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Cosmic-ray muon tomography: Applications in block cave mapping and modelling

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ABSTRACT

Cosmic-ray muons are charged elementary particles that arise naturally from cosmic radiation interacting with the Earth's upper atmosphere. Particle showers of muons bombard Earth steadily and are attenuated by their interaction with matter along their trajectory. Muons can penetrate deep into the Earth's crust, down to thousands of metres, and their attenuation in matter is proportional to the density of material the muon passes through.

By measuring the flux of surviving muons through detectors positioned beneath the surface, the average density along each ray path in the overburden within a wide field of view above the detector can be determined. Each detector produces a radiographic image of the rock mass above it, and combining these images yields three-dimensional tomographic reconstructions of subsurface density.

Muon tomography-derived density models can be used in a wide variety of settings across the mining life cycle. Ideon Technologies has successfully deployed muon tomography to monitor block cave propagation remotely, ensuring continuous cave production and avoiding operational hazards. This paper will present how muon tomography can be used to accurately delineate the ever-changing parameters of block cave edges, the growing air gap created, and the muck pile forming at the cave bottom, including the ability to resolve with a quantifiable precision of less than 20 metres across an entire cave, and on the order of 10 metres for most of the cave.

1 INTRODUCTION

Accurate and timely spatial information of block cave propagation is critical for greater ore recovery, delivered more safely, and with less dilution. In particular, knowledge of the main cave boundaries can help improve safety through the avoidance of hazardous air gap development, prevent the sterilization of ore and stope dilution, and provide more accurate mine production forecasts. In addition, identifying the location of previously mined workings can mitigate hazards during current and future mine development.

Current monitoring methods rely on the placement or deployment of instrumentation within drillholes, often consisting of time-series data of sparsely-distributed, point locations of beacons and trackers that capture initial caving or near real-time movement with the fragmented rock mass (J. Lett, 2026). Passive source tomography (J.P. Mercier, 2015) and seismicity can be used to recover a velocity model from which a partial cave geometry can be interpreted, or seismically active regions above the cave located.

While commonly employed in today's block cave mines, together these methods cannot accurately and reliably image the full cave back, the top of the muck pile, nor the consequent air gap to the required resolution, and sometimes instrumentation simply cannot be installed due to rock quality or instability. Other portions of the cave back may be difficult to access even via drilling. As a result, most of the cave back structure and nearly all the muck pile are not directly measured. The true location of a mine working or cave may be unknown, and a dangerous air gap may develop unmonitored. Interpolation from point data can lead to unquantifiable uncertainty of the interstitial cave profile that is inferred by qualified practitioners from a combination of multiple datasets.

We apply muon tomography to reconstruct the entirety of both the cave back and the top of muck surfaces to high resolution in both space and time, thus defining any development of an air gap throughout the lifetime of the cave. Structural models, together with an associated uncertainty, are provided frequently enough so response action can be taken to keep the cave safe and change mine plans and forecasts or take other remedial measures.

We show results of both block cave simulations along with field results showing successful in-mine imaging of mine workings from New Gold's New Afton Mine in Canada and BHP in Australia.

2 MUON TOMOGRAPHY

Muon tomography (D Schouten, 2022) is a geophysical method predicated on measuring the intensity of muons, which are naturally occurring sub-atomic particles arising from supernova explosions in space. Cosmic rays collide with matter in the Earth's upper atmosphere to create muon flux that travels to Earth in straight lines at almost the speed of light. Muons, which pass through the Earth's surface about once/minute for every square cm (J Beringer, 2012), are highly penetrating particles that progressively lose energy at a rate proportional to the density of the material through which they pass. By measuring the directional muon intensity [cm^{-2} s^{-1} sr^{-1}] using muon-tracking detectors placed underground the true underlying structure of average density emerges in the 2D radiographs produced by each detector. As the exposure time, and number of muons measured increases, the relative uncertainty of the observed muon intensity from each direction diminishes.

By combining data collected from multiple muon detectors deployed at different lateral placements or depths, and employing geometric inversion methods, we can directly infer block cave structures such as the cave-back and top of muck surfaces on time-scales useful to mine operations.

3 SIMULATIONS

To assess the theoretical capability, synthetic examples of realistic block caves have been prepared in consultation with MaxGT Consulting. The caves are attributed with in-situ density representing mineralization and host rock and simulated block cave operations with muck pile and air gap structures derived at monthly intervals for the life of the cave between 0 – 60 months.

Ideon has developed a complete physics model that predicts the intensity of muons along any slant depth (muon trajectory for a given zenith angle) through rock underground. As the muons propagate through rock, they lose energy at a rate that is heavily dependent on the density of the rock they traverse. Scattering of muons along their path can be ignored because it is almost always much smaller than the desired spatial resolution, and in fact decreases on average with depth. The probability that a muon survives through a certain rock opacity is calculated with Monte Carlo simulations and multiplied by the muon flux at sea level to determine the muon intensity at any given rock depth.

As described in detail in (D Schouten, 2022) and (D Schouten, 2018), the expected number of muons detected within a given pixel p of the radiographic image acquired by a detector underground, in which each pixel maps to a 3D solid angle Ω, is derived with the following equation:

$$N_{exp} = \Delta t \int_{\Omega_p} \left(\int_0^{\infty} D_{\mu}(E, \theta) \cdot p(E; \mathcal{O}) dE \right) \alpha(\hat{n})\, d\Omega$$

Ideon has developed a robust, precise model that describes the expected intensity of muons at the surface $D_{\mu}(E, \theta)$ as a function of initial muon energy E and zenith angle θ, using data collected over the past six decades (D Schouten, 2022). As the muons propagate through rock, they lose energy at a rate that is heavily dependent on the density of the rock they traverse. Therefore, the probability $p(E;O)$ that a muon survives through a certain rock opacity ($O = \int_{path} \rho(x,y,z)\, d\ell$) is calculated with Monte Carlo simulations and multiplied by the muon flux at sea level to determine the muon intensity at any given rock depth. The muon survival probability depends on initial energy; hence, the contribution is summed over all relevant energies. Finally, the detector active area and performance is accounted for in the $\alpha(\hat{n})$ term. The integration is performed over all angles corresponding to a cone Ω_p above the detector defined for each pixel p in the radiograph and multiplied by the exposure time Δt.

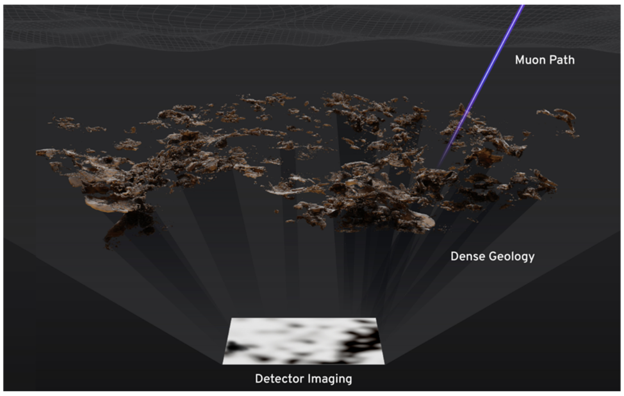

Figure 1 Diagrammatic representation of a muon detector radiographic image and how it relates to the geometry of muon paths and density of the varying geology.

Thus, for a given state of a block cave, we can model the expected directional intensity, i.e. radiographic images (Figure 1), for any number of detector locations within the extraction level or in boreholes. This allows reasonable and representative caves with varying structural scenarios and degrees of complexity to be accurately simulated. Together with validation of the physics model from using field-proven Ideon detectors in a variety of geological contexts around the world, we can optimize deployments and gain good confidence on applications prior to field deployment and acquisition of real muon data.

In the following example, detailed simulations are performed with the cave extraction level situated at 800 metres total vertical depth, under a relatively flat topography. Figure 2 shows the reconstructed cave back from an in-mine simulated muon deployment, based on data collected for a single month. The reconstructed shape almost exactly agrees with the true cave shape (shown as a semi-transparent grey surface). Because the statistical and systematic uncertainties within the muon intensity measurements are well characterized, we can also calculate the resultant precision of the reconstructed surface, given the observed data. For any point across the full cave back, the maximum probability estimate of the position of the cave surface can be evaluated, as well as the corresponding uncertainty at that position. This uncertainty follows a well-characterized normal distribution, which facilitates evaluation of confidence interval. The 95% confidence interval of the difference between the reconstructed cave back and the true cave is shown as the colour map of the surface in Figure 2. In this modeling example for one specific month snapshot, the CI=95% resolution is typically less than 10 metres and is only rarely greater than 15 metres. Given the reliability of the physics engine, and the proven capability of the muon tracking detectors, extrapolating to a real-world scenario can be done with confidence. Further, since the measurement is a temporal variation of the observed muon intensity as the block cave advances, inherent uncertainties arising from imperfect knowledge of the static geology within the fields of view of the sensors, can be completely mitigated in the analysis by performing comparative muon flux measurements across time.

In the full evaluation for this synthetic cave, across the full 60 months of the cave lifetime, from initiation to breakthrough, the modeling shows that cave is resolved with a quantifiable precision of less than 20 metres across the whole cave, and on the order of 10 metres for most (~85 %) of the cave (Figure 3).

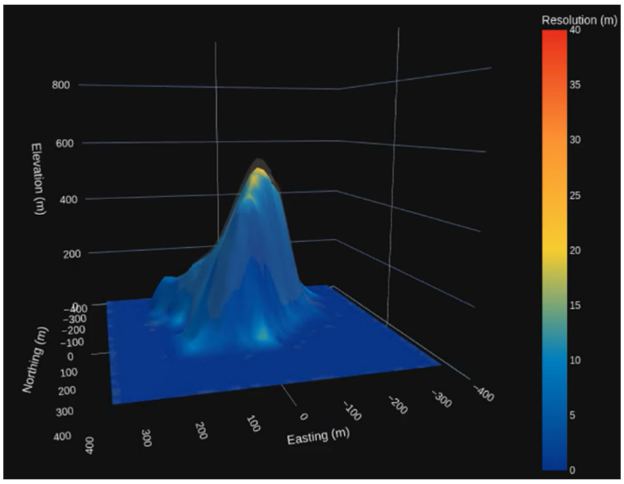

Figure 2 Simulated 3D cave-back reconstruction shown for a single month in the cave life, coloured by spatial resolution where most of the cave is resolved to within 10 metres.

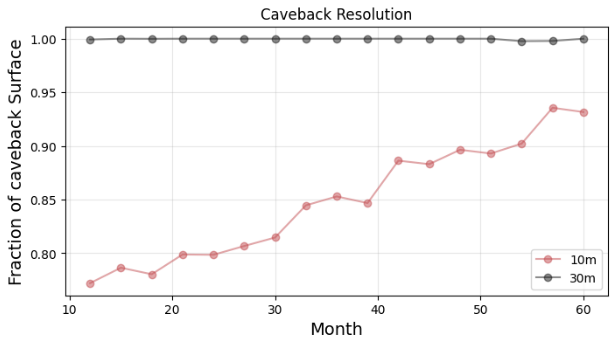

Figure 3 Fraction of the cave back for which the expected resolution is at least 30 metres (black points) or 10 metres (red points), when derived solely from simulated muon intensity measurements from 25 detector locations at 800 metres depth in the extraction level, across the 5-year lifetime of the cave beginning at year 1.

These results indicate that very good resolution across a whole cave back is readily achievable and the information the reconstructed cave back affords is timely, accurate, and precise. The muck pile is similarly well defined, and thus an air gap can be identified before it significantly increases, mitigating any serious hazards.

The evolution of the cave and muck pile can be tracked across multiple time frames with varying precision, and the uncertainty is quantifiable across the whole surface (no blind spots). Focused deployments can also be designed to increase resolution in specific areas, such as a developing cave front or area of complex faulting.

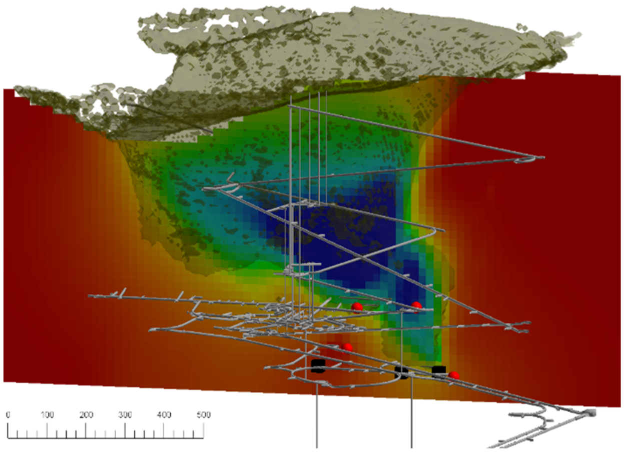

Figure 4 Ideon borehole muon detectors (orange) and Ideon in-mine muon detectors (black) simulated for deployment at New Gold's New Afton block caves A and B. Colour section represents density from 2.2 g/cc in the cave (blue) to 2.8 g/cc in the host rock (red).

3.1 New Gold New Afton Mine

Ideon is working with New Gold at its New Afton Mine to demonstrate the capability of muon tomography for block cave imaging. In advance of deployment, we conducted thorough simulations to optimize detector locations and de-risk the survey. At the New Afton mine in British Columbia, Canada, we have a phased approach where detectors are deployed to image the upper caves in B Zone, shown in Figure 4, while we simulate the deeper block cave. As seen from the semi-transparent surfaces, the small cave B to the lower right has already breached the larger cave, which itself had previously breached the topographic surface. Here the objective is to image any change in the cave boundary where no instrumentation can be installed due to unstable conditions and monitor for any air gap development. In addition, we hope to investigate imaging the flow of rock mass through the muck pile.

The simulation results seen for this deployment show excellent agreement between the known cave shape and the low-density parts of the model (blue) recovered from 5 in-mine muon detectors (black cubes, 3 of which are not obscured by the section) and 4 groups of borehole muon detectors (red spheres) also placed within mine developments. We look forward to sharing the results of this work as they become available in the coming months leading up to the conference.

4 DEPLOYMENT

In general, muon tracking detectors are deployed below target geologic or geotechnical structures to record the trajectory of each muon that passes through them. These detectors are placed at various positions on the extraction or access levels to capture muon trajectories from multiple paths through the region of interest.

Detectors can be deployed in-mine or down-hole as necessary to meet site-specific muon imaging objectives. Figure 5 shows Ideon's in-mine panel detector with a ceiling-mount installation away from mine traffic. The borehole muon detector can also be unobtrusively installed in-mine (Figure 6) or installed in HQ-sized boreholes from surface or underground.

Figure 5 Ideon's Mine Muon Hub installed in a mine.

We have successfully deployed muon detectors at numerous mines around the world where they are actively and autonomously acquiring data and transmitting them on a fast cadence in near real-time for processing, analysis, and modelling. These models are subsequently delivered to mine operations for integration into their geotechnical and production workflows.

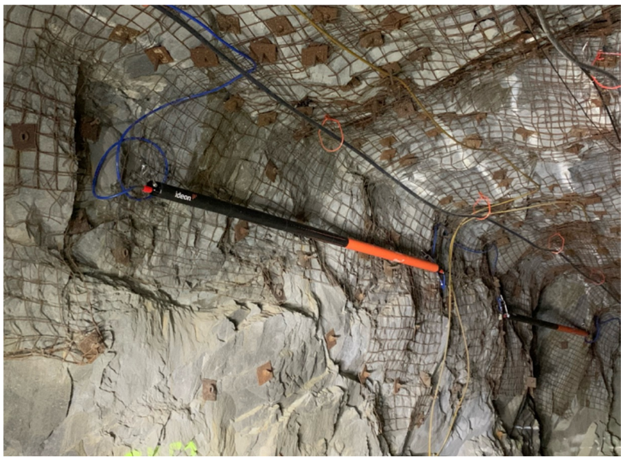

Figure 6 Ideon borehole muon detector installed in-mine.

5 RESULTS AND VALIDATION

We present two field examples now where in-mine muon detectors have successfully imaged mine workings and voids, with results from a third field example expected prior to the conference.

5.1 BHP Venus Mine

We deployed in-mine muon detectors (shown as red cubes in Figure 7) in a drift between BHP Nickel West's Perseverance and Venus deposits, and borehole muon detectors to the north proximal to the Rocky's Reward deposit. The achieved objective was to identify and image new, massive sulphide targets, and geologic structures. As well as providing important brownfield exploration information, the ongoing mine operations at Venus were seen in the modelling results, and identified by BHP after Ideon completed its analysis.

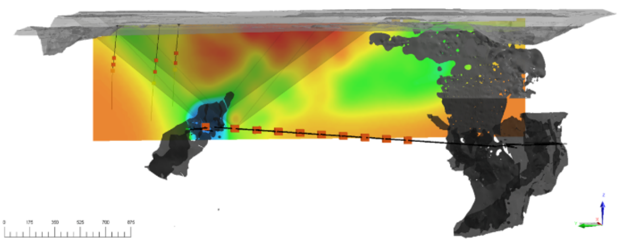

Figure 7 East-facing section through the joint in-mine muon, borehole muon, and gravity density inversion result (blue represents low density and red represents high density). Proximal to the Venus deposit, a very significant low-density structure was observed, and confirmed by BHP to align with ongoing mining activity. This was done with only a single in-mine detector field of view overlapping with the mining structures.

The muon data were inverted in combination with gravity, gravity gradient, and borehole data to generate a multi-physics model. The imaging of the mine workings mainly results from data acquired by a single muon detector, and partially from a second detector. This success provided early validation of muon tomography to clearly image voids from mining activity. A more detailed image of the mine working and the recovered multi-physics density inversion model is shown in Figure 8.

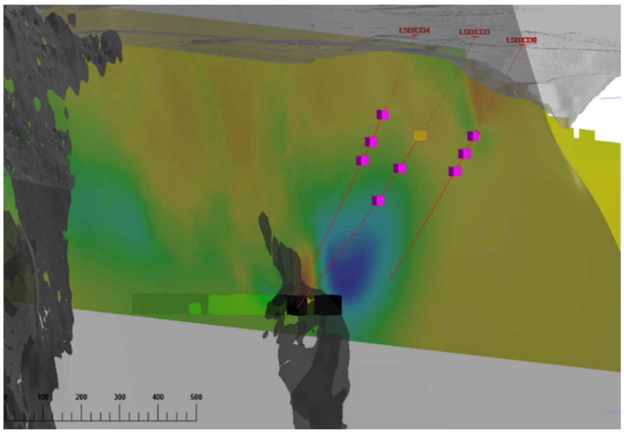

Figure 8 Vertical section of the joint 3D density inversion model. The locations of the borehole detectors are indicated (magenta cubes), and the in-mine detector locations (black cubes) are mostly obscured by the section shown. A strong low-density anomaly (blue) around the Venus deposit (semi-transparent grey) and below the borehole survey represents ongoing mine workings.

5.2 BHP Olympic Dam Mine

BHP's Olympic Dam, located in South Australia, is a significant multi-mineral ore body that includes copper, gold, and uranium mineralization. It lies beneath an approximately 300-metre-thick sedimentary cover sequence and is notable for its size and metal production. With mining ongoing since 1988, there are many areas that contain previously mined, large back-filled stopes.

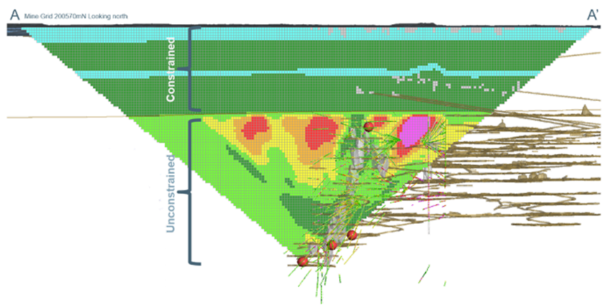

Figure 9 In-mine muon tomography result showing the accurate location of backfilled stopes at Olympic Dam.

Ideon has successfully completed an initial deployment of in-mine sensors at depths of up to 875 metres that, as well as imaging mineralization, have clearly imaged low-density back-filled stopes. A compelling correlation between a lower-density zone in a section through the recovered density model and the stope shapes is observed in Figure 9.

6 CONCLUSION

Through field data analysis and simulation, we have demonstrated an ability to image mine workings and voids and provide quantifiable precision to cave back and muck pile surfaces.

Muon detector deployments can be accurately simulated for a variety of geologic and geotechnical scenarios allowing detector arrays to be designed and optimized to meet site-specific resolution needs, such that block cave and sub-level mines can be successfully imaged.

For block cave mining operations, this offers an improved solution that measures the entirety of the cave to high accuracy, allowing mine operators to manage hazards pro-actively, improve ore recovery and production predictability, and reduce operational, financial, and ESG risks.

By the time of this presentation, we will have deployed in at least two more mines and expect to showcase additional, successful, mine imaging and block cave monitoring results.

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