance in the basement rocks in this district may be prospective for gold, as would be predicted for later gold mineralization in weak, decalcified rocks.

Hajnal *et al.* present the results of two brownfield (Shea Creek, McArthur River) and one greenfield (Keefe Lake) seismic investigations from the prolific Athabasca Basin (Canada) for imaging primary structures that host uranium mineralization. They also demonstrate that these investigations deliver high resolution (<10 meters) from surface to Moho depths; something not matched by other geophysical techniques. Beyond this, extended analysis of seismic signal attributes (amplitude, frequency), optical-tele-viewer (OTV), and full-wave sonic (FWS) data are studied to detail lithological characterization, including alteration zones, clay mineral content, as well as porosity and fracture density information. The latter are extremely important for mineral exploration geoscientists when targeting new discoveries. Finally, they compared the costs of all geophysical techniques to the cost of a single logged drill-hole. From this exercise, they illustrated and concluded that the results of a properly designed seismic data acquisition program not only leads to a more effective drilling program, but also to a much quicker recognition of the major mineralized zone(s), with a reduced number of required exploration boreholes.

Manzi *et al.* present new seismic attributes that sharpen seismic reflections, enabling additional structural information to be extracted from hard-rock seismic data. These are: (1) symmetry attribute that is based on the invariance of an object with respect to transformations such as rotation and reflection – it is independent of the trace reflection amplitude, and hence a better indicator of the lateral continuity of thin and weak reflections; (2) reflection-continuity detector attribute that is based on the Hilbert transform – it enhances the visibility of the peaks and troughs of the seismic traces, and hence the continuity of weak reflections. The effectiveness of these attributes is illustrated using a legacy 3D seismic data from the Bushveld Complex in South Africa where platinum ore bodies and their associated complex geological structures (faults, dykes, potholes and iron-rich ultramafic pegmatites) are well delineated.

Li *et al.* present a diffraction imaging method to identify the geological discontinuities in seismic explorations. These geological discontinuities, such as faults, collapsed columns and pinch-outs, are closely related to the mineral exploration. By emphasizing the energy outside the Fresnel zones, the reflection would be suppressed and the diffraction can be highlighted. However, the analysis shows the reflection cannot be eliminated thoroughly in this way. Therefore, considering the polarity reversal of edge diffractions, a reverse-polarity filter is used to suppress the residual reflection and improve diffraction imaging. Following this approach, clearer diffraction images can be provided for the interpreter to identify the geological discontinuities.

Dentith *et al.* study the effects of processes such as alteration, weathering, metamorphism, and strain, and variables such as porosity and stratigraphy on geophysical responses observed from mineral deposits. Three end-members are considered. Bulk behaviour depends on the physical properties of the dominant mineral components. Density and, to a lesser extent, seismic velocity show such behaviour. Grain and texture behaviour occur when minor components of the rock are the dominant controls on its physical properties

INNOVATIVE SOLUTIONS

Balestrini *et al.* illustrate a purely data-driven approach for surface-wave suppression in a legacy active-source reflection seismic dataset acquired for exploration of the iron oxide mineralization zone in Blötberget, in the Ludvika mining area, central Sweden. Seismic interferometry is applied to this dataset in order to estimate the surface-wave energy between receivers, followed by adaptive subtraction of these estimates from the original field data. Stacked sections obtained through the interferometric surface-wave suppression method show an improved delineation of the mineralization zone, and also new features above and below the known ore deposit. This study encourages new possibilities for hard-rock seismic data denoising, and for imaging of deep mineral deposits using seismic methods.

Papadopoulou *et al.* present a workflow for the estimation of P-wave static corrections using dispersion analysis of groundroll-related noise. The workflow is highly automatic and can be an alternative to the conventional statics-estimation method (tomostatics), which requires first-break picking. The workflow has proved to produce stacked sections comparable or better than those obtained by applying tomostatics.

Polychronopoulou, Lois, and Draganov propose an innovative, cost-effective and environmentally friendly passive seismic approach for mineral exploration. They take advantage of the abundance of local microearthquakes recorded by a dense passive seismic network, which was installed at the Gerolekas mining site, in Central Greece, and operated continuously during a period of 4 months. They exploit the P- and S-wave coda of the recorded microearthquakes and retrieve zero-offset virtual reflection responses below each of the recording stations by means of reflected-wave seismic interferometry by autocorrelation. They then process the retrieved responses using reflection-processing techniques, in order to produce zero-offset time and depth sections, both for P- and for S-waves. Furthermore, they evaluate the quality of the acquired results using existing active seismic data, as well as an elastic forward-modelling procedure.

Da Col *et al.* present an application of surface-wave tomography to a 3D active seismic dataset acquired close to the Siilinjärvi phosphate mine in Eastern Finland. The aim of the survey is to map the horizontal and vertical extension of the mineralized ore body in this area, which will be mined in the future. The authors show in detail all steps of the acquisition and processing of the dataset. First, they performed an accurate survey design to optimize the illumination from the active sources. Then, they extracted path-averaged Rayleigh-wave dispersion curves using a two-station method. Finally, they inverted the curves using a computationally efficient inversion code. Output is a pseudo-3D S-wave velocity volume in which the main geological features of the area are well resolved. Specifically, the method was able to detect the location of the formation carrying most of the mineralization up to a depth of 270 m. Furthermore, close-to-vertical waste rock dykes within the mineralized body were located correctly. For these reasons, the authors conclude that the method is very promising for mineral exploration.

Girard and Shragge *(a)* introduce an ambient direct migration approach using an ambient (deconvolution) extended imaging condition as a tool for validating ambient migration images. Direct migration examples are shown with simulated synthetic ambient-wavefield seismic data (AWSD) for two different models and a large-N field data set acquired over a 4 km^2 area at Lalor Lake, Manitoba, Canada, with over 300 hours of ambient seismic recordings. Images created from the field data set are broadly consistent with those of a co-located active-source survey. This means that extracting reflected body-wave information from ambient seismic recordings is valuable for exploration purposes.

Girard and Shragge *(b)* outline an automated processing workflow and several quality-control tools to assist in identifying and mitigating coherent noise events in ambient seismic recordings. The processing flow is applied to an ambient seismic data set acquired on a large-N array at a mine site near Lalor Lake, Manitoba, Canada. The quality-control measures illustrate that the processed data have enhanced body-wave energy with respect to the raw ambient records, allowing images of subsurface reflectors to be enhanced in ambient direct prestack migration experiments.

STATE-OF-THE-ART EQUIPMENT

Bellefleur *et al.* present wireline logs and distributed acoustic sensing (DAS) data acquired in two boreholes intersecting the alteration halo and mineralization at the Cu-Au New Afton porphyry deposit, Canada. They use straight and helically-wound fibre-optic cables using standard fibres and a fibre engineered to increase the intensity of backscattering for a new generation of DAS interrogator providing higher signal-to-noise ratio. Depth images that benefitted from new migration weights accounting for the directional sensitivity of the straight fibre-optic cable show several reflectors with shallow dips to the NW, some explained by faults intersecting the surveyed boreholes.

Walter, Braun, and Fotopoulos present the results of a high-resolution unmanned aerial vehicle aeromagnetic survey conducted over a mineral exploration target within the Shebandowan greenstone belt of Ontario, Canada. The case study compares the resolution and coverage capabilities of an 85 m AGL regional heliborne aeromagnetic survey, a 35 m AGL UAV-borne aeromagnetic survey, and a terrestrial magnetic survey over an area of ~500 m x 700 m. The results demonstrate that UAV-borne aeromagnetic surveys can reliably collect industry-standard total magnetic-field measurements, providing a contemporary data product between the capabilities of the two traditional magnetic surveying methods. The enhanced interpretation potential of the unmanned aerial vehicle aeromagnetic data, coupled with historical data, aided in delineating structural controls related to gold mineralization on site and yielded a new gold mineralization discovery assayed at 15.7 g/t.

ACKNOWLEDGEMENTS

The editors of the Special Issue thank Smart Exploration project for supporting this work and the time allocated to edit and review the articles. Smart Exploration has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 775971.

REFERENCES

Buske, S., Bellefleur G. and Malehmir, A. 2015. Introduction to Special Issue on “Hard Rock Seismic Imaging”. Geophysical Prospecting **63**, 751–753.

Eaton D., Milkereit B. and Salisbury M. 2003. Hardrock seismic exploration: mature technologies adapted to new exploration targets. Hardrock Seismic Exploration. SEG Books. ISBN 978–1–56080–114–6.

International Mining, 2018. 20% increase in global expenditure for mineral exploration in 2018. https://im-mining.com/2018/03/12/20-increase-global-expenditure-mineral-exploration-2018/ (last accessed 2019-11-28).

Malehmir A., Urosevic M., Bellefleur G., Juhlin C. and Milkereit B. 2012. Seismic methods in mineral exploration and mine planning. Geophysics **77**, WC1–WC2.

Malehmir, A., Holmes P., Gisselø P., Socco L.V., Carvalho J., Marsden P., Onar Verboon A. and Loska M. 2019. Smart Exploration: Innovative ways of exploring for critical raw materials of the EU. EAGE Annual Meeting, London-UK, June 2019.