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From deep space to shallow crusts and asteroids: muons as one possible tool in the future of mineral exploration, planetary missions, and asteroid mining

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Abstract

Many mineral deposits are associated with drastic density gradients in the form of lithological contacts, structural breaks, the excess accumulation of dense (or low density) minerals, hydrothermal alteration and/or weathering. Variations in rock densities can be geophysically followed by a variety of methods, the principles of most based on classical physics. One of the fields of physics not yet applied widely in mineral exploration is that of muography, although its principles were introduced already in 1955. The method is currently experiencing a renaissance due to new-generation semiconductors, increasing computing power and advanced particle physics codes. However, in geosciences the method is currently mostly used in volcanology, not in mineral exploration.

Muons are heavy, charged electron-like particles originating from the upper atmosphere due to constant interactions between high-energy cosmic rays and air molecules. Some muons have so high energies that they travel in rocks for tens to hundreds of meters, the really rare ones even up to a few kilometers. While muons travel through dense materials, they lose energy until attenuated. This phenomenon is directly related to an average density of the rock column and can be exploited in muography for constructing X-ray like density variation maps of the rock material between the ground and the muon detector(s). Muography applied to mineral exploration is thus based on extracting relative rock densities in various directions from the statistics of muons passing through the detector (or an array of detectors).

We anticipate muography to find its place it the plethora of geophysical methods in the following few decades. One challenge is that muography originates outside the realm of classical physics and hence most geoscientists are not yet familiar with its principles. However, as the technology matures it may become a competing option for detecting density variations in both greenfield and brownfield exploration. There already are solutions to apply muography via tunnels and drill holes, and we can foresee that method development will continue for many more decades. Preliminary analyses show that theoretically muography can be applied at least up to 2 km depth and brought to celestial objects like the Moon and Mars. If the atmosphere is thin (Mars), or there is no atmosphere whatsoever (Moon, asteroids), other natural muon generation mechanics may occur. At the Moon and Mars muography could be used to locate resources (water ice and other raw materials for In-Situ Resource Utilization, ISRU) and caverns for human settlements, storage space and the search for life. The imaging of the asteroids using muons, on the other hand, may provide a useful tool for screening which ones have the highest potential for mining. In the time frame of one hundred years, many such activities could be automatized by robots and AI. It is also possible that we are able to manufacture transportable muon generators in the distant

future. With those, all types of muon-based imaging techniques could be brought to the mainstream and as deep in terrestrial crusts as there are tunnels available.