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Using seismic reflection profiles to model 3D geology of VMS districts in the Raahe-Ladoga belt, Finland

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SUMMARY

Volcanogenic massive sulphide (VMS) deposits of Pyhäsalmi, Vihanti and Outokumpu in Finland belong to the same mineralized belt but are different in terms of age and detailed deformation history. Results of sonic and density logging show that in these mining camps rock formations hosting the known ore deposits are reflective which encourages the use of seismic reflection method for mapping the subsurface geological structures. A network of seismic reflection profiles was acquired in each study site and these data are utilized in the geological 3D-modeling and deep mineral exploration.

Key words: Seismic reflection, 3D modelling, VMS, deep exploration, Finland, Europe

INTRODUCTION

The Geological Survey of Finland (GTK) led a seismic reflection project called HIRE (HIgh-REsolution reflection seismics for ore exploration) during 2008–2010 (Kukkonen et al., 2011). In this project, 2D seismic reflection profiles were acquired at several mining camps in Finland, including the Pyhäsalmi, Vihanti and Outokumpu areas belonging to the Raahe-Ladoga mineralized belt. Over 90% of the known sulphide mineral resources in Finland are located in this belt. The belt trends across the country from northwest to southeast and separates Archean rocks to the north and younger Paleoproterozoic island arc complexes to the south. The Raahe-Ladoga belt and location of the mining districts are shown in Figure 1.

Outokumpu (1.97 Ga) is the oldest of the deposits and sulphide mineralization in this area is associated with mantle derived serpentinite. In the Vihanti-Pyhäsalmi district massive sulfides are hosted by highly deformed and metamorphosed (amphibolite to granulite facies) bimodal volcanic rocks. Several mines have been, and are, operating in these districts and several deeply buried mineral deposits still likely remain undiscovered at depth.

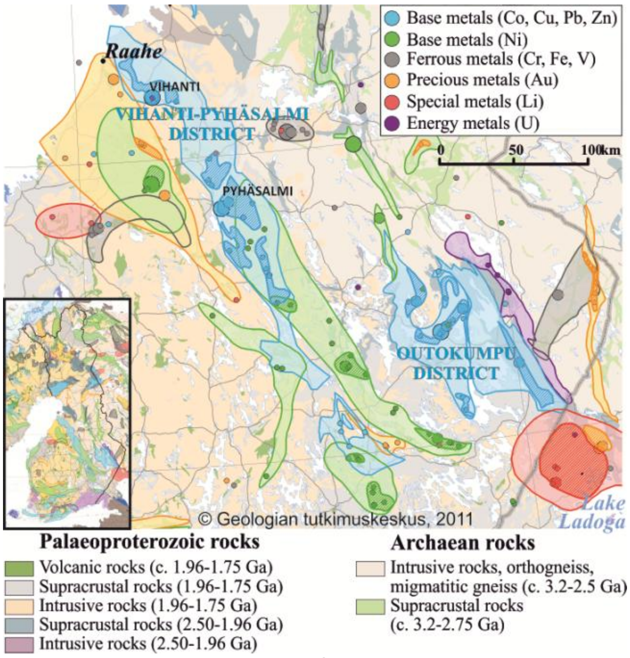

Figure 1. Metallogenic map of the Raahe-Ladoga belt in Finland. The Pyhäsalmi-Vihanti and Outokumpu districts have high potential for new base metal discoveries (shaded areas) and especially deep exploration is active in these areas. Figure modified from the Metallogenic Map of the Fennoscandian Shield (Eilu et al., 2011).

SEISMIC REFLECTION SURVEYS

The seismic reflection profiles in Pyhäsalmi-Vihanti and Outokumpu areas had the same acquisition parameters enabling easy comparisons of data. Mainly a Vibroseis source was used but also explosives were used in swampy or otherwise rough terrains. Vibroseis sources employed sweep frequencies of 30-165 Hz. Nominal source spacing was 25 m and receiver spacing was 12.5 m. The spread length was 5025 m with 402 active channels. The HIRE-surveys had a very high nominal fold of stack of up to 100 and recorded seismic signal from depths exceeding 5 km.

In Pyhäsalmi, six seismic profiles were acquired using both Vibroseis (4 lines) and explosive sources (2 lines). In Outokumpu, five Vibroseis profiles and one explosive profile were acquired. In the former mining camp of Vihanti, a total of 12 seismic profiles were measured including four explosive lines. Total line kilometres for Pyhäsalmi, Outokumpu and Vihanti were 39 km, 54 km and 125 km respectively.

Data quality of the HIRE seismic reflection surveys was excellent as is demonstrated in the raw shot gather in Figure 2. Good quality seismic sections were achieved with standard processing flows used in hardrock seismic processing. However, later studies by Heinonen et al. (2012) and Koivisto et al. (2012) have shown that stack quality can be further improved by reprocessing the data with specific emphasis on careful velocity analysis.

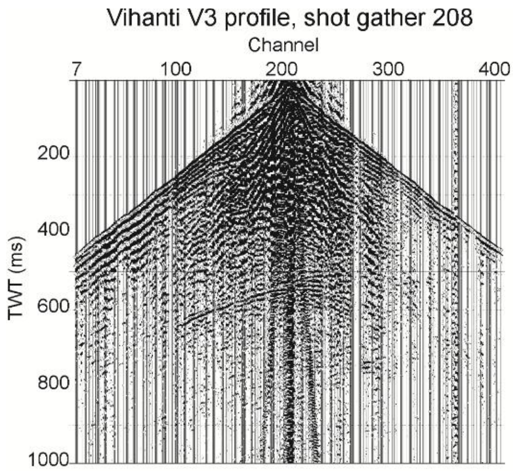

Figure 2. Example of Vibroseis field record from Vihanti showing the excellent data quality with strong first breaks at far offsets and a clear reflection.

PETROPHYSICAL CONSTRAINTS TO SEISMIC INTERPRETATION

Seismic velocities and densities derived from full waveform sonic logging and gamma-gamma density measurements provide crucial information about physical rock properties. The product of seismic P-wave velocity and density, i.e., the acoustic impedance, is used to calculate the reflection coefficients. Reflection coefficient is proportional to the difference in acoustic impedances of the rocks in contact with each other. Salisbury et al. (2000) estimated that a minimum 0.06 reflection coefficient is required to produce detectable reflection in hardrock environments.

The average rock properties from Pyhäsalmi show that sulphide ore is a strong reflector in contact with any other lithology in the area (Figure 3). Also contacts between mafic volcanic rocks and other rock types are expected to be imaged, but for example granites in contact with felsic volcanic rocks have too small reflection coefficients to produce detectable reflection. Outokumpu assemblages hosting ore contain both high acoustic impedance skarns as well as serpentinites with low acoustic impedance, which makes them strongly reflective in the mica schist environment of Outokumpu district. In Vihanti, skarns also are found in close association with the mineralization making the ore hosting lithology reflective.

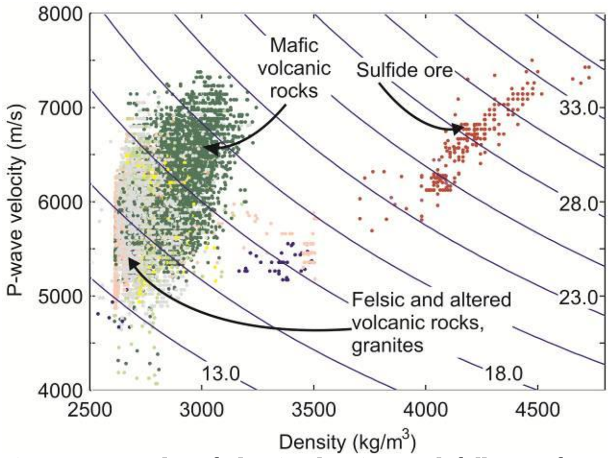

Figure 3. Results of density logging and full waveform sonic logging in Pyhäsalmi show that massive sulphide ore has acoustic properties distinct from its surroundings. Measured values for mafic and felsic volcanic rocks partly overlap but their average properties suggest strong impedance contrast. Blue lines are isocurves of acoustic impedance and their distance corresponds to a reflection coefficient 0.06.

Drill hole measurements help to estimate the causes of reflectivity and are thus important for seismic interpretation. Geophysical drill hole logging results from Pyhäsalmi, Vihanti and Outokumpu show that massive sulphide ore as well as its hosting lithology can cause strong reflections in these deformed and metamorphosed areas. This provides a solid basis for seismic deep exploration.

GEOLOGICAL INTERPRETATION OF SEISMIC PROFILES

In all study areas, the network of profiles enables interpolation of the 2D interpretations to 3D and thus creation of 3D models of the target areas. The occurrence of the out-of-plane reflections is a challenge for interpretation of the crooked-line seismic reflection data. It is impossible to accurately pin point the real subsurface location of certain reflectors at depth even, if data processing was done perfectly. Even a moderate change in migration velocity can move a reflection several hundred meters in the inline direction and accurate positions of strongly 3-dimensional features cannot be determined from the 2D reflection data only. However, seismic profiles provide new information about structural style and continuation of known geological features at depth. Seismic profiles create a framework for geological 3D-models that other data fleshes out. Accuracy of the seismic interpretation is best when deep drill holes are available and can be correlated with seismic reflection data preferably using synthetic seismograms.

Besides the acoustic impedance, also the size and orientation of a geological structure influence its reflectivity. In Pyhäsalmi, it was shown that subvertical structures are not imaged directly with seismic reflection data and only the subhorizontal fold hinges are visible in seismic sections (Figure 4), while steep flanks need to be interpreted indirectly by recognizing changes in reflectivity characteristics (Heinonen et al., 2012). Even though physical properties of massive sulphides suggest the ore to be strong reflector, no clear seismic signal was observed from the deposit. The noise caused by the active mine, heterogeneous geological surroundings and unfavourable shape of the ore deposit are likely causes for the lack of obvious seismic signal.

The Vihanti VMS deposit is slightly younger than Pyhäsalmi and deformation in the area is less intensive. This is seen as gentle folding interpreted from the seismic profiles. Near the historical Lampinsaari mine a major reverse fault causes displacement of the subhorizontal reflectors including the rock formation hosting the ore. Seismic data indicates the continuation of the ore hosting lithology towards the south. In Pyhäsalmi, reflectivity indicates continuation of strongly reflective mafic and felsic volcanic rock sequence underneath the intrusive granites. This observation has opened up new exploration ground at depth. Discontinuities in the interpreted volcanic rock sequences are caused by thrust faults (Figure 4). Reverse faults are also present in the seismic reflection data acquired in Outokumpu. Faults have close association with ore or ore hosting lithologies and more research is required to understand their importance for current structural position of the ore.

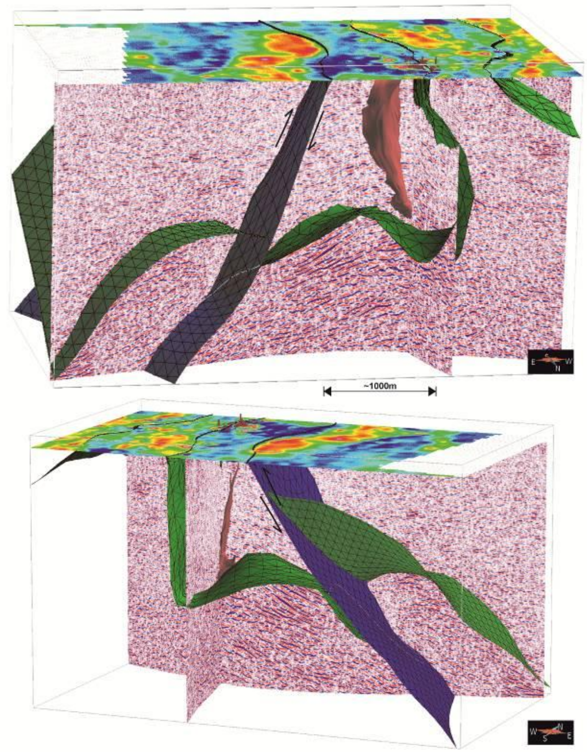

Figure 4. 3D-model of the contact between felsic and mafic volcanic rocks (green), a reverse fault (blue) and ore (red) in Pyhäsalmi shown together with the seismic reflection profiles and aeromagnetic map on top.

CONCLUSIONS

A network of seismic reflection profiles was acquired in the vicinity of Pyhäsalmi, Vihanti and Outokumpu VMS deposits. Data is of good quality enabling mapping of subsurface structures down to 5 km depth. Data interpretation is supplemented with geophysical drill hole logging revealing that ore hosting lithologies are strongly reflective in these areas. The framework provided by reflection seismic data is important for geological 3D-modeling. Reverse faults were recognized in the seismic data in Vihanti, Pyhäsalmi and Outokumpu. Faulting and folding during the different phases of deformation history has likely played a significant role in the current structural position of the ore.

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