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INTRODUCTION

Introduction to the special issue on "mineral exploration and mining geophysics"

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Energy transition from fossil fuels to green-type technologies is more than ever accelerated. This is evident as governments push enormously to accelerate this transition with subsidies and more research possibilities. There is, however, a major obstacle that alternative sources of energy require access to raw materials for generation, storage and transportation. After two successful special issues on this topic, in 2015 (Buske et al., 2015) and 2020 (Malehmir, Manzi, et al., 2020), we observe more research and industry works in the mineral–mining sector to help accelerate the energy transition.

The mineral exploration industry continues to chase deep-seated deposits in onshore regions while making sure intermediate ones are also effectively explored using state-of-the-art technologies (e.g., Malehmir, Gisselø, et al., 2020) that are socially acceptable but also provide sufficient resolution for drilling programmes. As demand increases, the mining industry also faces an increasing push to produce more raw materials in more difficult and challenging mining environments prone to seismicity and unknown geological structures. This introduces challenges but also possibilities where exploration and mining can link together and support each other.

This special issue of *Geophysical Prospecting* addresses these challenges and provides several solutions. In the following, we provide a brief introduction to the papers included in the special issue. The included articles are divided into three main categories: three-dimensional imaging solutions, machine-learning solutions and integration, and mine seismicity, safety and monitoring while drilling. Interested readers are also encouraged to check other special volumes on similar topics by Eaton et al. (2003 and the references therein) and Malehmir et al. (2012 and the references therein).

THREE-DIMENSIONAL IMAGING SOLUTIONS

Sasha Ziramov, Carl Young, Jai Kinkela, Greg Turner and Milovan Urosevic investigate and address various issues in relation to the imaging techniques for high-resolution, high-density three-dimensional (3D) seismic surveys outside oil and gas exploration. The study focuses on the extraction of maximum value from the seismic dataset recorded for gold exploration by optimization of acquisition parameters, processing flow, imaging and velocity model building algorithms. High-precision subsurface imaging utilizes the full-depth imaging workflow that respects shallow lateral velocity variations in the overburden and fully implements seismic tomography. By using a unique depth imaging workflow, they are able to delineate shallow gold hosting structures and render an accurate picture of the interior of an excessively complex hard rock area of the Yilgarn craton in Western Australia.

Saeid Cheraghi, Felix Hloušek, Stefan Buske, Alireza Malehmir, Ademola Adetunji, Rasmus Haugaard, David Snyder and Rajesh Vayavur investigate a two-dimensional (2D) crooked seismic profile acquired at the Swaze east area, Abitibi subprovince, Ontario, Canada. This seismic profile was acquired for the Metal Earth project. They evaluated the imaging capability of dip moveout-corrected-stacked migrated sections versus more advanced methods including prestack time migration and prestack depth migration (PreSDM). The crooked nature of the profile facilitates their application of the swath 3D processing. The 3D seismic images are visualized versus 3D magnetotelluric sections for better interpretations. Their investigations indicate that 3D prestack depth migrated sections provided the best imaging results for a complex subsurface architecture in a crystalline rock environment.

George A. Donoso, Alireza Malehmir, Joao Carvalho and Vitor Araujo reprocessed a 3D seismic dataset from the world-class Iberian Pyrite Belt in Portugal. The main objective was to improve the seismic signature of two known deposits: Lombador and Semblana. Despite the mixed signal-to-noise ratio, the reprocessed seismic cube reveals both shallow and deep 3D structures, allowing to account for the deposits' lateral extension beyond the capabilities of 2D seismic imaging alone. Given the data-processing approach taken, it was possible to distinguish strong diffraction patterns, interpreted as originating from faults and edges of the Lombador deposit. This illustrates the usefulness of diffraction patterns for better interpretation of geological features in hard rock environments.

Alba Gil, Alireza Malehmir, Puy Ayarza, Stefan Buske, Ramon Carbonell, Dirk Orlowsky, Jorge Carriedo and Anja Hagerud present the results of a sparse 3D seismic survey that was conducted in the Zinkgruvan mining area, in the Bergslagen mineral district of central Sweden. A total of 1311 receivers and 950 shot points in a fixed 3D geometry setup were employed for the survey. Nine 2D profiles and a smaller 3D mesh were used. An analysis of the seismic fold coverage at depth was used to determine the potential resolving power of this sparse 3D setup. The data processing had to account for cultural noise from the operating mine and strong source-generated surface waves, which were attenuated during both pre- and post-stack processing steps. The overall geological architecture at Zinkgruvan is interpreted as two EW overturn folds, an antiform and a synform, affected by later NS-trending folding. Two strong sets of shallow reflections, associated with the Zn–Pb mineralization, are located at the hinge of an EW-trending antiform, while a strong set of reflections, associated with the main mineralization, is located at the overturned apex of the EW synform. This case study illustrates that sparse 3D data acquisition, even while it has its own challenges, can be a suitable replacement for 2D profiles while line cutting and environmental footprints can totally be avoided.

Hossein Jodeiri Akbari Fam, Mostafa Naghizadeh, Richard Smith, Oz Yilmaz, Saeid Cheraghi and Kate Rubingh applied a novel 2.5-D multifocusing stacking method to improve the subsurface imaging of a crooked 2D seismic profile in the Larder Lake area of Canada's Superior Craton with a complex hard rock geological setting. The new algorithm not only enhances the image quality but also accurately extracts 3D structural information through wavefield parameter analysis using a global optimization algorithm. The proposed approach addresses challenges posed by survey geometry and outperformed conventional processing methods in terms of resolution, coherence and signal-to-noise ratio. This new innovative processing method could lead to significant improvement in subsurface imaging and interpretation.

Ndamulelo Mutshafa, Musa S.D. Manzi, Michael Westgate, Ian James, Bojan Brodic, Julie E. Bourdeau, Raymond J. Durrheim and Lindsay Linzer reprocessed two legacy reflection seismic profiles acquired in 1988, north of the Kloof–Driefontein Complex East Mine in the West Rand goldfield (South Africa). Special interest was given to the Black Reef Formation, which hosts a known gold ore body. The original legacy data are of low quality, especially in areas that are dominated by dolomitic outcrops. To improve the structural imaging resolution, the authors tried pre-stack time migration, pre-stack depth migration and post-stack time migration using the Kirchhoff algorithm. PreSDM most improved the imaging of deeper reflections due to its ability to honour complex lateral variations in the velocity field. Both pre-stack time migration and post-stack time migration enhanced the continuity of the near-surface reflections below the dolomitic rocks.

MACHINE LEARNING SOLUTIONS AND INTEGRATION

Artem Gorbunov, Stephen Fraser, Prince Cuffey, Emmanuel Lansana, Henry Deen and Tim Archer present machine learning results from the world's highest resolution national airborne geophysical survey (Sierra Leone). Arguing that traditional methods of data interpretation suffer from human assumptions that are often biased and usually incomplete, they present two examples of data-driven interpretation products that help to challenge and overcome these limitations. More specifically, they present initial results of convolution neural network classification to locate magnetic lineaments in plan and in depth that compare favourably with more conventional ridge detection and Euler deconvolution techniques. Initial results of self-organizing map clustering as a tool for joint analysis of multiphysics datasets and construction of pseudo-lithology maps are also presented and discussed.

Magdalena Markovic, Reza Malehmir and Alireza Malehmir developed a workflow for a self-supervised learning technique, an autoencoder, for diffraction denoising on synthetic seismic, ground-penetrating radar and hard rock seismic datasets. The authors coupled the autoencoder with Hough transform and pixel edge detection filters to facilitate the workflow. Coupled with additional image processing steps, they successfully isolated a diffraction signal that was generated from a known volcanogenic massive sulphide deposit. The encouraging results suggest that the self-supervised learning techniques such as the autoencoder can be used for seismic mineral exploration purposes and are worthy to be implemented as additional tools for data processing and target detection.

Sikelela Gomo, Moyagabo K. Rapetsoa, Musa S. D. Manzi, Emmanuel Onyebueke, Jureya Dildar, Mpofana Sihoyiya, Ndamulelo Mutshafa, Wesley Harrison, Julie E. Bourdeau, Oleg Brovko, Ian James Gordon R. J. Cooper, Stephanie Scheiber and Raymond J. Durrheim employ an integrated geophysical approach, using magnetics, electrical resistivity tomography, seismic refraction tomography, ground penetrating radar and borehole data, to map boulders and geological features (e.g., lithologies, fractures, iron-rich ultramafic pegmatites, weathering zones and thickness of the topsoil) that have the potential to impede mining operations at a mine in the Bushveld Complex, South Africa. Such features often pose a challenge for mining activities as they introduce complexities and delays in mining, drilling, blasting and excavation programmes, which subsequently increase mining costs. The results obtained from the different geophysical techniques are found to complement each other and successfully delineate boulders, fractures, iron-rich ultramafic pegmatites and the variation in weathering and layering across the area.

Xiaolong Wei, Kenneth Li and Jiajia Sun present a case study using airborne geophysical data, borehole and physical property measurements to characterize the Elk Creek carbonatite complex located in the southeast of Nebraska, USA. It hosts the largest known niobium deposit in the United States and contains a high level of rare earth element mineralization. They performed three-dimensional (3D) joint inversion of the airborne gravity gradiometry and magnetic data to produce structurally similar density and susceptibility models. They carried out geology differentiation, a process of classifying recovered physical property values into distinct units and obtained a 3D quasi-geology model for the Elk Creek carbonatite complex. The study demonstrates the added value of 3D geophysical joint inversions and geology differentiation in the context of critical mineral exploration under a thick sedimentary overburden.

MINE SEISMICITY, SAFETY AND MONITORING WHILE DRILLING

Tarek S. Imam, Tatsunori Ikeda, Takeshi Tsuji, Jiro Uesugi, Takeshi Nakamura and Yoshinori Okaue have developed an innovative seismic exploration technique aimed at identifying ore deposits in mining sites. Their technique utilizes a blast signal as a seismic source, which they analyse to conduct reflected-wave seismic interferometry through autocorrelation to retrieve zero-offset virtual reflection responses. By utilizing dense station spacing, they can obtain a three-dimensional (3D) shallow seismic reflection volume of the mining site. The high frequency and energy of the blast signals make it possible to image lithological boundaries with high spatial resolution using only a single blast signal.

Richard T. Masethe, Musa S. D. Manzi and Raymond J. Durrheim analyse the source mechanisms of 75 large mining-related seismic events (ML 1.5–2.7) that caused damage to stopes in the Kloof Gold Mine in South Africa and used legacy 3D reflection seismic data to delineate the ore body and geological structures that may be correlated with mining-related seismic events. The source mechanisms of mining-induced seismic events aid in understanding the dominant modes of failure. Planes of weakness may be the result of mining-induced stresses or pre-existing geological structures such as faults and dykes. Approximately 44% of the events showed a strong correlation with the known underground mapped and seismically imaged geological structures (faults and dykes), whereas 56% of the events were related to elements of the mining geometry (dip pillars, abutments and remnants). This information enables mining layouts to be modified to minimize the risk of rockbursting.

Bernd Trabi and Florian Bleibinhaus use a large dataset of more than 4000 observations of peak ground velocity (PGV) from mine blasts recorded by an array of 81 seismic three-component sensors in and around an iron ore open-pit mine to compare the performance of various analytic PGV predictors used by mining engineers to design the charge weights. They find that the prior information implicitly encoded in standard scaled-distance PGV predictors through linking the charge-weight exponent to the radial-decay constant is inappropriate because the two parameters are fully uncorrelated, and the link degrades the predictions. As an alternative, they present several ways to independently calibrate those parameters that would also work with small datasets.

Florian Bleibinhaus and Bernd Trabi use the full waveforms of the same dataset to develop a Laplace-domain model of the source-time function of a single mine blast that accounts for the impact of the charge weight on the frequency spectrum. The model also includes the interference from a sequence of blast holes and predicts the corresponding resonance modes and Doppler shifts. The authors calibrate their model with the individual waveforms from 39 electronically detonated mine blast sequences that comprise between 5 and 32 single blasts, each. Based on an agreeable match with the observations, the authors suggest that their source-time-function model could be used in more advanced numerical PGV predictions that also account for subsurface heterogeneity.

Zbigniew Wilczynski, Ayse Kaslilar, Monika Ivandic and Christopher Juhlin present a seismic-while-drilling method for drill-bit positioning. They introduce a shift-and-stack method to enhance the direct arrivals from the percussive drill-bit source (field experiment) and use the relative arrival times to locate the source position, with the accuracy of the results depending on data quality and source depth. The approach is validated with two numerical studies. The methodology is also considered applicable to drill-bit sources with random and non-percussive signatures. They discuss the method's limitations in terms of manual picking of arrivals and hammer drilling and highlight the potential for automation of arrival picking grid search.

Ali Cankurtaranlar and Emin Demirbağ utilized ambient noise seismic interferometry (ANSI) to retrieve a virtual shot gather for seismic imaging in the Soma coal basin, Western Turkey. They processed continuous seismic records, eliminating non-noise signals and enhancing the signal-to-noise ratio. By cross-correlation and cross-coherence, they successfully produced a zero-offset virtual shot gather, observing P-wave arrivals and reflections from the coal layer. The study demonstrates the effectiveness of using ANSI with ambient noise in areas where active seismic sources are challenging to use. It offers a cost-effective and environmentally friendly alternative for seismic imaging and monitoring. The virtual shot gathers obtained through this method yield comparable results to active seismic sources. This approach has particular relevance for monitoring dynamic conditions in coal mines involved in the production or in situ gasification processes.

Abhay Kumar Bharti, Satyendra K. Singh, Sanjit Kumar Pal and Krishna Kant Kumar Singh present two-dimensional and 3D electrical resistivity tomography results for the delineation of underground workings including voids/cavities (air or water-filled). Refinement of the model by half-unit electrode spacing was conducted and showcased from a coal mine in India. 3D resistivity volumetric model was also developed with the help of five electrical resistivity tomography parallel profiles for better apprehension of the subsurface. Data analysis provided important inputs for stability analysis using 3D finite-difference numerical modelling. The analysis of the modelling exhibited a low safety factor below 1.0 for the top two layers, indicating potholing/localized subsidence susceptibility. The other three layers, mainly fine-grained sandstone, exhibited a relatively higher safety factor of around 2.0, indicating moderately stable zones, but not on a long-term basis. The remedial measures hence suggest the mine to be closed.

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None.

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