3D Seismic Data Are an Asset for Exploration and Mine Planning: Kevitsa Ni-Cu-PGE Deposit, Northern Finland

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ABSTRACT

Kevitsa is a disseminated Ni-Cu-PGE (platinum group elements) ore body in northern Finland, hosted by an extremely high-velocity (6500–8500 m/s) ultramafic intrusion. It is currently being mined at a depth of approximately 100 m using open-pit mining method. The life of mine is expected to be nearly 20 years, with the final pit depth reaching around 550–600 m. Based on a series of 2D seismic surveys and given the expected life of mine, a high-resolution 3D seismic survey was justified and acquired in winter 2010 prior to the start of the mining operation. Various researchers and teams have exploited these data since the acquisition because of the unique nature of the host rock and the data being challenging to interpret however rich in reflectivity. Here, we first present the earlier 3D reflection data processing results and then complement them by 3D first arrival traveltime tomography that was recently conducted. The combined results help to provide constraints on the nature of some of the reflectors within the intrusion. It for example shows how the tomography results can be correlated with rock quality data and for further planning of the pit. In particular, we observe a major fracture system, resolved by the tomography results and running in the northern parts of the planned pit, with the reflection data providing better information on its depth extent, estimated to be at least 600 m with a lateral extent of 1000 m. The fracture system appears to spatially limit the lateral extent of the economic mineralzsation and partitioned mainly within the intrusion. It can be related to the paleostress regime forming similar features in the study area and will likely be important for mining at deeper levels. Using the Kevitsa 3D seismic data set, we argue that 3D seismic data should routinely be acquired prior to the start of mining activities to not only maximize exploration efficiency at depth, but also to optimize mining as it continues towards depth. 3D seismic data are valuable and can be revisited for various purposes but difficult to impossible to be acquired with high quality when mining commences.

INTRODUCTION

The 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 HIgh REsolution reflection seismics for ore exploration (HIRE) national seismic program of the Geological Survey of Finland (Kukkonen et al., 2009; Koivisto et al., 2012, 2015) with the primary goal of being used for open-pit mine planning and deep exploration of massive sulphide occurrences within the resource area (Malehmir et al., 2012a; Malehmir et al., 2014). Disseminated Ni-Cu-PGE (platinum group element) mineralization is hosted in olivine pyroxenite, the Kevitsa intrusion, and 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 vertical seismic profile (VSP) measurements (Malehmir et al., 2012a). During the processing of the 3D data set, 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 metres of the migrated reflection volume (Malehmir et al., 2012a). Pronounced reflectors within the planned open-pit and greater Kevitsa intrusion were observed starting 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 and mining at the site. No tie with surface geology has been possible until the 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 paper.

The main objectives of this study are to (1) review the 3D reflection data and discuss overall cause of the reflectivity in the study area, (2) carry out 3D diving-wave traveltime tomography on first breaks to examine its potential over ray- and layered-based refraction method in resolving weakness zones, and (3) compare the velocity model with the existing rock quality data derived from several boreholes in the study area and examine if the velocity models can be further used for rock blasting and block selections for detailed mining and crushing (mixing competent and incompetent rocks) purposes. The tomography results have been interpreted and combined with deeper information obtained from the reflection volume and surface observations from the open-pit.

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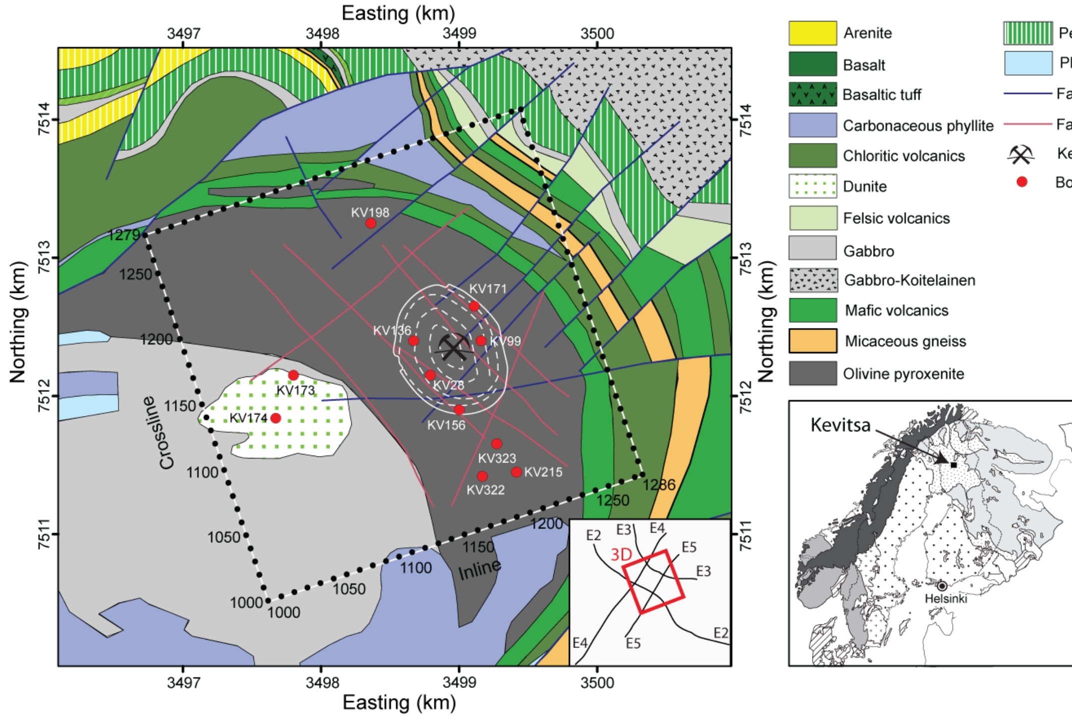

Figure 1: Geological map of Kevitsa showing the location of the planned open-pit (stage 4), 3D seismic survey area, and 2D seismic profiles E2-E5 in the inset map. The 3D seismic data and derived tomography results are the focus here.

GEOLOGY OF KEVITSA

The Kevitsa ore body, 160 Mt proven and probable, is hosted by a mainly ultramafic intrusion in northern Finland (Figure 1) and surrounded by volcano-sedimentary rocks; it is a low-grade, disseminated Ni-Cu sulphide ore (0.3% Ni and 0.41% Cu), with also significant PGE and Au content (Gregory et al., 2011). Mining commenced in 2012 using an open-pit mining method by First Quantum Minerals Ltd. and as of summer 2016 by Boliden. The current open-pit depth is about 100 m and the pit will extend to 550 m depth within 20 years (mine's life). The Kevitsa deposit was discovered in 1987 and since then the surrounding area has been a target of numerous geological and geophysical investigations. For example, the Sakatti super-rich Ni-Cu-PGE deposit was recently discovered (Coppard, 2014; Brownscombe et al., 2015) just 10 km south-southwest from the Kevitsa mine; it sits likely within the same geological setting as the Kevitsa ore. Two boreholes led to the discovery of the Sakatti deposit intersected two massive sulphide lenses with ~40 m at 3.40 wt% Cu, 3.54 wt% Ni, 1.81 g/t Pt, 2.09 g/t Pd, and 0.45 g/t Au (Brownscombe et al., 2015).

Important types of mineralization in the area include contact-related and possibly remobilized types (usually massive to semi-massive, occurring at or below the contact with the intrusion), false types (usually disseminated, dominated by pyrrhotite, and occurring at the margins of the intrusion), and normal types (which are rich in Ni and occur within the intrusion where a magmatic stratigraphy is present). Figure 2 shows a schematic geologic cross section through the Kevitsa intrusion, not strongly constrained by borehole data, illustrating the different types of mineralization proven to exist in the region. These deposits, particularly the massive ones, are the targets of several new exploration works in the study area.

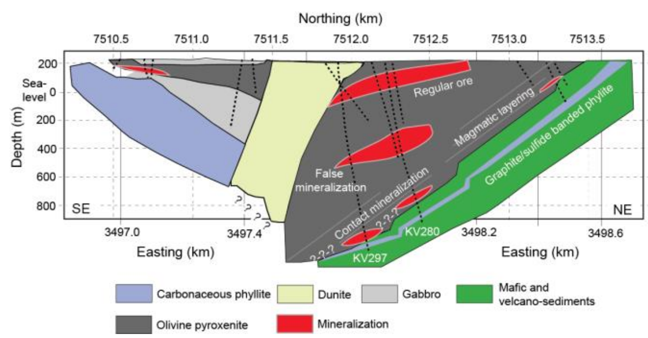

Figure 2: Schematic cross section constrained by deep magnetotelluric (MT) and borehole data, showing the main Kevitsa intrusion (hosting the main mineralization-regular ore) and proven massive sulphide mineralization occurring as false and contact mineralization in the study area.

KEVITSA 3D SEISMIC DATA

Data Acquisition

Kevitsa 3D seismic data (Figure 3) were acquired during winter 2010 primarily for open-pit mine planning and for deep exploration of massive sulphide occurrences within the resource area (Malehmir et al., 2012a; Malehmir et al., 2014). Prior to the

3D survey, four seismic profiles (Figure 1) crossing the Kevitsa intrusive complex were acquired in 2007 as a part of the HIRE national seismic program of the Geological Survey of Finland (Kukkonen et al., 2009). These profiles contributed to the imaging and understanding the geometry of the intrusion and large-scale structures associated with the Kevitsa deposit (Koivisto et al., 2012, 2015). Details of the 3D data acquisition can be found in Malehmir et al. (2012a) and the 2D data in Koivisto et al. (2012). Nearly 3300 shots were recorded in nine receiver lines each comprising of 96 receivers. The survey area was covered using nine overlapping patches (50% both shot and receiver lines) and this led to an average fold of 75 using a 10 by 10 m common depth point (CDP) bins (Figure 3b). Vibsist^{TM} (Cosma and Enescu, 2001) was used as the main source although approximately 300 explosive shots (0.5 kg at about 3 m depth) were also recorded in areas inaccessible with Vibsist^{TM}. The acquisition took place in winter 2010 with temperature changing from -35° in the beginning of the survey to +5° at the end of the survey in April, from nearly 1 m of snow to almost no snow. This obviously led to different ground conditions and receiver coupling. Additionally, a mixture of instruments was used for the data acquisition, namely Sercel 408^{TM} and Seistronix^{TM} each with different capabilities.

Reflection Seismic Data Processing

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. The processing work followed a conventional prestack dip-moveout (DMO) and poststack migration approach (Malehmir et al., 2012b and references therein), with careful focus on refraction static (high-quality first break picking using manual quality control and corrections where needed), velocity analysis and prestack and poststack noise attenuations using various filtering and deconvolution approaches. Poststack migration was performed taking into account the high-velocity background. This however likely introduced image distortion because some shallow reflections became weaker or totally disappeared after this step.

Although the data were of relatively 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 metres of the migrated reflection volume (Malehmir et al., 2012a). Pronounced reflectors within the planned open-pit and greater Kevitsa intrusion were observed starting from 150–200 m depth.

Previous Reflection Imaging Results

Figure 4 shows a series of depth slices from the 3D reflection cube, showing the overall structures around the Kevitsa intrusion and a clear northwest-southeast striking reflector (labeled R8 to be consistent with Koivisto et al., 2015) that dips towards the southwest just at the edge of the planned open-pit starting at 10 m below sea level. It is possible to track the R8 reflector to at least ~390 m below sea level after which it becomes diffuse. Average surface elevation in Kevitsa is 235 m above sea level. Given that this reflector appeared at the edge of the planned pit it was unclear if it was significant for the open-pit mine planning or if it had any role in the distribution of economic mineralization within the open-pit area. This reflector is the main focus of this study as it will be recalled when the tomography results are presented.

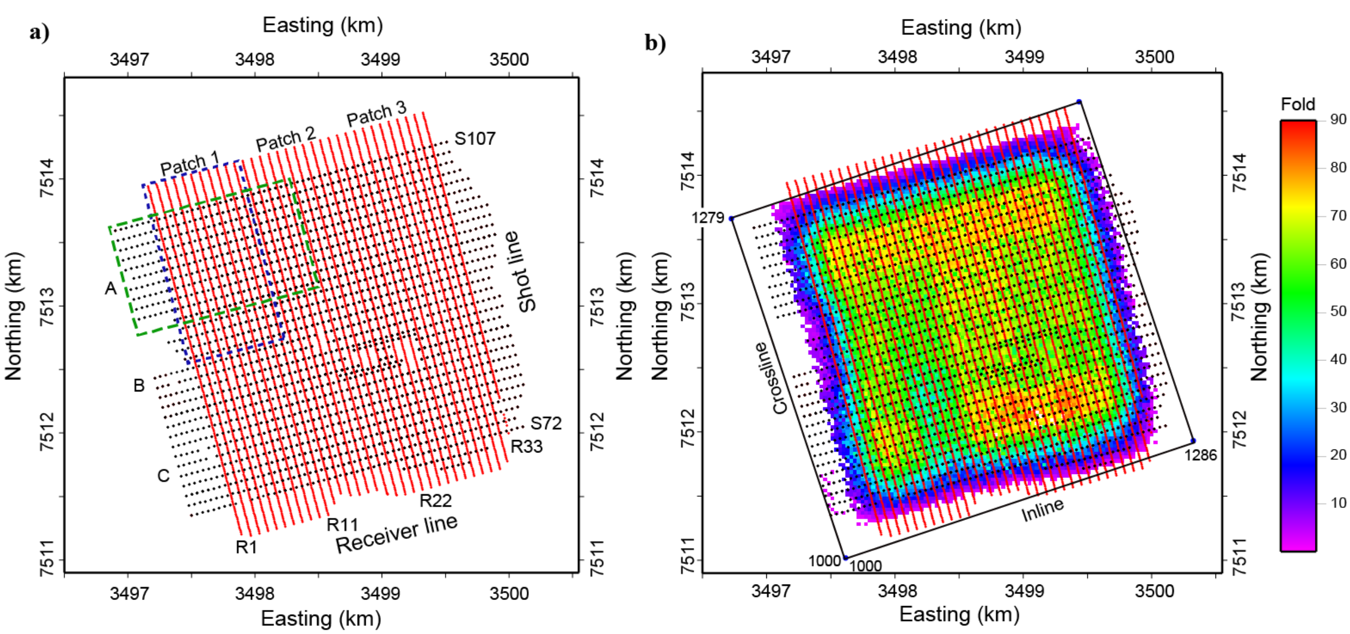

Figure 3: (a) The Kevitsa 3D seismic data were acquired using nine overlapping (50%) patches. For example, patch 1A (green and blue boxes) shared 50% of its source and receiver lines (repeated) into a neighboring patch. (b) CDP fold coverage calculated from a CDP bin size of 10 by 10 m.

The 3D reflection seismic data supported by MT models also provided a target at the southwestern contact of the intrusion (high seismic amplitude and conductive) at about 390 m below sea level (labelled B in Figure 5a). It was drilled and downhole logged, and it became clear it was related to a disseminated, layered-type mineralization (interpreted to be related to magmatic pulses within the intrusion), not to a massive sulphide mineralization (Malehmir et al., 2012a). Within and at the bottom of the intrusion false and basal massive sulphides are highly prospective some of which were intersected in a few boreholes but none were of major size. These types of targets are today highly prospective within the Kevitsa intrusion and similar ones in the area (e.g., Sakatti). The base of the Kevitsa intrusion was modelled using the seismic data and existing boreholes in addition to the reflections either observed directly in the data or structures speculated based on discontinuity observed in the reflections from one inline to another (Figure 5b). It shows the Kevitsa intrusion is open towards the southwest implying that the root of the Kevitsa can be further in the southwest. This also suggests neighbouring regions there can also highly be prospective.

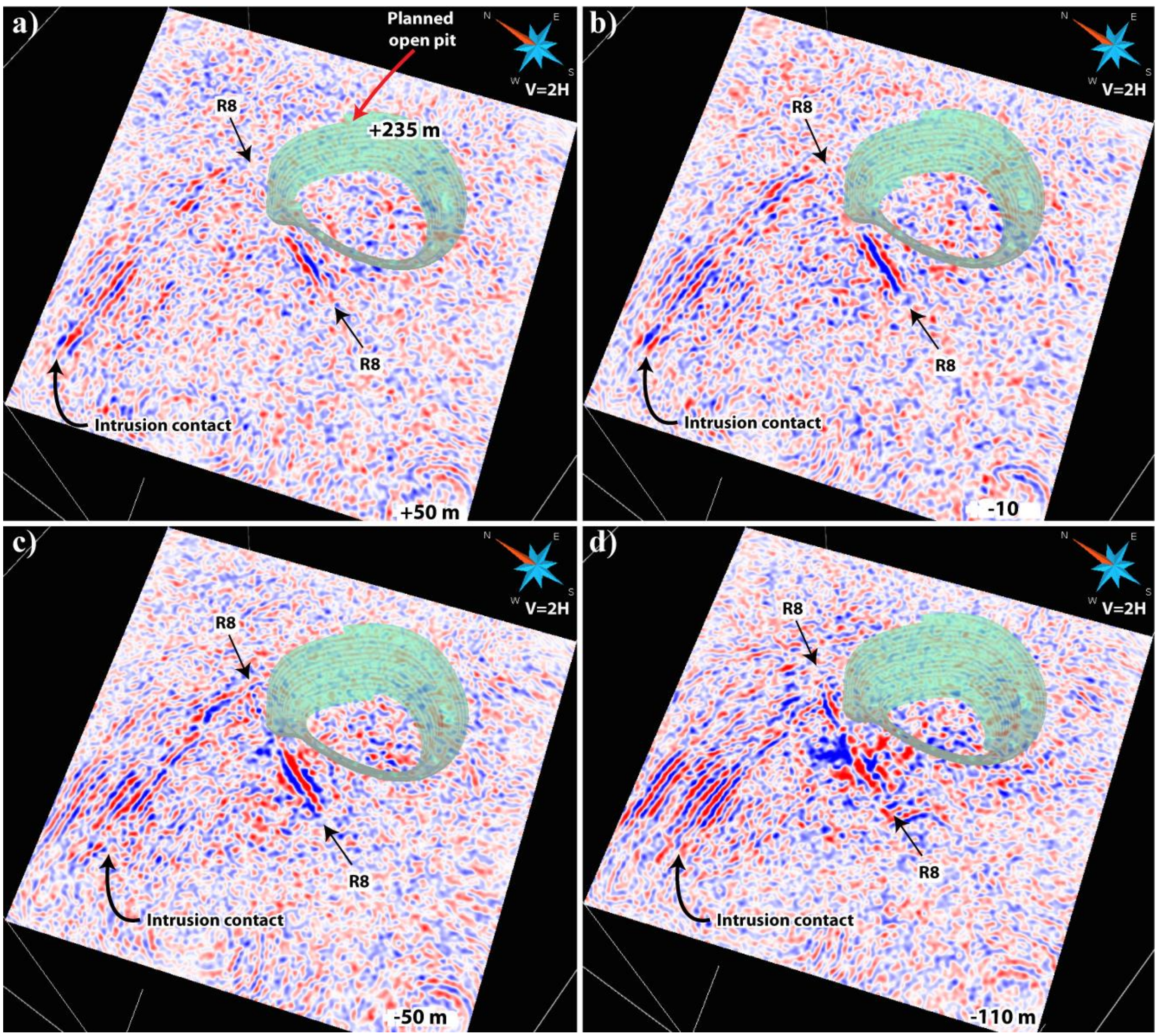

Figure 4: A series of depth slices at (a) 50 m, (b) -10 m, (c) -50 m, and (d) -110 m, relative to sea level, shown with the planned open-pit shell (stage 4 or the final pit model). Volcano-sedimentary rocks surrounding the Kevitsa intrusion and how they dip inwards (or mainly to the south and east) are evident from the 3D reflection volume. R8 is the only major reflector that cuts the planned open-pit at its western margin. Note that the average surface elevation is 235 m above sea level in the study area.

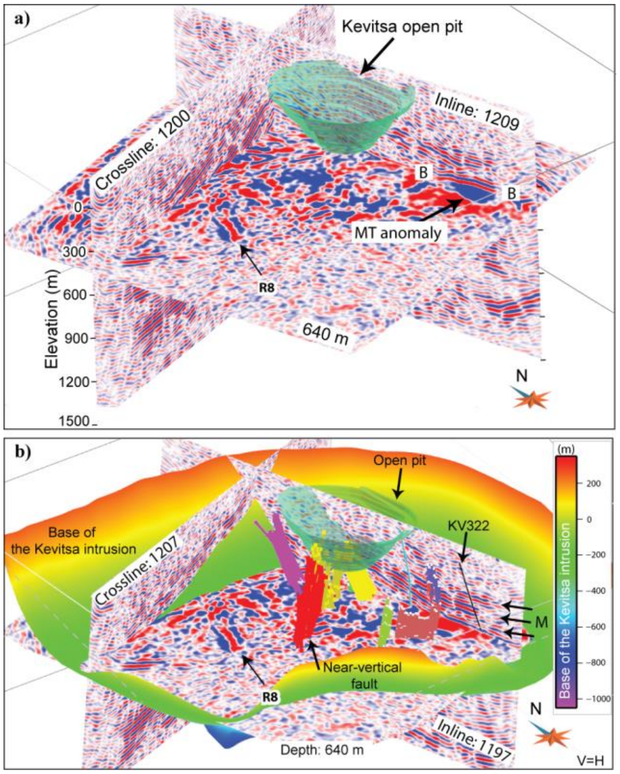

Figure 5: (a) 3D visualization of the seismic reflection data with the planned open-pit mine and (b) the picked near-vertical faults and the base of the Kevitsa intrusion. KV322 is a borehole that intersects areas of sulphide mineralization and shows good correlation with reflections observed in the seismic volume (see events marked as B and M). R8 reflector is also evident in this depth slice (approximately 600 m depth).

3D FIRST-BREAK TOMOGRAPHY

Turning-ray 3D traveltime tomography (Tryggvason et al., 2002) was carried out using approximately 2.5 millions of first breaks (Figure 6) after testing various parameters and tuning the inversion parameters, and excluding bad quality picks. Tests were carried out using various cell sizes and various upper and lower velocity bounds. Finally, an inversion cell size of 10 x 10 m horizontally and 5 m vertically for the top of the model were selected. Below 50 m depth, cells of 10 x 10 x 10 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.

RESULTS AND INTERPRETATION

Figure 7 shows a series of depth slices from the tomography volume. The Kevitsa intrusion stands out in all these slices as a high velocity (6500–8000 m/s) region with sedimentary rocks juxtaposing it as regions with velocities between 4000–5000 m/s. There is even an indication of the inward dip of the Kevitsa intrusion when these depth slices are carefully compared. Within the planned open-pit, a low velocity zone (also labeled R8 in Figures 7a and 7b) is evident but it quickly becomes unclear at depth. Two regions of extreme high-velocity materials are also observed in the southwest corner of the depth slices but it is not evident what causes these. 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. Gabbroic and dunitic rocks in the southwestern parts of the study area are highly altered (to even talc) and this may explain their low velocities comparable to the volcano-sedimentary rocks of the northern parts.

The bedrock surface was surveyed after the removal of the overburden using an accurate DGPS (differential global positioning system). The exposed bedrock, 3D photometry of the exposed bedrock and drillhole fracture data then allowed a careful studying of brittle fracture and fault systems in the study area (Lindqvist, 2014; Lindqvist et al., 2017). These suggest a

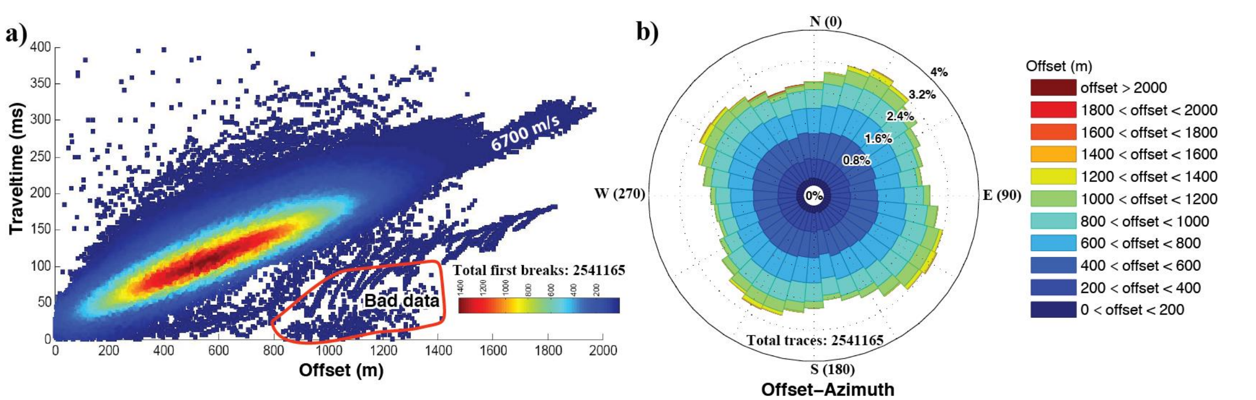

Figure 6: (a) Picked first arrivals versus offset used for the 3D velocity tomography and (b) offset versus azimuth showing a good illumination of the structures almost in all directions. Bad quality data in (a) were automatically rejected during the iterative processes of tomography inversion.

gently to moderately west-northwest dipping (35°–45°) fracture system associated with the low-velocity zone and the reflector R8. Lindqvist (2014) carefully mapped the fracture systems and modelled them in 3D. The fractures modelled by Lindqvist (2014) then were visualized in 3D with the tomography results and the reflection data.

Figure 8 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, rock quality designation (RQD) and tomography velocity models. Several bedrock lineaments are notable particularly one running nearly in the north-south direction (R8). The 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 8d). 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 8a) with similar orientation as the low-velocity zone suggesting the same structures. The exposed bedrock (Figure 8b) and drillhole fracture data indicate a brittle fracture and fault system (Lindqvist, 2014) that moderately (about 35°) dips towards the northwest. Based on drillhole data and 3D photometry studies, it is estimated to be 5–20 m wide. 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).

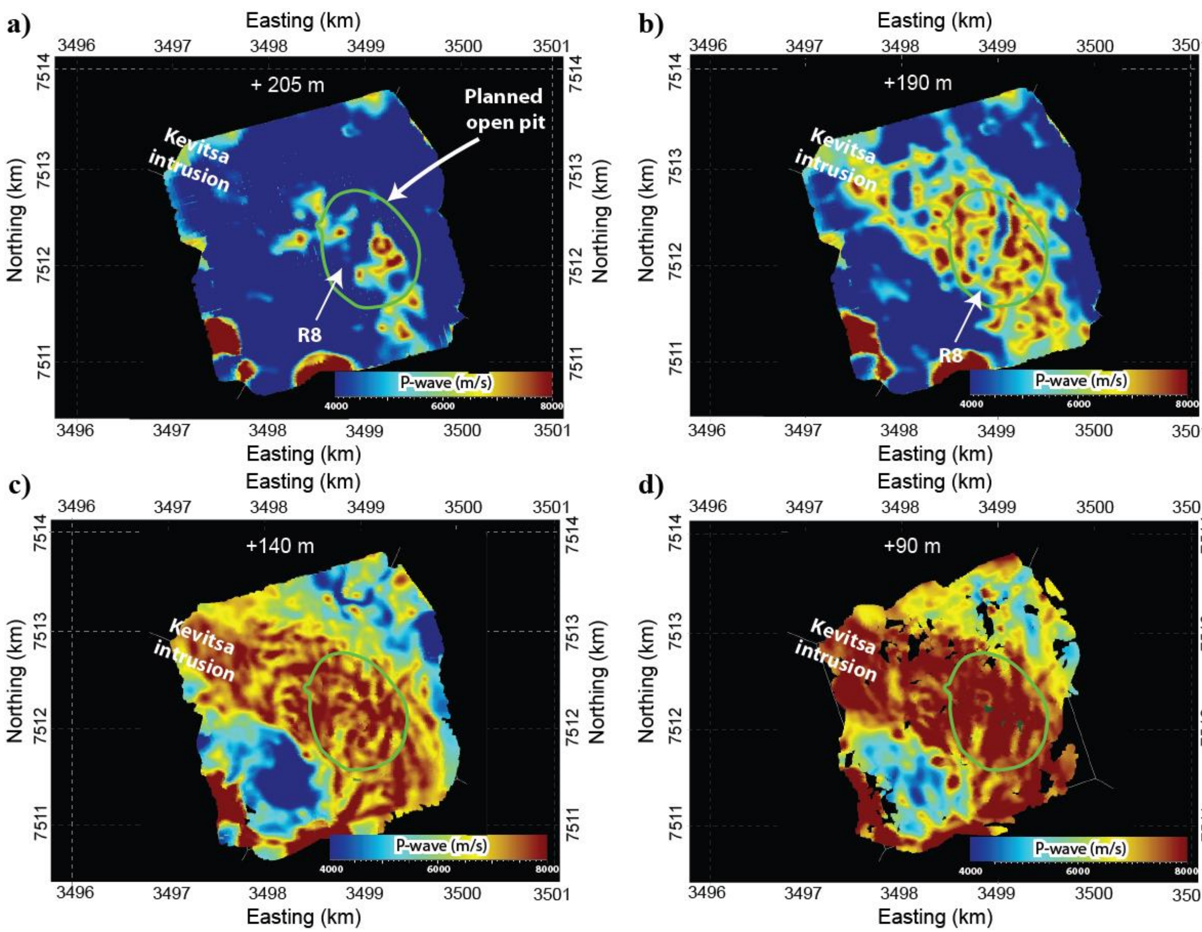

Figure 7: A series of depth slices from the tomographic velocity volume at (a) 205 m, (b) 190 m, (c) 140 m, and (d) 90 m above sea level clearly showing the high velocity (6500–8000 m/s) rocks of the Kevitsa intrusion and the low velocity (4000–5000 m/s) volcano-sedimentary and highly altered gabbroic and dunitic rocks, as well as a clear low-velocity lineament (R8) running in the middle of the planned open-pit (a and b). The low-velocity zone loses its definition at deeper levels.

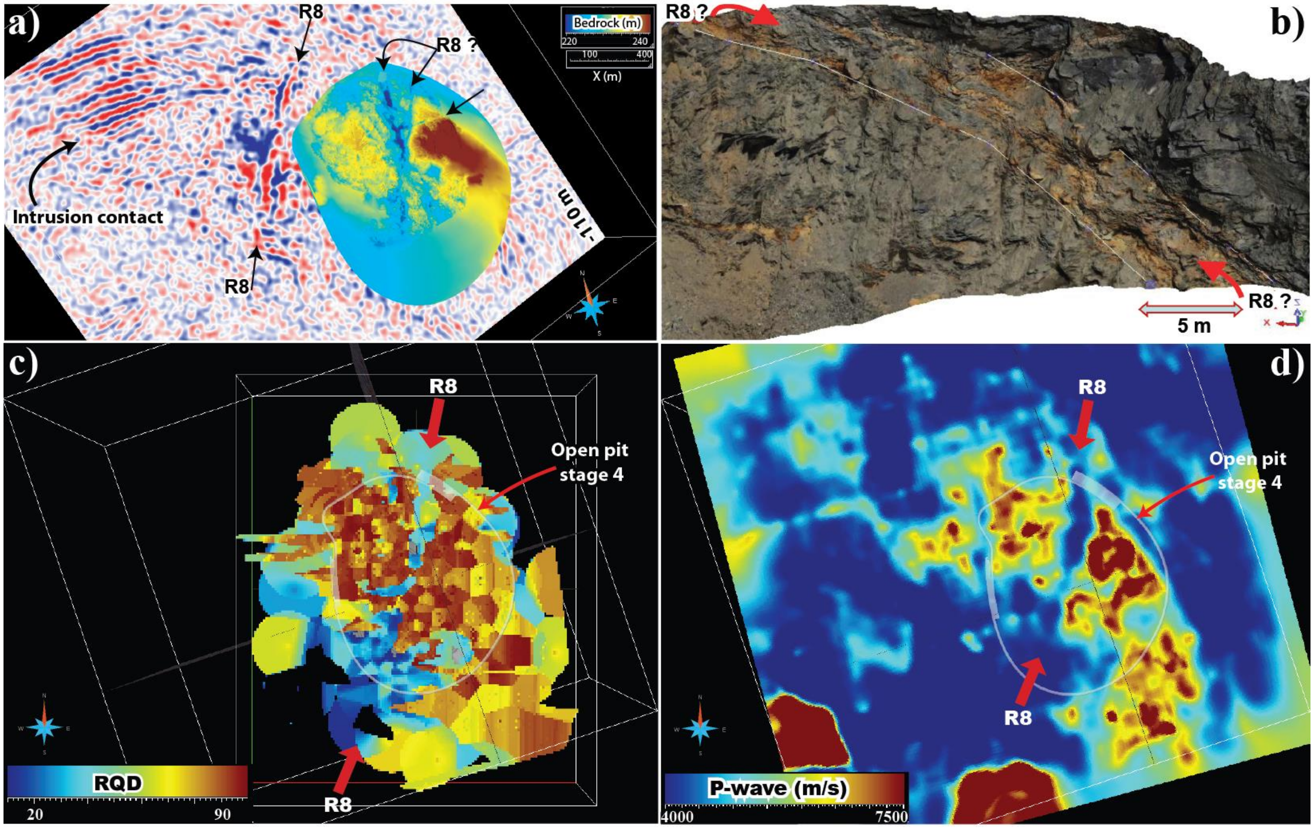

Figure 8: 3D views showing (a) a depth slice from the migrated volume at about 110 m below sea level, and bedrock surface (coloured region around 230 m above sea level) and lineaments (black arrows) as surveyed after the removal of the overburden and before mining activities commenced. Note some of the 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 moderately 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.

DISCUSSION

Rock Quality and Slope Stability

One of the primary 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 and close to large structures, and to talc alteration (Wijns, 2016), which has important implications for crushing and mineral processing. A visual comparison between the RQD and tomography models (Figures 8c and 8d) 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 behaviors. To further illustrate this, we carefully studied the relationship between the two models. Assuming that these values are representative and not biased by interpolation used in the RQD model, we noticed that the correlation between the two models follows a second or higher order. At low velocities and up to 5000 m/s, the two models show a linear relationship but at higher velocities this becomes non-linear suggesting that there may be poor quality rocks (RQD at around 50) exhibiting velocities up to 6000 m/s. This is not surprising given the ultramafic rocks of the Kevitsa intrusion.

The bedrock surface model derived from the DGPS surveying also suggests other fracture systems crosscutting R8 (see black arrows in Figure 8a) on the northern side of the planned pit. An immediate implication is that the wedge-shaped block, formed by the intersection of the gently dipping fracture zone R8 and these sub-vertically north-northwest-striking fracture systems on the northern side of the planned pit, is an important feature for slope stability and further planning of the Kevitsa pit at later stages. The northern parts of the planned open-pit may be most problematic in terms of rock stability, although other factors need to be considered as well.

Resolution of the Seismic Data

The fracture system mapped by Lindqvist et al. (2017) is about 5–20 m thick (Figure 8b). Our results therefore provide this as a proxy for the detection capability of the 3D data (and for such an acoustic impedance contrast), which is remarkably encouraging given the high-velocity background in Kevitsa. Earlier, using boreholes intersecting a rock unit at its top and bottom contact, Malehmir et al. (2012a) provided a proxy for the vertical resolution of the data at 1000 m depth to be at least 100 m.

Tectonic and Mineralization Implications

Since the R8 fracture system does not appear to extend (much) into the volcano-sedimentary rocks, the regional deformation was likely partitioned between the intrusion and the host rocks. For this reason, the fracture systems (e.g. R8) within the structurally isotropic intrusion (no penetrative deformation fabrics) could reflect the paleostress regime, while the deformation within the hosting supracrustal rocks was accommodated by pre-existing structures with variable orientations. The R8 reflector also appears to provide a boundary to the reflectivity within the intrusion and thus may be a major structure controlling economic mineralization and its spatial extent (Koivisto et al., 2015). Most of the economic mineralization occurs on the eastern side (footwall) of the R8 reflector.

CONCLUSIONS

We have reviewed the 3D seismic data from the Kevitsa Ni-Cu-PGE deposit and showed how together with the 3D tomography results the 3D seismic data can help to link near-surface geological features with those interpreted from the reflection seismic volume. The tomography revealed a major low-velocity zone in the bedrock associated with a moderately dipping reflector observed at about 150 m depth and extending to depths of more than 600 m with a lateral extent of more than 1000 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. The Kevitsa 3D case, while challenging due to the extreme high-velocity background, clearly illustrates the value of 3D seismic data not only for detailed exploration but also for mine-planning applications. This is encouraging and therefore we recommend it to be regularly done together with other methods during the development of a deposit to a mine.

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REFERENCES

Brownscombe W., R. J. Herrington, J. J. Wilkinson, A. J. Berry, J. Coppard, C. Ihlenfeld, S. Klatt, C. Hartshorne, A. J. Boyce, and R. N. Taylor, 2015, Geochemistry of the Sakatti magmatic Cu-Ni-PGE deposit, northern Finland: 12th Biennial SGA Meeting on Mineral Deposit Research for a High-Tech World.

Coppard J., 2014, Discovery history of the Sakatti Cu-Ni-PGE deposit, Finland: https://www.segweb.org/SEG/_Events/Conference_Archives/2014/Conference_Proceedings/data/papers/abstracts/0393-000039.pdf , accessed 16 April 2017.

Cosma, C., and N. Enescu, 2001, Characterization of Fractured Rock in the Vicinity of Tunnels by the Swept Impact Seismic Technique: International Journal of Rock Mechanics and Mining Sciences, 38, 815 – 821.

Gregory J., N. Journet, G. White, and M. Lappalainen, 2011, Kevitsa Copper Nickel Project in Finland: Technical Report for the Mineral Resources and Reserves of the Kevitsa Project, First Quantum Minerals Ltd., 52 p.

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

Lindqvist, T., P. Skyttä, E. Koivisto, T. Häkkinen, P. Somervuori, 2017, Delineating the network of brittle structures with geotechnical, structural and reflection seismic data, Kevitsa open pit, Northern Finland: In review at GeoREsJ.

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

Koivisto, E., A. Malehmir, N. Hellqvist, T. Voipio, and C. Wijns, 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.

Kukkonen, I., I. Lahti, P. Heikkinen, 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 Q 23/2008/59, 38 p.

Malehmir, A., C. Juhlin, C. Wijns, M. Urosevic, P. Valasti, and E. Koivisto, 2012a, 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., R. Durrheim, G. Bellefleur, M. Urosevic, C. Juhlin, D. White, B. Milkeriet, and G. Campell, 2012b, Seismic methods in mineral exploration and mine planning: a general overview of past and present case histories and a look into the future: Geophysics, 77, WC173–WC190.

Malehmir, A., E. Koivisto, M. Manzi, S. Cheraghi, R. Durrheim, G. Bellefleur, C. Wijns, K. Hein, and N. King, 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., S.T. Rögnvaldsson, and Ó.G. Flovenz, 2002, Three dimensional imaging of P- and S-wave velocity structure and earthquake locations beneath southwest Iceland: Geophysical Journal International, 151, 848–866.

Wijns, C., 2016, Airborne EM for mine infrastructure planning: Exploration Geophysics, 47, 279–284.