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Natural stone assessment with ground penetrating radar

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Abstract. The usability of ground penetrating radar in quality assessment of natural stone deposits was tested in porphyritic granite and soapstone. The main interest was to evaluate how the soundness, fracturing, and physical defects can be studied with the method. Ground penetrating radar is a suitable and fast investigation method for natural stone evaluation, but the geological and geophysical characteristics of the rock have to be known in advance to help the interpretation of the results.

Key words: natural stone, ground penetrating radar, GPR, rapakivi, granite, soapstone.

INTRODUCTION

Ground penetrating radar (GPR) has been widely used in the investigation of rock properties, especially fracturing. Fractures in a rock mass are discontinuities that for GPR act like electromagnetic boundaries where part of the radar pulses are reflected back to the surface, producing an interpretable measuring profile (Annan 2004). In particular, horizontal and sub-horizontal fractures are easily observed, provided they are open enough and preferably water saturated. Vertical or sub-vertical fractures can be left unnoticed since they do not offer a large enough reflection plane for the radar wave. Moreover, GPR as a technique is very fast and the results can be preliminarily checked instantly on the recording unit. Ground penetrating radar performs well with rocks, which have low electric conductivity and low magnetic permeability, like e.g. granite and granodiorite. In rocks containing e.g. conductive minerals the penetration of the radar wave is usually restricted due to the electromagnetic properties of the rock. The penetration of the signal and the detection resolution of GPR depend also on the frequency of the antenna used. Generally, the antennae of higher frequency give better detection of individual targets and fractures but the attenuation of the signal is also stronger, giving less penetration in the rock. The antenna is often chosen as a compromise between detection and penetration.

This study is a part of a large research project to characterize different natural stones and their material properties as well as the research methods. Among others, the chemical, mechanical, and physical properties of the rocks were tested. As one of the research methods GPR was tested in granite, schist, soapstone, and marble. This paper presents in detail the study of GPR combined with the mapping of geological and structural features of the rocks performed on two typical Finnish natural stone types, granite and soapstone. The properties of these stone types are consistently different, challenging the use of GPR as a prospecting tool.

In the first case study the material was porphyritic granite and the study area was located in the eastern part of the Central Finland Granitoid Complex (CFGC) in southeastern Finland (Fig. 1). A typical feature in the porphyritic granite batholith is pronounced horizontal or sub-horizontal exfoliation-type fracturing. In this case the continuity of the fracture planes was of special interest.

In the second case study the material was soapstone, belonging to an Archaean greenstone belt, situated in

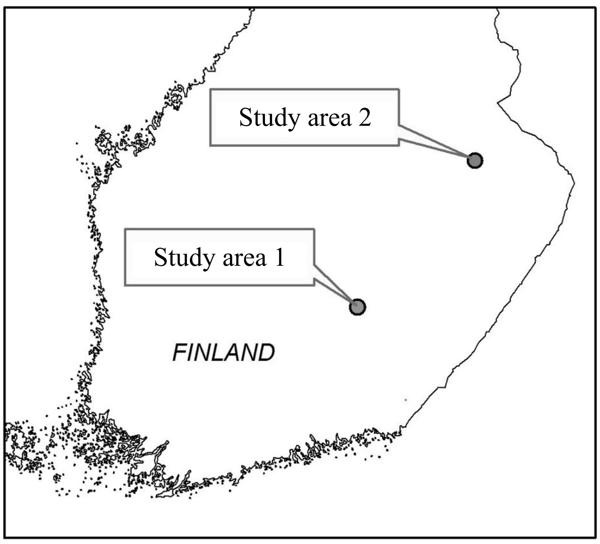

Fig. 1. Location of the study areas.

North Karelia in the border zone between the Archaean area and the Palaeoproterozoic North Karelian Schist Belt (Fig. 1). A typical feature of this material is a strong internal lineation with conductive minerals oriented along it, which can be mixed in GPR results with fracturing. In both cases the measurements were conducted in a quarry environment, where geological features like fracturing and lineation could be observed on the quarry benches to verify the GPR results.

GEOLOGICAL OUTLINE OF THE STUDY AREAS

Study area 1 with porphyritic granite is situated in south-eastern Finland. It belongs to the CFGC, which covers an area of about 40 000 km^2 consisting mainly of granodiorite and granite but also of gabbros, subvolcanic rocks, and remnants of supracrustal belts (Nironen et al. 2000).

Study area 2 belongs to an Archaean Nunnanlahti greenstone belt, situated in North Karelia in the border zone between the Archaean area and the Palaeoproterozoic North Karelian Schist Belt. This particular greenstone belt is a highly deformed unit with an intense shear zone development (Lehtinen et al. 2005). The complex history of the formation is also partly visible in the quarried soapstone material as textural deformation. The rock itself is mainly composed of talc and magnesite, which makes it very easy to work and suitable for several construction purposes.

METHODS OF STUDY, INSTRUMENTATION, AND ARRANGEMENTS OF THE MEASUREMENTS

The GPR measurements were conducted along traverses, by dragging the antenna directly on the rock surface. The GPR control unit used in this study was GSSI SIR-2000, manufactured by Geophysical Survey Systems, Inc. For the porphyritic granite, the measurements were carried out with the antennae of 200 and 400 MHz (Fig. 2). In the soapstone case the antennae of 100, 200, and 270 MHz were used. The measurement results were verified with fracture mapping along the traverses and quarry benches.

For the porphyritic granite deposit (study area 1) a set of 18 measurement traverses was planned to study the fracturing and its characteristics. The measurement traverses were oriented in groups that were perpendicular to each other to investigate the propagation of the fracturing in different directions.

In the soapstone deposit (study area 2) the measurement traverses were planned according to the internal structure of the rock to see how it appears in the measured data. Two separate measurement grids of approximately 30 m by 30 m were planned having a total of 12 measurement traverses. Planning of the traverses was partly guided by the operation in the quarries at the time.

The visualization and interpretation of the results was performed using Radan 5.0 for Windows by Geophysical Survey Systems, Inc.

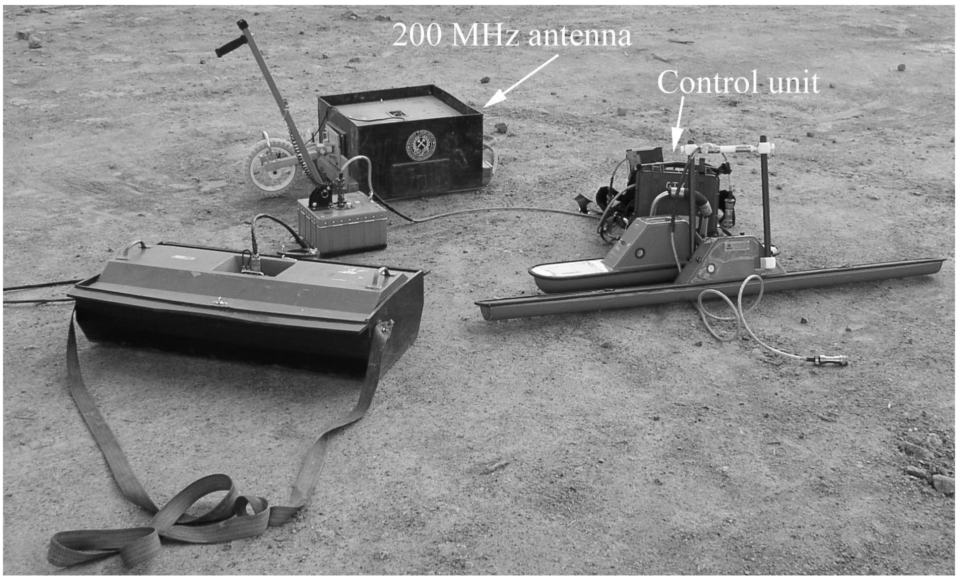

Fig. 2. The GPR equipment used in the study.

RESULTS

Study area 1, porphyritic granite

Porphyritic granite is described as postkinematic in relation to the deformation of the CFGC (Nironen et al. 2000). The rock consists mainly of plagioclase, potassium feldspar, quartz, and biotite and is massive without lineation. A typical feature of the rock is a strong horizontal or sub-horizontal exfoliation-type fracturing. The rock in the porphyritic granite deposit is homogeneous without orientation. Strong horizontal or sub-horizontal exfoliation-type fracturing is typical (Fig. 3). Usually, the fractures are well open, containing water or moist, thus providing a good plane for the radar wave reflection. Besides the main fracturing, the rock has some very tightly closed horizontal fractures. Vertical fractures are sparsely distributed and usually dipping steeply.

The GPR measurements show well the fracturing of the rock and the direction of the fracture planes (Fig. 4). Fractures are discontinuous and the reflections of the same fracture can have variation in the intensity. Between

Fig. 3. Sub-horizontal and sub-vertical fracturing of porphyritic granite. Height of the bench is about 5 m.

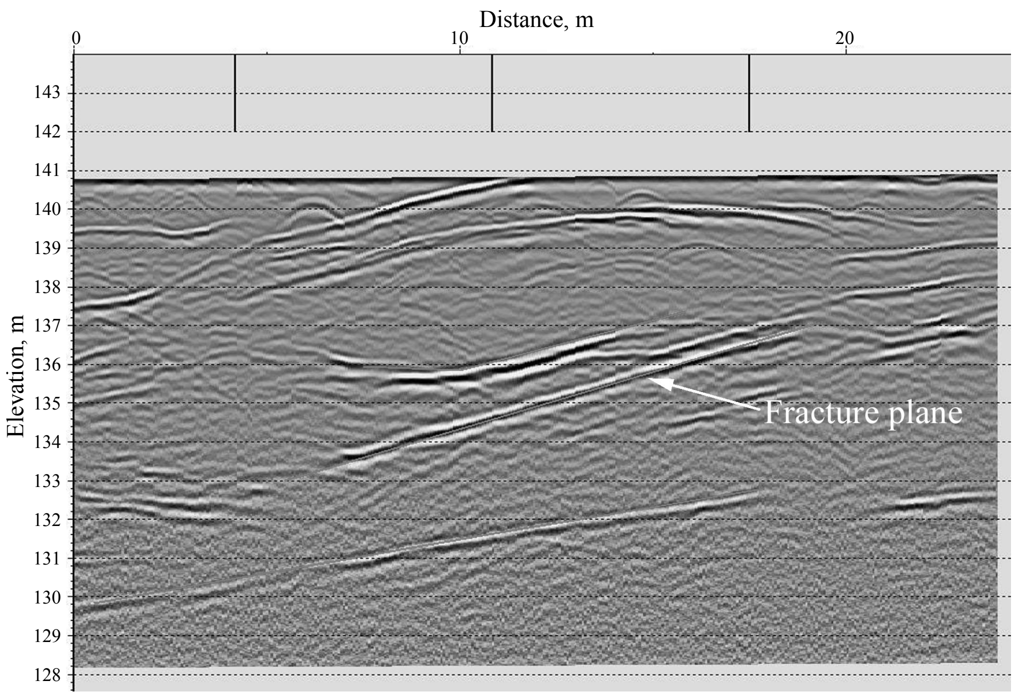

Fig. 4. Measurement traverse showing gently dipping sub-horizontal fracture planes in porphyritic granite (antenna 200 MHz). Length 25 m, depth span about 13 m.

clearly visible fractures there are also weaker reflections that may come from tight minor fractures. Vertical or near-vertical fractures are difficult to detect due to their small reflection surface towards the measuring antenna.

The sub-horizontal fractures near the surface were sometimes strongly weathered, providing space for surface water to collect. Those spaces were detected as individual targets (hyperbolic reflections) on the radar measurement profile (Fig. 5). The targets represent weathering along the fractures, since the weathering of the surface was not detected in the analysis of mechanical and physical properties of the rock, like water absorption and open porosity.

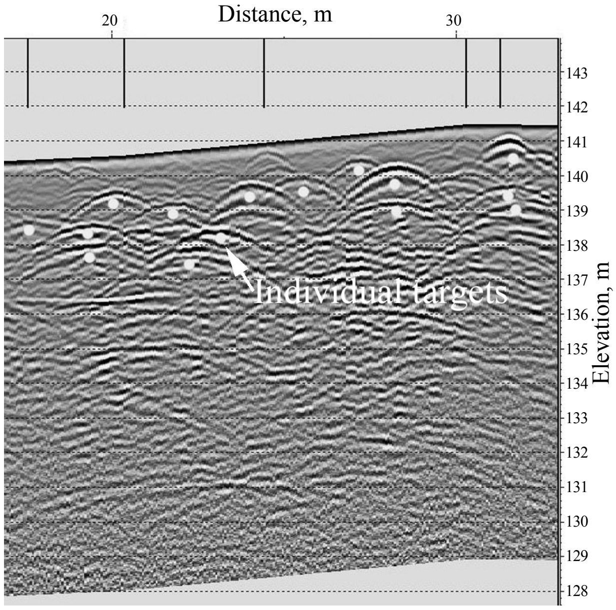

Fig. 5. Individual targets near the surface of the porphyritic granite deposit (emphasized). Antenna 200 MHz.

Study area 2, soapstone

Soapstone is typically massive, lineated, and slightly schistose. The lineation is in the plane of the schistosity. Sparse oblique and sub-horizontal open fracturing is usually developed parallel to the lineation/schistosity plane and perpendicular to it (Fig. 6).

The measurement traverse (Fig. 7) perpendicular to the lineation of the rock brings out the internal structure of the rock mass (Fig. 8), since the conductive minerals that are oriented according to the schistosity plane offer targets to the radar wave reflection. The schistosity with lineation appears as concordantly dipping planes. In the measurement, performed parallel to the lineation, the essential visible features are fractures (Fig. 9). Some of the features can be reflections of the schistosity planes, but clear orientation is not visible.

The penetration of the radar wave depends on the electromagnetic properties of the rock. In general the attenuation of the radar signal is smaller in rocks having low electric conductivity and low magnetic permeability. Soapstone contains some amount of magnetite, which increases the conductivity of the rock. Due to this the radar wave attenuates strongly and the depth of the interpretable profile is only a few metres. The reflections of the radar wave in magnetite-bearing soapstone are very weak even in the surface and no reflections are detectable under a depth of 5 m (Fig. 10).

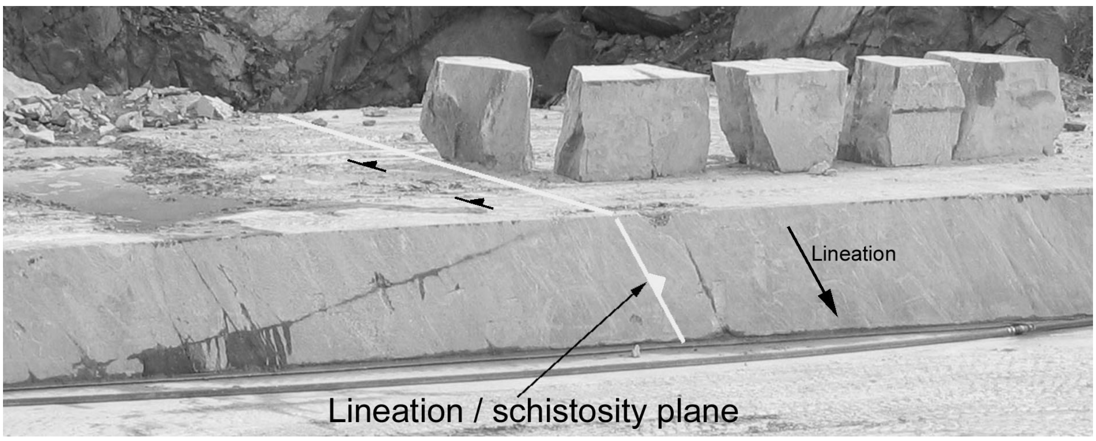

Fig. 6. Massive soapstone with parallel lineation and schistosity. In the middle an open fracture parallel to the lineation/schistosity plane and a perpendicular fracture dipping to left at a low angle. Height of the quarry bench is about 1.5 m.

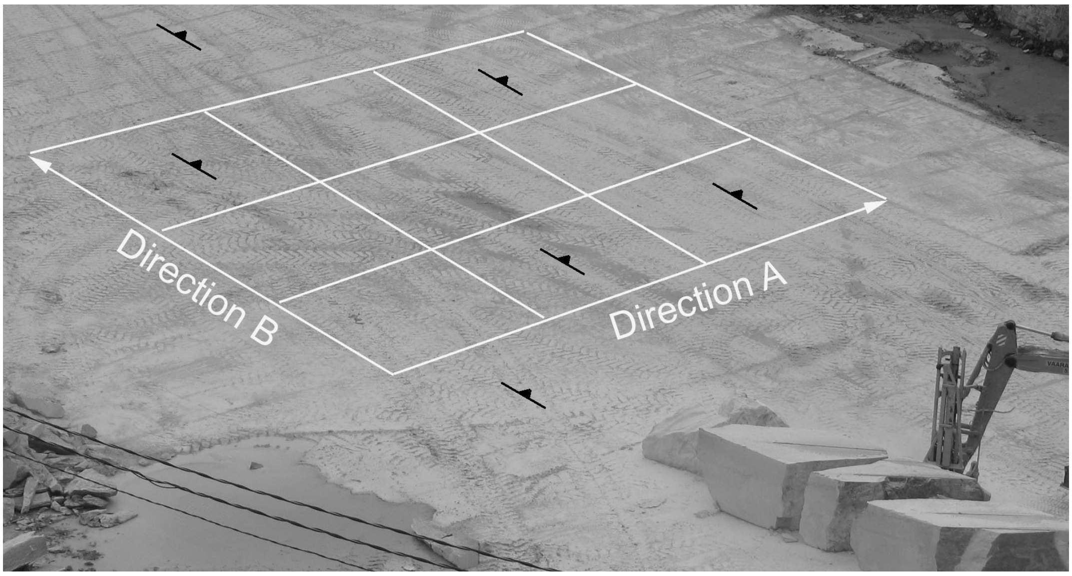

Fig. 7. A measurement grid on the quarry bench. Traverses in direction A are perpendicular to the lineation/schistosity plane and traverses in direction B are parallel to it. The measurement direction is shown with arrows. The distance between the positions in pictures 6 and 7 is about 100 m.

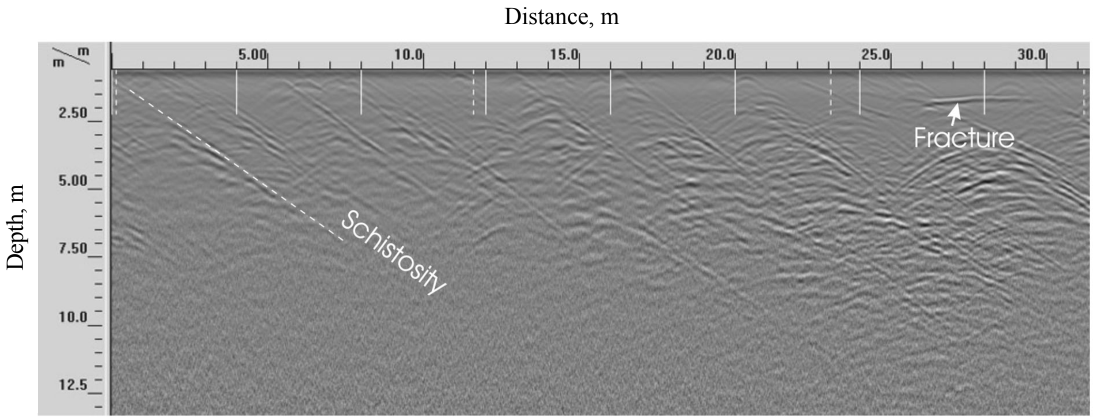

Fig. 8. Radar measurement of soapstone in direction A (Fig. 7) showing the schistosity plane (reflections dipping right at about 45°) and a horizontal fracture. Antenna 200 MHz.

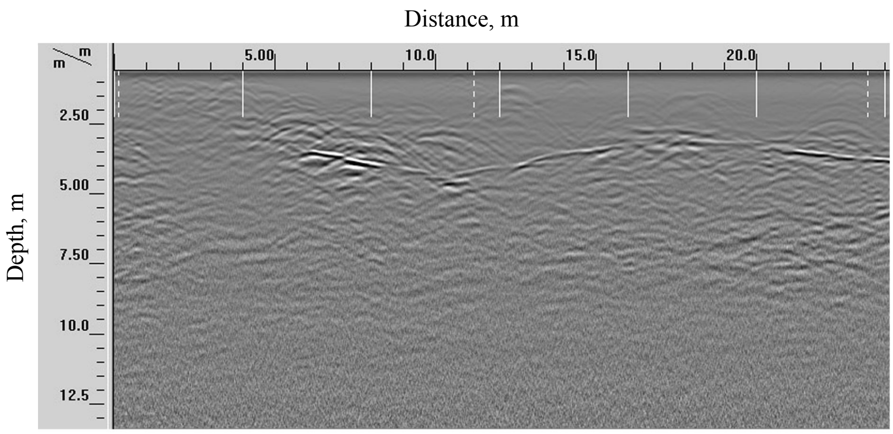

Fig. 9. A traverse measured in direction B (Fig. 7). Now the lineation is not shown but instead a strong wavy horizontal fracture occurs at about 3–4 m depth. Antenna 200 MHz.

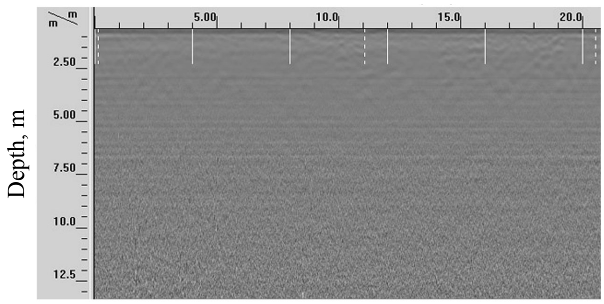

Fig. 10. Measurement traverse in a magnetite-bearing soapstone, having very weak radar reflections. Antenna 200 MHz.

DISCUSSION

The GPR measurement has become one method of the investigation and assessment of natural stone. The instrumentation used in this study represents a common one employed for this purpose. The objective of the study was to get an overview of the capabilities of GPR in characterizing fracturing.

The horizontal and sub-horizontal open fractures that are prominent in the porphyritic granite of study area 1 are quite easily detected with the GPR equipment, while tight and dry small cracks can be left unnoticed. The profiles show a clear picture of gently wavy sub-horizontal fracture planes that are also observed on the vertical quarry benches. Often the fractures can be followed from the quarry bench into the rock mass below just by continuing the observations on the GPR profile. Since the sub-horizontal fracturing is easily detected with GPR, it can be used in preliminary evaluation of the general soundness and quarrying properties of granitic rocks in general.

In case of the soapstone of study area 2 the electromagnetic properties of the rock became more important than with porphyritic granite. The rock mass containing conductive minerals has a strong impact on the radar wave propagation and thus the interpretation of the results. The conductive minerals act also as points for the radar wave to scatter, appearing in the measurement data as detectable features. The fracturing of the rock is strongly connected to the schistosity and the main fracture systems are formed parallel and perpendicular to it. Depending on the measurement direction the schistosity is also revealed in the results, which makes the distinction between the fractures and the schistosity difficult. It is especially important to know the basic geological structures in advance.

Within a larger research project, to which this study belongs, also other rock types were studied to get an overview of the GPR capabilities. In homogeneous granites and rapakivi granites the horizontal and sub-horizontal fracturing is easy to detect and it gives useful information on the soundness of the rock. The sub-horizontal fractures can be seen as reflection fronts presenting the shape of the fracture and the fracture pattern in general. The profiles reveal also the discontinuity of the fracture planes, although in some cases the low visibility and apparent absence of the fractures can be caused by measurement conditions. As expected, the vertical or sub-vertical fractures were generally so steeply dipping that they left only very weak signs on the GPR profiles.

Three-dimensional visualization of the profiles, which was also tested with rapakivi granite in the project, can contribute to a better understanding of the shape and continuation of large sub-horizontal fracture planes, which is essential information for the planning of quarrying operations (Fig. 11). Though, a three-dimensional visualization requires a dense grid of measurement data to produce a useful model.

In the evaluation of both the three-dimensional GPR data and normal single traverses and their interpretation from a quarrying point of view the accurate positioning of the measurements on the site and the need for them to be detected and followed back into the rock mass were emphasized.

CONCLUSIONS

The GPR measurements with the instrumentation available on the market enable quite easy data acquisition for a GPR model. The antennae used affect the accuracy of the model. In this study the antenna of 200 MHz was evaluated to obtain the most useful data.

In this study the case of porphyritic granite gave the results that were easy to interpret because of the low conductivity and homogeneity of the material, while soapstone gave more complex results due to high and sparsely distributed conductive mineral content. For both materials though the detection of horizontal and sub-horizontal fractures was achieved with an accuracy needed for the evaluation and modelling.

The knowledge of the structural features of soapstone was emphasized, since the measurements showed also the lineation and schistosity of the rock. In porphyritic granite both the fracturing system and the weathering of the rock were more prominent.

As the final conclusion, the method works well as a tool for rough fracture pattern estimation. A three-dimensional visualization gives better understanding of the fracture planes and their propagation but needs

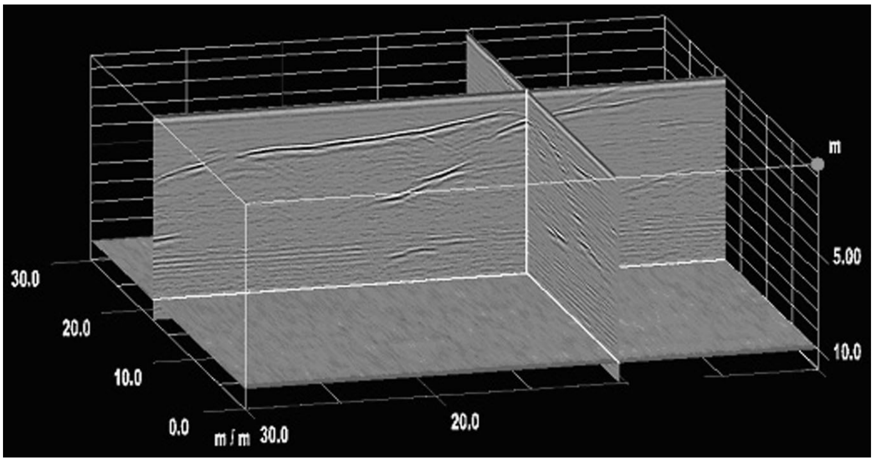

Fig. 11. A schematic presentation of the three-dimensional GPR visualization showing the propagation of the fracture planes in perpendicular directions.

a dense grid of measurement data. For more detailed investigations higher-frequency antennae having a better resolution have to be used together with a larger number of measurements.

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Loodusliku ehituskivi hindamine maagikivimit läbiva radariga

Hannu Luodes

Maagikivimit läbiva radari (MLR) kasutamiskõlblikkust looduslike ehituskivide maardlate kvaliteedi hindamisel on kontrollitud graniitporfüüri ja steatiidi leiukohas. Autorit huvitab, kuidas saab selle meetodiga uurida kivimi tugevust, lõhelisust ja füüsikalisi defekte. MLR on sobiv ja kiire uurimismeetod looduslike ehituskivide hindamiseks. Tulemuste tõlgendamist hõlbustavad eelteadmised kivimite geoloogilistest ja geofüüsikalistest omadustest.