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Studying bedrock fracture and weathering patterns with cosmic-ray induced muon particles

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Subsurface fracturing and weathering in bedrock are typically studied and imaged with conventional remote geophysical techniques. We introduce a new technique, muography, for carrying out such studies. This technique is based on the detection of atmospheric cosmic-ray induced muon particles after they pass through rock. The method plots the attenuation of muon flux in materials of different thickness and density (simply, dense materials “stop” more muons). The raw muon flux is translated into 2D images and 3D models showing variations in mean densities in a visually meaningful manner. As a rule of thumb, a 1% density difference between two rock bodies yields approximately 3% difference in the respective muon fluxes. The muographic density maps cover the Volume of Interest (VOI) that is located between the muon detector(s) and the source of muons (sky). Hence, the detector must be installed behind the VOI. Appropriate settings for muography include the sides of mountains, hills, cliffs and gorges, and in tunnels or boreholes below the ground surface.

Muography provides an interesting new opportunity to study and remotely image subsurface fracturing and weathering. Understanding fracturing and weathering is important as they control, for example, erosion, soil formation, the stability of rock and soil slopes, and stability of tunnels. Weathering also has a link to past climates, palaeogeographic reconstructions, and natural geochemical cycles. Weathered bedrock is also a target for mineral exploration. Due to these reasons, we are planning field surveys in northern Finland. These surveys are also used for fine-tuning the muon detector’s operational parameters and to improve its current design to cope with operating conditions in the Arctic. The survey area around Vuotso lies within the ice-divide zone of the Fennoscandian ice sheet, a zone of low glacial erosion through the Pleistocene. We have identified two survey targets: (i) a tor-studded granite dome at Riestovaara, with extensive granite

outcrops that show curved sheet joints and (ii) Mäkärä, a rare-earth mineral prospect in the Tana Belt where amphibolites and garnet–biotite gneisses are covered by thick kaolinitic saprolites of pre-Pleistocene age and overlain by clay-rich till enriched in La and Y. Reconnaissance muon surveys across these contrasting terrains can be calibrated against a wealth of existing GTK data from field mapping and boreholes. The muon survey aims to provide important new subsurface information on fracture patterns at depth on the Riestovaara dome and on deep weathering patterns at Mäkärä. Muography has potential to become a fundamental tool for low-cost subsurface surveying, with applications in geomorphology, mineral exploration, and civil and mining engineering.