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# Blind Test of Muon Geotomography for Mineral Exploration

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## SUMMARY

Muon geotomography is a new geophysical imaging technology that creates 3D images of subsurface density distributions. Similar in concept to computed tomography scanning, muon geotomography uses naturally occurring cosmic radiation that gets attenuated when traversing matter. Cosmic ray muon data were acquired in the Pend Oreille Zn-Pb mine in Metaline Falls, Washington State, USA without prior knowledge of the presence or absence of ore bodies. The resulting 3D density distribution indicated a substantial volume of rock with higher density than the host stratigraphy above the survey location. Subsequently, a model of existing ore shells based on drill core data was provided and a simulation of the expected muon tomography data was found to be consistent with the muon geotomography measurements. This is the first blind test demonstration of muon geotomography applied to mineral exploration.

**Key words:** mineral exploration, muons, geotomography

## INTRODUCTION

Cosmic ray muons (CRM) are unstable particles created in the upper atmosphere that can penetrate the earth, reaching several kilometers below the surface. The intensity of the muons falls exponentially with depth. Underground muon flux measurements can reveal dense deposits such as massive sulfides or uranium deposits that cause additional reduction of the muon flux. Bryman *et al.* (2014) described a field study in which a volcanic hosted massive sulfide ore body was successfully imaged.

Muon tomography imaging is similar in concept to computed tomography (CT) used in medical and industrial imaging. In muon geotomography (MGT), underground sensors determine the directions of CRM trajectories, and after a suitable observation period the data set for each sensor position represents the intensity distribution or number of events observed at various angles. The information obtained from a set of sensors at different locations may then be inverted to obtain a 3D density map of regions of the earth above the sensors (Bryman *et al.*, 2014).

In the present work, muon sensors were placed in the MX700 tunnel at the Pend Oreille Zn-Pb Mine in Metaline Falls, Washington. No information regarding the presence or absence of ore bodies in the region being surveyed was provided prior to the study.

## MUON GEOTOMOGRAPHY AT THE PEND OREILLE Zn-Pb MINE

The Pend Oreille mine is a Mississippi Valley Type (MVT) Zn-Pb deposit located in Metaline Falls in northeastern Washington State, USA at an elevation of approximately 2300 ft above sea level. The region's mountainous topography was measured by an aerial LIDAR survey. St. Marie and Kesler (2000) describe the geological setting, which is summarised below. The Pend Oreille mine hosts several zinc-lead ore bodies within the Metaline Formation in the southern portion of the Kootenay arc, an arcuate, narrow belt of sedimentary, volcanic and metamorphic rocks separating Precambrian metasediments to the east and Mesozoic volcanic and sedimentary units to the west. Mineralization at the Pend Oreille mine is located within the Yellowhead horizon of the Metaline Formation, an intensely altered stratabound dolomitic solution breccia, which has been invaded and replaced by fine grained pyrite with lesser zinc and lead sulphides. The sulphide zone has relatively simple mineralogy. Sphalerite and galena are the two ore minerals of interest. Gangue minerals include pyrite, dolomite and calcite.

Data were recorded in the MX700 tunnel in the Pend Oreille mine. The site provided a blind test for the MGT method, and no information as to the presence or absence of mineralisation was provided prior to the delivery of the results. Muon sensors were placed at four survey locations in the tunnel approximately 490 m (1600 ft) below the surface, for exposures of 2-5 months. These locations were chosen based on the availability of secure off-road positions and the locations and orientations of the sensors were surveyed. The muon tracking sensors, based on detector designs used in the MINERνA experiment (Minerva Collaboration, 2006) each had an active area of 2 $m^2$. Muon trajectories were reconstructed with angular resolution <1°, from vertical down to a zenith angle of 60°.

A unique relationship exists between the directional muon rate and the material thickness between the sensor and the surface. This relationship is determined by the muon intensity model used to calculate the measured rock thickness assuming uniform density in each direction. This was compared to the predicted rock thickness, which was the distance from a muon sensor to the surface in the chosen direction based on the measured topography; the predicted length is also referred to as the topographic length. The measured and predicted rock thicknesses were inputs to geophysical inversion codes that produced 3D density images of the sub-surface volume.

## RESULTS

Rock thicknesses differing from the predicted thickness, assuming uniform host rock density ($\rho_h$) of 2.79 g/cm$^3$, which is an average for rocks of the Ledbetter and Upper– and Middle-Metaline Formations, were calculated for all directions for each muon-sensor data set. Excess rock thickness measurements for one location are shown in Figure 1. A region of significant excess length, or excess density, was indicated.

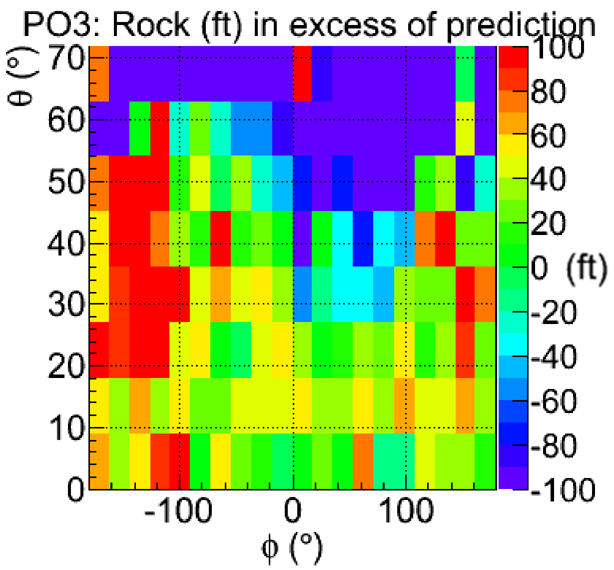


**Figure 1: Excess rock thickness measurements in feet for one location ("PO3") in the MX700 tunnel at the Pend Oreille mine. Excess length is the thickness of rock measured by MGT (assuming uniform host rock density) minus topographic length. Excess thickness, or excess mass, was identified over the region $-180° < \phi -100°$ and $20° < \theta < 50°$.**

A 3D density image produced by the inversion code using data from all locations is shown in Figure 2. A substantial region of excess high density material is evident directly above the sensor regions.

After completion of the data analysis and inversion, a 3D wire frame model of two ore shells and a 3D density distribution for cells within the model were provided. The MGT image was found to be consistent with the ore shell models, although the excess mass identified is about 20% larger than that derived from core drilling for the mineralized zone under investigation. However, the excess mass estimate from the inversion includes potential regions of additional mineralisation and/or dolomitisation that fall outside the modelled ore shells of the mine's model.

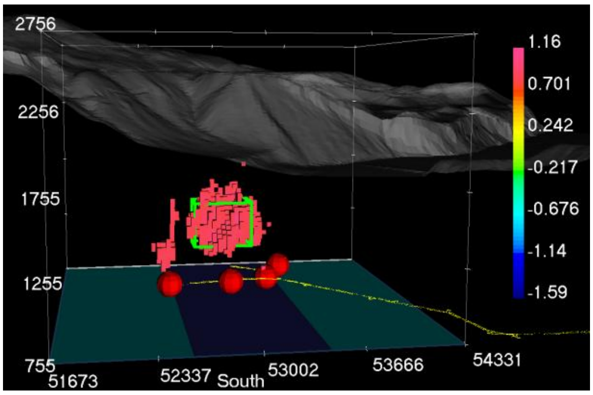


**Figure 2: Three dimensional representation of the inversion result using MGT field data. The color scale indicates density in excess of the host rock density. A minimum density cut-off is applied so that only regions with density $\rho > 3.6$ g/cm$^3$ are displayed. Axes units are feet. The red spheres are the muon sensor locations. The green cuboid approximates the region where the excess mass signal is strongest.**

## CONCLUSION

The muon tomography survey at Pend Oreille represents the first successful example of muon geotomography imaging an ore body without any prior knowledge of its existence demonstrating of the applicability of muon geotomography to mineral exploration.

Three dimensional images from muon geotomography surveys may in the future be used in conjunction with other geophysical data to guide drilling operations towards regions of high density contrast, thereby contributing to the reduction of technical risk, while also potentially decreasing the production costs and environmental impacts associated with locating, delineating, and ultimately mining ore bodies. The environmental benefits assume that improved imaging will reduce surficial disturbance owing to reduced trenching and drilling, while reduced production costs would primarily relate to decreased dilution. The achievement of these goals will require improved image reconstruction that can be provided by a more extensive network of muon sensors which is not limited to existing tunnels. To that end, the development of borehole sensors has been proposed and is currently under review.

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