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Why 3D seismic data are an asset for both exploration and mine planning? Example of Kevitsa Ni-Cu-PGE, Finland

A. Malehmir[1], A. Tryggvason[1], C. Wijns[2], E. Koivisto[3], T. Lindqvist[3], P. Skyttä[4] and M. Montonen[5]

[1]Uppsala University, Uppsala, Sweden
[2]First Quantum Minerals Ltd., Perth, Australia
[3]University of Helsinki, Helsinki, Finland
[4]University of Turku, Turku, Finland
[5]Boliden FinnEx Oy, Kevitsa, Finland

E-mail: alireza.malehmir@geo.uu.se

Kevitsa is a disseminated Ni-Cu-PGE ore body in northern Finland, hosted by an extremely high-velocity (6-8 km/s) mafic-ultramafic intrusion. It is currently being mined at a depth of about 100 m using open-pit mining method. The mine life is expected to be about 20 years, with the final pit depth at around 400-500 m. Based on a series of 2D seismic surveys and given the expected mine life, a high-resolution 3D seismic survey was justified and acquired in winter 2010. Various researchers and teams have exploited these data because of the unique nature of geology, and the data being challenging to interpret but rich in reflectivity. In this study, we present 3D reflection data processing results and complement them with 3D first break tomography work recently carried out. The combined results allow to provide some insights about the nature of some of the reflectors. It for example shows how the tomography results can be used for rock quality studies and further planning of the pit. In particular, we observe a major fracture system, resolved by the tomography results and running in the middle of the planned pit, with the reflection data providing information about its depth extent, estimated to be at least about 500 m. We argue that 3D seismic data should be acquired prior to commencement of mining activities in order to maximize exploration efficiency at depth, but also to optimize mining as it continues towards depth.

Keywords: 3D seismic, hard rock, exploration, mining, Kevitsa

1. Introduction

Kevitsa 3D seismic survey (~ 9 km^2; winter 2010, Figure 1) was motivated by four 2D seismic profiles acquired in 2007 as a part of the HIRE national seismic program of the Geological Survey of Finland (Kukkonen et al., 2009; Koivisto et al., 2012 and 2015), with the primary goals of the 3D survey being open-pit mine planning and deep exploration of massive sulphide occurrences within the resource area (Malehmir et al., 2012; Malehmir et al., 2014). Disseminated Ni-Cu-PGE mineralization is hosted in olivine pyroxenite, Kevitsa intrusion, surrounded by volcano-sedimentary rocks. These various rock units exhibit velocities ranging from 4000 to 8000 m/s in more than 11 deep (> 800 m) boreholes logged using full-waveform sonic and VSP measurements (Malehmir et al., 2012). During the processing of the 3D data, it became obvious from the refraction static model that the bedrock required high velocities on the order of 7500 m/s within the planned open pit. Although the data were high seismic fold, respective receiver and shot line spacing of 70 and 80 m, and receiver and shot point spacing of 15 and 45 m, the high velocity background resulted in poor reflectivity signatures in the first couple of hundred meters of the migrated reflection volume (Malehmir et al., 2012). Pronounced reflectors within the planned open pit and greater Kevitsa intrusion were observed to start from 150-200 m depth and were related to either magmatic layering within the Kevitsa intrusion or faults and fracture systems both of which had implications for the design of the pit and future exploration at the site. A tomography test was conducted to cover the near surface reflectivity gap and, if possible, to be used for rock quality studies to aid mining at the site. No tie with surface geology has been possible until recent advance of mining to almost 100 m depth

in certain locations, allowing improved interpretation of the reflection and tomography results, which will be the focus of this study.

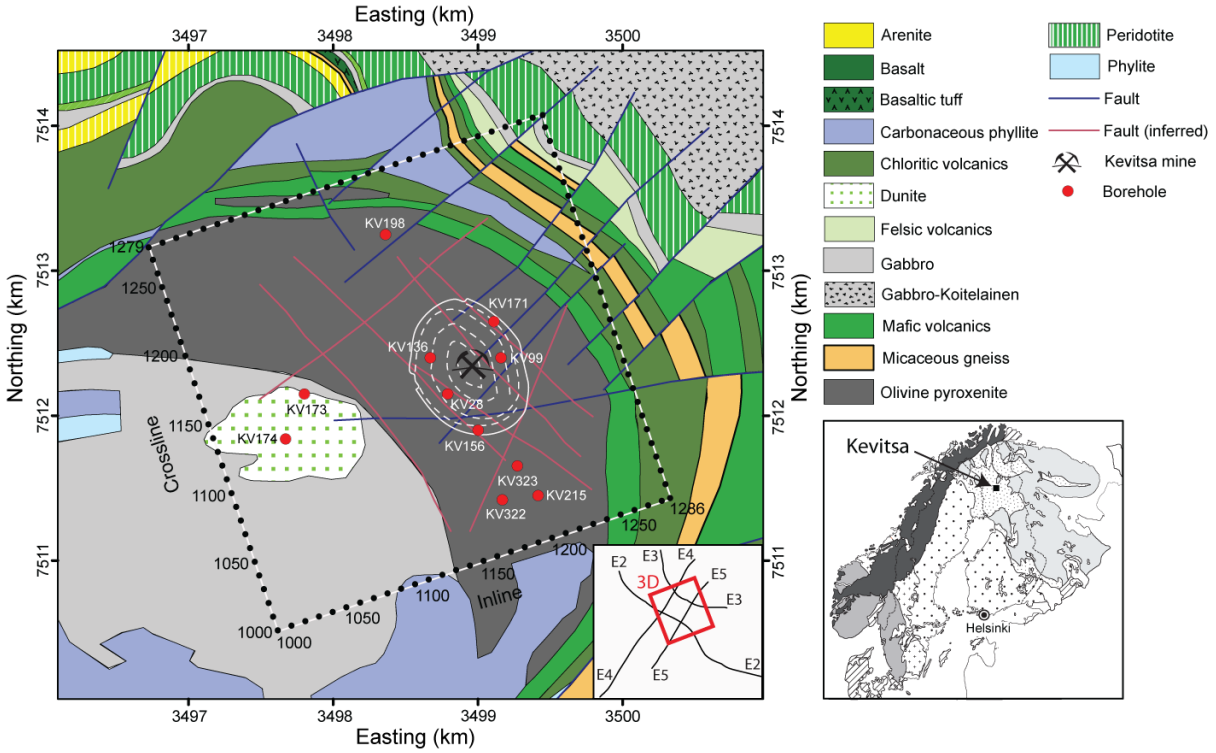

Figure 1. Geological map of Kevitsa showing the location of the planned open pit (stage 4), 3D seismic survey area, and 2D seismic profiles E2, E3, E4 and E5 in the inset map. The 3D seismic data and derived tomography results are the focus here.

2. 3D first break tomography

Turning-ray 3D traveltime tomography (Tryggvason et al., 2002) was carried out using about 2.5 millions of first breaks after testing various parameters and tuning the inversion parameters, also excluding bad quality picks. Tests were carried out using various cell sizes and various upper and lower velocity bounds. Finally, an inversion cell sizes of 10x10 m horizontally and 5 m vertically for the top of the model were selected. Below 50 m depth, cells of 10x10x10 m were used. The smaller cells on the top of the model were used to better account for the variable bedrock depth and to avoid velocity artefacts in deeper cells due to a large velocity contrast at the bedrock interface. In this case, a large velocity contrast between the glacial sediments and the bedrock was expected. In the end, the inversion was done in several steps, using a subset of the data to derive a coarse model that was later resampled to the final cell sizes. The final seven iterations with all the data were then done using this model as a starting model. This procedure was time consuming, but resulted in better data fit and a more reasonable model than if all the data were inverted in one step starting for example from a 1D starting model. The final 3D tomography model shows a maximum depth penetration of about 200 m with some gaps in the model (no ray coverage) around this depth range.

3. Results

Figure 2 shows a series of 3D views from the reflection seismic volume, bedrock surface as surveyed after the removal of overburden and prior to the start of mining, RQD and tomography velocity models. Several bedrock lineaments are notable particularly one running nearly in N-S direction (R8). Kevitsa intrusion is clearly notable in the tomography model as a region of

high velocity. Nevertheless, a major low-velocity zone in the same direction as R8 and crossing the planned open pit can be seen in the depth slice of the tomographic model (Figure 2d). There are also indications of low and high velocity regions within the intrusion that may indicate variations in rock competency, probably due to the degree of talc alteration and fracturing. The low-velocity zone loses its definition towards greater depths in the tomography volume. However the reflection volume suggests a pronounced reflector (R8 at about -110 m elevation in Figure 2a) with similar orientation as the low-velocity zone suggesting the same structures. The exposed bedrock (Figure 2b) and drillhole fracture data indicate a brittle fracture and fault system (Lindqvist, 2014) gently WNW-dipping (about 35°). The R8 structure appears to also provide a boundary to the reflectivity pattern within the intrusion and thus may be important in controlling mineralization and its lateral extent in Kevitsa (Koivisto et al., 2015).

One of the objectives of the 3D tomography was to use the velocity model to predict probable blasting and crushing conditions in terms of rock competency. Rock competency can be related to both degree of fracturing, which is important in the near-surface region and close to large structures, and to talc alteration, which has important implications for crushing and processing. Figure 2c shows a 3D visualization of the RQD model derived from existing boreholes (interpolated using a distance weighting method) and can be compared with the tomography results shown in Figure 2d from the same view. A visual comparison between the

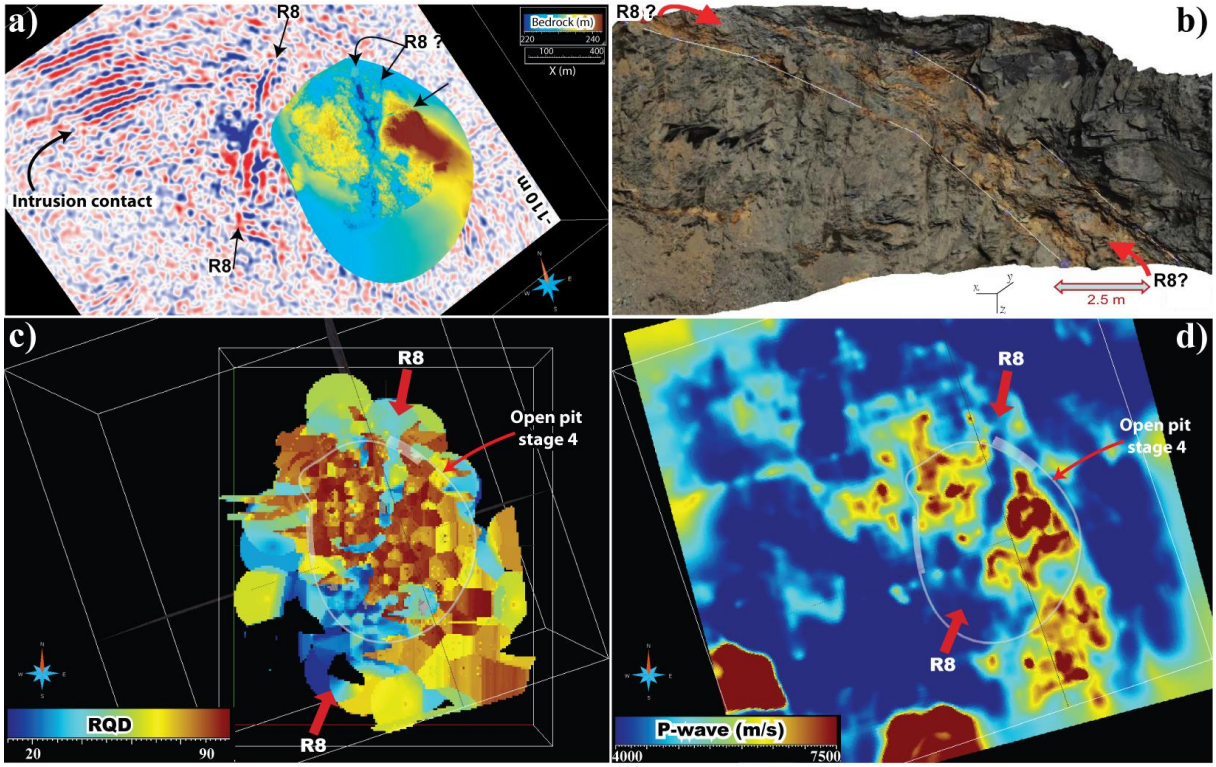

Figure 2. 3D views showing (a) a depth slice from the migrated volume at about 110 m below sea level, and bedrock surface (coloured region around 230 m above sea level) and lineaments (black arrows) as surveyed after the removal of the overburden and before mining activities commenced. Note some of the lineaments have similar orientation as the reflector (R8) seen at -110 m level in the reflection volume. (b) R8 is believed to be associated with a gently dipping fracture system as it is now being exposed and mined. (c) RQD versus (d) tomography models showing an excellent correspondence between the two and clear signature of the R8 fracture system in the models.

two models suggests a good correspondence between the low-velocity zones and low RQD regions suggesting that the velocity model can be used to help inform blasting, crushing, and processing behaviours.

4. Conclusions

3D tomography was employed to link near-surface geological features with those interpreted from the reflection seismic volume, given that the reflection seismic survey parameters and extremely high velocities caused a major loss of reflectivity near the surface. The tomography revealed a major low-velocity zone in the bedrock associated with a gently dipping reflector observed at about 150 m depth and extending to depths of more than 500 m. Qualitative correspondence between the velocity and RQD models implies that the velocity model can be used for predicting rock competency, and thus material behaviour during blasting, crushing and processing.

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References:

Lindqvist, T., 2014. 3D characterization of brittle fracture zones in Kevitsa open pit excavation, northern Finland. MSC thesis, University of Helsinki, Finland, 87 p.

Koivisto, E., Malehmir, A., Hellqvist, N., Voipio, T. and Wijns, C., 2015. Building a 3D model of lithological contacts and near-mine structures in the Kevitsa mining and exploration site, northern Finland: constraints from 2D and 3D reflection seismic data. Geophysical Prospecting, 63, 754-773.

Koivisto, E., Malehmir, A., Heikkinen, P., Heinonen, S. and Kukkonen, I., 2012, 2D reflection seismic investigations in the Kevitsa Ni-Cu-PGE deposit, northern Finland. Geophysics, 77, WC149-WC162.

Kukkonen, I., Lahti, I., Heikkinen, P., and HIRE Working Group of the Geological Survey of Finland, 2009. HIRE Seismic Reflection Survey in the Kevitsa Ni-PGE deposit, North Finland. GTK Report Q23/2008/59, 38 pp.

Malehmir, A., Juhlin, C., Wijns, C., Urosevic, M., Valasti, P. and Koivisto, E., 2012. 3D reflection seismic investigation for open-pit mine planning and exploration in the Kevitsa Ni-Cu-PGE deposit, Northern Finland. Geophysics, 77, WC95-WC108.

Malehmir, A., Koivisto, E., Manzi, M., Cheraghi, S., Durrheim, R., Bellefleur, G., Wijns, C., Hein, K. and King, N., 2014. A review of reflection seismic investigations in three major metallogenic regions: the Kevitsa Ni-Cu-PGE district (Finland), Witwatersrand goldfields (South Africa), and the Bathurst Mining Camp (Canada). Ore Geology Reviews, 56, 423-441.

Tryggvason, A., Rögnvaldsson, S. Th. and Flóvenz, Ó.G., 2002. Three-dimensional imaging of the Pand S-wave velocity structure and earthquake locations beneath Southwest Iceland. Geophys. J. Int., 151, 848-866.