Developing Mining Camp Exploration Concepts and Technologies – Brownfield Exploration Project 2013–2016
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DEVELOPMENT OF MINING CAMP EXPLORATION AND TECHNOLOGIES FOR THE OUTOKUMPU BROWNFIELD REGION

by

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This article introduces the objectives and main achievements of the project Developing Mining Camp Exploration Concepts and Technologies – Brownfield Exploration (2013–2016), funded by the Tekes Green Mining programme and jointly conducted by the Geological Survey of Finland and the University of Helsinki. The project focused on developing deep exploration concepts and technologies for previously explored and exploited mining camps in crystalline bedrock areas. The Outokumpu Cu-Co-Zn-Ni-Ag-Au ore belt (Outokumpu Belt), situated in the Outokumpu brownfield region (Outokumpu Mining Camp area), North Karelia, Eastern Finland, and having an exploration and mining history extending back over a century, was chosen as the domain of the study.

The project defined the Outokumpu Mining Camp (OMC) area, comprising the Outokumpu Belt, Miihkali Basin and Kylylahti mine area as the main research sub-areas, to demonstrate the development of the deep exploration concept by using state-of-the-art applications in deep geophysical data acquisition and modelling. The project surveyed the bedrock and ore potential of the OMC to the depth of 2 km, and to 5 km in cases, using seismic reflection data, audiomagnetotellurics, the airborne Z-axis tipper electromagnetic method, and electromagnetic and potential field methods (gravity and magnetic).

The project compiled and further developed quantitative deep geophysical interpretations and common earth models of the subsurface of the OMC based on its petrophysical, elastic, electric, density and magnetic properties in concordance with interpretations of regional to target scale structural and bedrock geology in order to trace deep existing conductive, dense, reflective and magnetic zones implying anomalies related to Outokumpu assemblage rocks having mineral potential. By combining coeval geophysical and geological modelling, the deep exploration concept for Outokumpu-type mineral deposits was improved in an iterative multidisciplinary approach involving geophysics, structural and bedrock geology and geochemistry. The project produced digital geo-referenced, visually or computationally integrated earth models, in the form of surfaces, profiles and 3D objects.

Keywords: mineral exploration, deep-seated deposits, bedrock, multidisciplinary research, concepts, methods, geophysics, geology, geochemistry, interpretation, three-dimensional models, integration, Palaeoproterozoic, Outokumpu, Finland

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INTRODUCTION

In this paper, we introduce a common geophysical, geological and geochemical approach of the Geological Survey of Finland (GTK) and the University of Helsinki (UH) to develop the integration of deep exploration concepts and methods, digital conceptual or quantitative earth models and common earth modelling for locating or identifying the deep-seated ore potential of Paleoproterozoic Outokumpu-type serpentinite-derived formations (Outokumpu assemblage). The Outokumpu assemblage is disguised in or under packages of conductive layers of black schists included in Kalevian metasedimentary rocks rimming the western edge of the Archaean craton in North Karelia, Finland (Figs. 1 and 2). The deep exploration concept developed for Outokumpu-type deposits in this project is referred to as the Outokumpu deep exploration concept (OKUDEX concept).

BACKGROUND

There is a continuously increasing global need for metals. More efficient recycling is important, but the recycling rate of infrastructure metals is already close to the maximum in the EU. Thus, continuous exploration for and discoveries of base metals are required to feed the mining and metal industries with new resources. This requires the development of data- and model-based concepts of exploration in areas with resource potential.

In modern society, all exploration activities have to take into account environmental, land-use and societal factors to a greater degree than before. Exploration in existing mining camps, known as brownfields, is one of the feasible alternatives for locating new resources. Brownfield exploration aims to grow or sustain the value of existing operations. The primary aim is to find or acquire new deposits within an economic transport distance of existing mines and processing facilities. Many mining camps that are considered to be geologically well known on the near surface level might actually hide undiscovered deposits not observed in previous exploration activities. In most cases, success requires going to depths previously only poorly covered by geophysical surveys and drilling.

As mining camps have in most cases already been explored to depths of 200–300 m, or even deeper, using airborne and ground geophysics and drilling, the natural next step is to direct exploration activities exceeding this level. Going deeper at existing mining camps provides several advantages, such as the existing mining infrastructure, often extensive geological, for instance drill core, and geophysical databases, and in many cases easier societal acceptance of further exploration and mining than in areas with less or no previous exploration history (greenfields). Although the present mining industry does not yet routinely carry out exploration at such great depths, we anticipate that in the future there will be increasing interest in developing exploration and mining technologies for much greater depths than is common at present. One example of future deep mining is the giant Resolution Cu-Mo deposit in the USA, where an exploratory shaft has been constructed to over 2000 m below the surface (Hehnke et al. 2012).

Industrial exploration approaches to find metal ore potential at greater depths in Fennoscandian crystalline bedrock areas have already been developed and demonstrated for decades in greenfields by exploration and mining companies, such as by the Swedish company Boliden from at least the 1970s and 1980s onwards (Juhani Nylander, Jarmo Vesanto pers. comm. 2015). The deep prospecting field activities in companies have continued until today based on state-of-the-art geophysical applications, e.g. by acquiring helicopter-borne Z-axis tipper electromagnetic data in Finland (Kuronen 2013) for a combined greenfield-brownfield approach.

Current technological capabilities provide several geophysical deep exploration methods to survey the uppermost crust in detail, such as reflection seismic surveys, active transient time domain methods (both ground and airborne), magnetotelluric soundings and classical potential field (magnetic and gravity) modelling. However, deep exploration of existing mining camps calls for well-integrated geophysical and geological modelling and interpretation of the conductive, dense and reflective structures. There are challenges related to both the resolution and depth extent of the applied methods, as well as geological modelling of the detected anomalous features.

During the last decade, GTK and the University of Helsinki, Institute of Seismology (UH), have

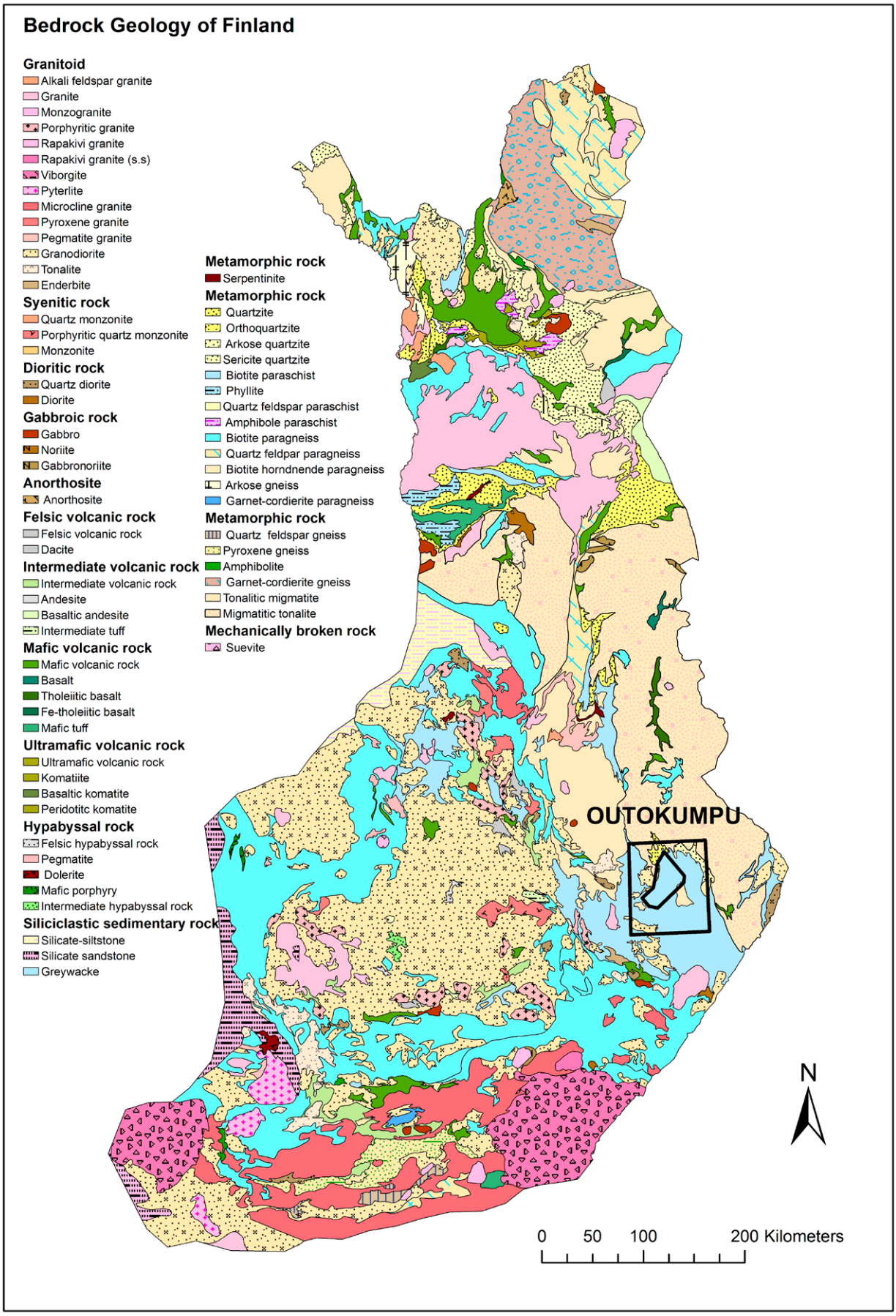

Fig. 1. Location of the Outokumpu Mining Camp (OMC) area outlined in black inside the Outokumpu Mineral District (larger black rectangle) in Eastern Finland, plotted on the generalized bedrock map of Finland (scale of source material 1:10 000 000). Data from the digital archives of GTK.

been developing their knowledge base for deep exploration methods and Precambrian bedrock research with deep geophysical data acquisition, applications and tools (e.g. Kukkonen et al. 2006, Airo et al. 2011, Jokinen et al. 2011, Heinonen et al. 2011, Korpisalo 2011, Kukkonen 2011, Kukkonen et al. 2011, Kukkonen et al. 2012, Heinonen 2013, Airo et al. 2014, Niiranen & al. 2014, Airo 2015, Karinen et al. 2015, Koivisto et al. 2015, Lahti 2015, Laine et al. 2015, Korpisalo 2016).

At the same time, globally, 3D geological modelling has taken revolutionary steps towards regional interpretations and more quantitative common earth modelling (CEM) in solid bedrock geology, besides the oil industry applications (e.g. McGaughey 2006, Sprague et al. 2006, Martin et al. 2007, Bellefleur et al. 2015, Schetselaar et al. 2016).

The study area has been covered by systematic low-altitude geophysical surveys (by GTK), 82 line-km of high-resolution seismic reflection surveys (FIRE and HIRE projects, Kukkonen et al. 2012), over 900 drill cores (mostly acquired by Outokumpu Company), and ground gravity surveys. In addition, before the present project, GTK had measured test lines of audiomagnetotelluric (AMT) soundings in 2012, showing the potential of the method to test seismic reflectors for their conductivity (Lahti et al. unpublished, Lahti et al. 2015). Furthermore, GTK acquired a novel ZTEM airborne survey of the study area in 2013, which provided a systematic survey of resistivity to a depth of about 1–2 km (Kurimo et al. 2016). The existing drill core and petrophysical data compiled by the GEOMEX joint venture project in 1999–2003 (Kuronen et al. 2004) was an important asset for detailed analysis of potential field data. All the existing public datasets were available for the present project.

As a continuation to all these multi-domain advances in data, concepts and technologies, Finnish research organizations and international companies operating in North Karelia, Eastern Finland, identified an opportunity to join the progress, partly due to the exhaustion of more easily detectable shallow depth metal resources in the Outokumpu Mining Camp (OMC, Fig. 1) area (Kuronen et al. 2005, Kontinen et al. 2006, Peltonen et al. 2008, Rasilainen et al. 2014), and partly due to recent developments in the availability of 3D digital data from the research area, and applications and tools for geomodelling at the mining camp scale (e.g. Laine et al. 2012, Saalmann & Laine 2014, Laine et al. 2015).

AIMS OF THE PROJECT

The present investigation aimed to carry out a methodological and comparative analysis of concepts and technologies for deep exploration in the OMC area, one of the most important mining areas in Finland. The OMC is hosted by the Outokumpu Cu-Co-Zn-Ni±Ag-Au ore belt, also known as the Outokumpu Ore Belt or Outokumpu Belt (Figs. 1 and 2). One of the objectives in this project was to apply the concept of common earth modelling to deep mineral exploration in the area. Modern 3D software codes enable the construction of digital earth models and common earth models (CEM) comprising all available data from an area of interest. A CEM can be edited and updated after new data are collected so that the model fits the data constraints simultaneously, whether these data are geological or geophysical. This type of quantitative model can be further tested by drilling, as well as using other independent geophysical data. The project aimed at a modelling concept that is more quantitative than qualitative and a more efficient and reliable tool for exploration than traditional earth models, which are often collections of qualitative thoughts and descriptions about the subsurface.

On a general level, the present project focused on developing methods, skills and concepts for deep exploration in mining camps using the Outokumpu Belt as an example case. With the help of deep geophysical data, surface geology, geochemistry and drilling data, geological 3D interpretations and models were compiled as constraints for further testing with forward and inverse geophysical modelling. The aim was to expand the surface and drilling information to much greater depths than had previously been feasible, i.e. to depths of 1–2 km below the ground surface, and optionally to 5 km if the data allowed.

Geological modelling of geophysical deep structures was carried out in 3D with a future option to extend the modelling to 4D (i.e., additionally including the temporal evolution). The aim was to understand the geological evolution, structural development and ore potential of the area. One of the main questions was related to geologically interpreting the seismically reflective packages in

the Outokumpu Belt and to developing cost-effective means to classify the reflectors with deep EM and potential field data. Although the metal sulphide ore deposits are known to be dense, electrically conductive and seismically reflective, the spatial resolution of common EM and potential field methods is not sufficient for the direct detection of typical deposits in the Outokumpu area at depths exceeding 500–1000 m. Therefore, the aim was to provide models of the geological formations hosting the deposits for more direct testing in the future (i.e., deep drilling and drill-hole-based geophysical surveys).

STUDY AREA AND GEOLOGICAL SETTING

The present OMC study area is included in Outokumpu Mineral District (OMD) of this study, covering about 7200 km^2 and sharing the outlines of the previous GEOMEX project, which compiled most of the digital data from Outokumpu available before this project (Kuronen et al. 2005, Kontinen et al. 2006) (Figs. 1–5). At the beginning of this Tekes project, the GTK project group collaborated closely with the geophysical airborne ZTEM data acquisition project group of GTK (Kurimo et al. 2016) to adjust the ZTEM flight area to suit the needs of both of the projects. The flight operation area later came to outline the area of the interest with a surface area of circa 1200 km^2. The Outokumpu Belt area inside the OMC, having a size of 30 km x 50 km, includes the main ore belt outcropping between the localities Kuusijärvi, Outokumpu and Polvijärvi. The OMC study area also included the extinct Keretti and Vuonos mines and the active Kylylahti and Horsmanaho mines, and the Miihkali Basin area (Figs. 2–5). Based on Kukkonen et al. (2012), an assumption was made that the minimum thickness of the interesting parts of the Outokumpu assemblage would be about 500 m.

The Outokumpu ore deposit was discovered in 1910 and mining started shortly thereafter. It can well be said that the discovery of the Outokumpu ore deposit led to the development of the modern metal industry in Finland. Due to its paramount importance to the metal industry, the Outokumpu Belt has been the target of numerous geological and geophysical studies over the last 100 years (see summaries in Koistinen (1981) and Peltonen et al. (2008)). Nowadays, the bedrock geology of the upmost 300 m of the research area is quite well known.

Tectono-stratigraphically, Outokumpu assemblage rocks can be found in the Outokumpu nappe complex, consisting of the Outokumpu, Miihkali, Sukkulansalo and Kokka nappes (Aatos 2016, Lahti et al. 2016, Laine 2016). These nappes consist of 1970-Ga-old reworked Palaeoproterozoic metaperidotites and metasediments emplaced on top of the Karelian Supergroup. The latter was deposited in a passive margin setting and thrusted upon the Archaean craton (Peltonen et al. 2008, Laajoki 2005, Bedrock of Finland - DigiKP). The age range of the Palaeoproterozoic subunit is from 2500 to 1600 Ma, of which the Orosirian period extends from 2050 to 1800 Ma (ICS 2015), coinciding with the age of global 2100–1800 Ga orogens portending the assembly of the pre-Rodinia supercontinent (Zhao et al. 2002), and having analogous simultaneous periods of mafic-ultramafic magmatic activity (Heaman et al. 2009, Peltonen et al. 1996). Lahti et al. (2016) and Laine 2016 have more thoroughly summarized the geological setting of the Outokumpu nappe complex.

The Outokumpu-type, massive to semimassive, polygenetic Cu-Co-Ni ore deposits are bound to ophiolitic-sedimentary units with original or tectonic contact to skarns, quartz, carbonate rocks and black schists named the Outokumpu assemblage (Kontinen et al. 2006, Peltonen et al. 2008). According to Peltonen et al. (2008) the Outokumpu ore deposits include two main types: the primary Cu-rich proto ore and secondary disseminated Ni ore.

The Outokumpu Belt hosted three major metal mines during 1913–1988. The Outokumpu mine achieved a total production of 28.5 Mt at 3.8% Cu, 0.2% Co, 0.1% Ni, 1.1% Zn and 25.3% S. The Vuonos mine produced 5.89 Mt @ 2.45% Cu, 0.15% Co, 1.6% Zn, 0.13% Ni, 0.1g/t Au, 11.0g/t Ag and 24.8% S (Papunen 1987, Parkkinen 1997, Peltonen et al. 2008), whereas the Luikonlahti mine produced 7.5 Mt of ore at 1.0% Cu, 0.1% Co, 0.5% Zn, 0.1% Ni and 16.5% S (Parkkinen 1997, Kontinen et al. 2006). In 2014, Altona Mining Limited announced that the new Kylylahti underground mine in operation due northwest of the Outokumpu Belt had measured resources of 8.8 Mt at 1.33% Cu, 0.78 gt Au and 0.54% Zn. The mine was acquired by Boliden from Altona Mining Limited in 2014 (Altona Mining

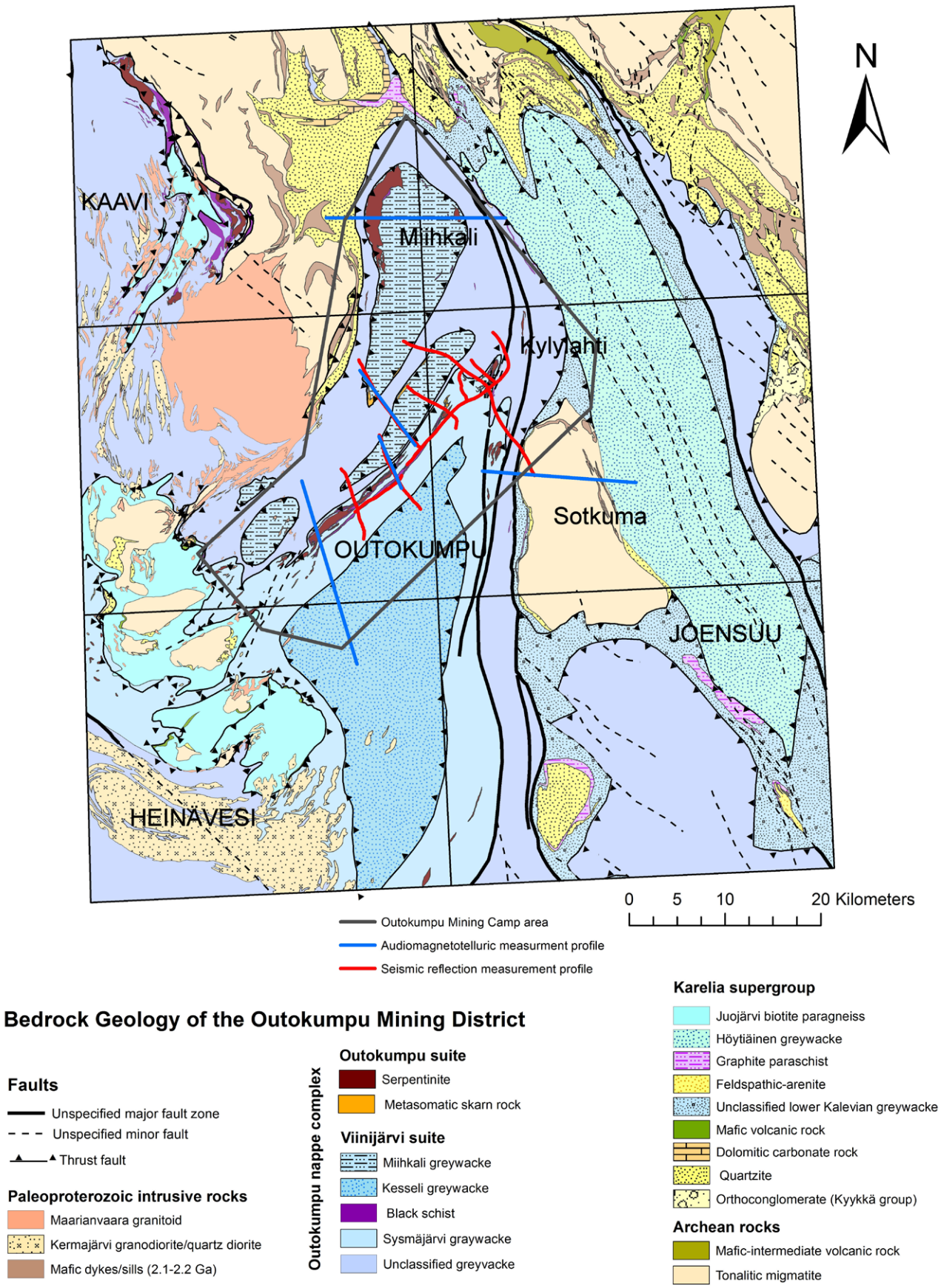

Fig. 2. Geological bedrock map (modified after Bedrock of Finland – DigiKP) of the Outokumpu Mineral District, including the Outokumpu Mining Camp research area (grey outline), audiomagnetotelluric measurement lines (blue, Lahti et al. 2016) and FIRE and HIRE seismic reflection lines (red, adapted from Kukkonen et al. 2012).

Limited 2014, Boliden 2016, New Boliden 2016). In addition to metal sulphide deposits, the Outokumpu Belt hosts talc deposits, one of which is situated in Horsmanaho, presently being mined by Mondo Minerals B.V. Branch Finland. Moreover, exploration in the Outokumpu Belt is active and there are tens of exploration claims and permits (both active and pending) by several companies.

DATA AND METHODS

The available geological and geophysical datasets on the Outokumpu Belt included geological maps and models with a large coverage, over 900 drill cores, airborne low-altitude geophysical surveys (magnetic, electromagnetic (EM), U-Th-K gamma ray), ground geophysics (especially gravity) and petrophysical measurements of rock samples. Recently, the ore belt has been covered by extensive 2D reflection seismic surveys (Kukkonen et al. 2006, Kukkonen et al. 2011), which suggest possible deep-seated host rock formations of the metal sulphide ore deposits (Kukkonen et al. 2012) (Fig. 2). A 2500-m-deep research borehole (the Outokumpu Deep Drill Hole) was drilled in 2004–2005 to reveal the geological character of the seismic reflections (Kukkonen 2011) (Fig. 2).

Due to its depth extent of several kilometres, the modern deep EM audiomagnetotelluric (AMT) method is a very efficient means to map the electrical conductivity of the uppermost crust. Thus, AMT data provide an important dataset for classifying the seismic reflectors based on their electric

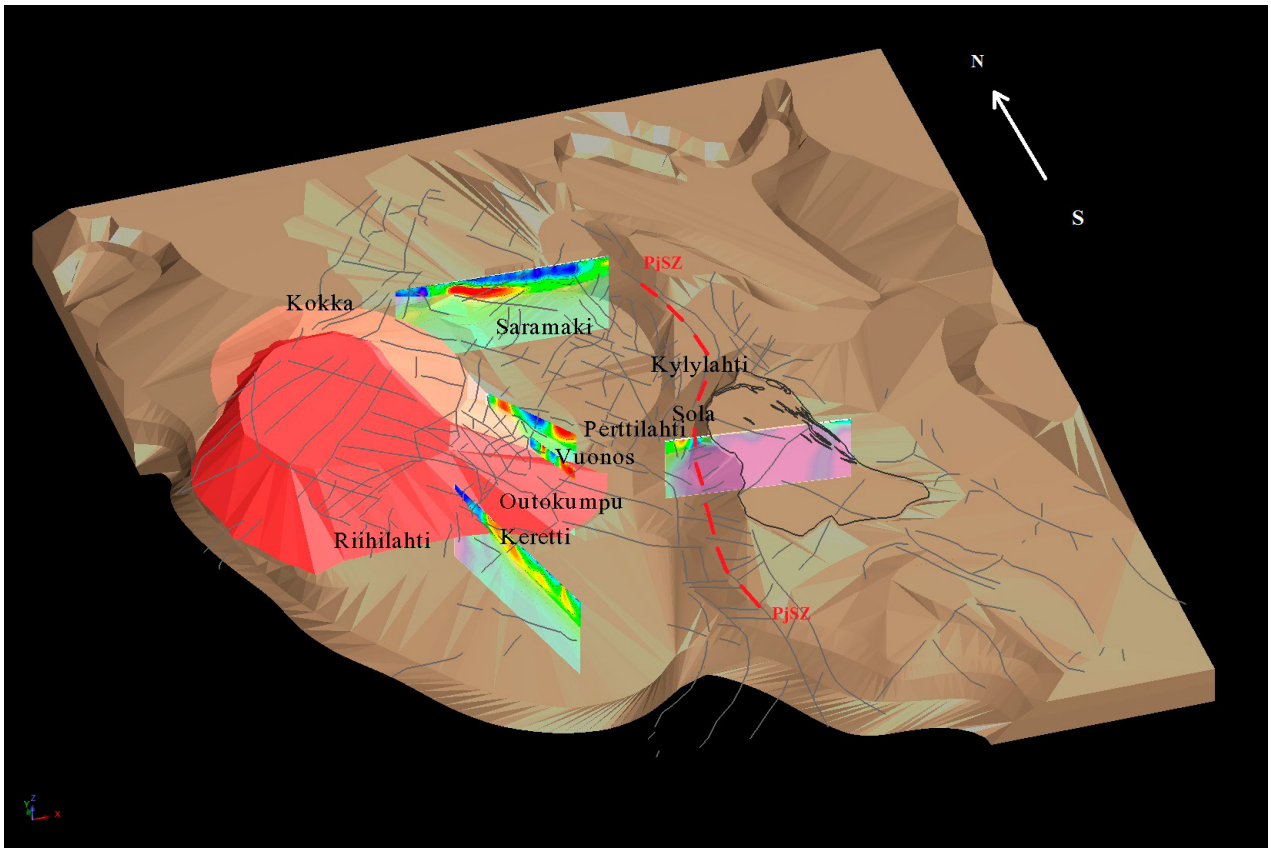

Fig. 3. An illustrated example of geophysical survey data from the Outokumpu area integrated into a 3D bedrock geological earth model of the Outokumpu Mineral District (OMD). Geophysically interpreted AMT model data are suitable for delineating large regional deep conductive and resistive features and structures (Lahti 2015, Lahti et al. 2015, Lahti et al. 2016). Integrated model data on AMT profiles (purple = resistive, red = conductive bedrock) modelled by I. Lahti were inserted into a regional 3D geological interpretation (beige = Archaean basement rocks, red = Maarianvaara granitoid, grey lines = inferred and sketched faulting) by S. Aatos. The bedrock geological and fault interpretation were based on the digital bedrock map of Finland (Bedrock of Finland – DigiKP), the gravity map of the GEOMEX project (Ruotoistenmäki 2006), and aerogeophysical raster data (Airo et al. 2014). PjSZ = Polvijärvi Shear Zone. The extent of the geological solid model in the background is about 80 km x 90 km x 5 km. The depth of AMT model profiles ranges up to 8 km.

conductivity (Lahti 2015). At the beginning of the project, AMT data were rather limited in the Outokumpu Belt, although the first two test lines had been surveyed by GTK in 2012. During this project, four more test lines were measured over the research area, two of them concatenated (Figs. 2 and 3). The ground-based AMT was complemented in 2013 with the already commercially available ZTEM (Z-axis tipper electromagnetic) airborne method designed for surveying deep resistivity distributions to a depth of 1–2 km (Kurimo et al. 2016). The Outokumpu Belt provided an excellent opportunity to test the AMT and ZTEM methods in a well-known ore belt, as Lahti et al. (2016) demonstrated also in the Miihkali Basin area.

Analysis of potential fields (magnetic and gravity anomalies) was performed to estimate the sizes of geological formations and major ore potential deposits. Existing field measured gravity data of GTK were complemented with selected profile measurements (Leväniemi 2016) (Figs. 4 and 5). Together with petrophysical information, these were fitted with seismic observations of acoustic impedance discontinuities to produce border surfaces of geological objects (Komminaho et al. 2016, Tuomi 2016). Frequency-domain electromagnetic measurements were carried out at a known deep-seated mineralization in Perttilahti (Figs. 4 and 5) to test the depth penetration of the method and to interpret the data with layered earth modelling application vs. geological interpretation (Nousiainen & Leväniemi 2016).

Geological 3D modelling and visualization required the use of special software applications designed for geology and mine planning, structural and subsurface geology, geostatistics (Laine 2016), and 3D GIS (Aatos 2016) and 3D visualisation system tools. GIS modelling and visualisation tools with geo-processing and raster analysis modules enabled 2D prospectivity mapping and the development of digital interpretation concepts and aids for bedrock mapping (Aatos 2016). All these codes had specific features, and reflected different aims of modelling (for 3D, see e.g. Laine et al. 2012). The choice of software was highly relevant to later applications and needed to be carefully considered in designing concepts for deep exploration and modelling.

A regional 3D bedrock geological interpretation was constructed (Fig. 3) based on a 2D pseudo-lithological computational GIS interpretation (Aatos 2016), existing gravity interpretation (Ruotoistenmäki 2006), present geological and structural geological knowledge of the model area, according to the national stratigraphic guide (Strand et al. 2010), and the bedrock geological map database (Bedrock of Finland - DigiKP). The concept model unit geological boundaries were further optimized according to the existing 3D bedrock geological observational and lithogeochemical data, structural geological 3D interpretations, and reflection seismic and ZTEM data (Aatos 2016).

The project provided an excellent opportunity to establish a geophysical test line for deep-reaching geophysical methods. There is a need for validated data on deep exploration methods, especially their depth extent and spatial resolution. The research group evaluated the premises of the reflection seismic lines measured earlier in HIRE and FIRE programmes (Kukkonen et al. 2006, Kukkonen et al. 2011) to choose an eligible test line. The chosen test line was vibroseismic line V7 of the HIRE project with known drilled targets at <1.5–2 km depth that had previously been surveyed and were surveyed again in this project with different methods (Heinonen et al. 2016).

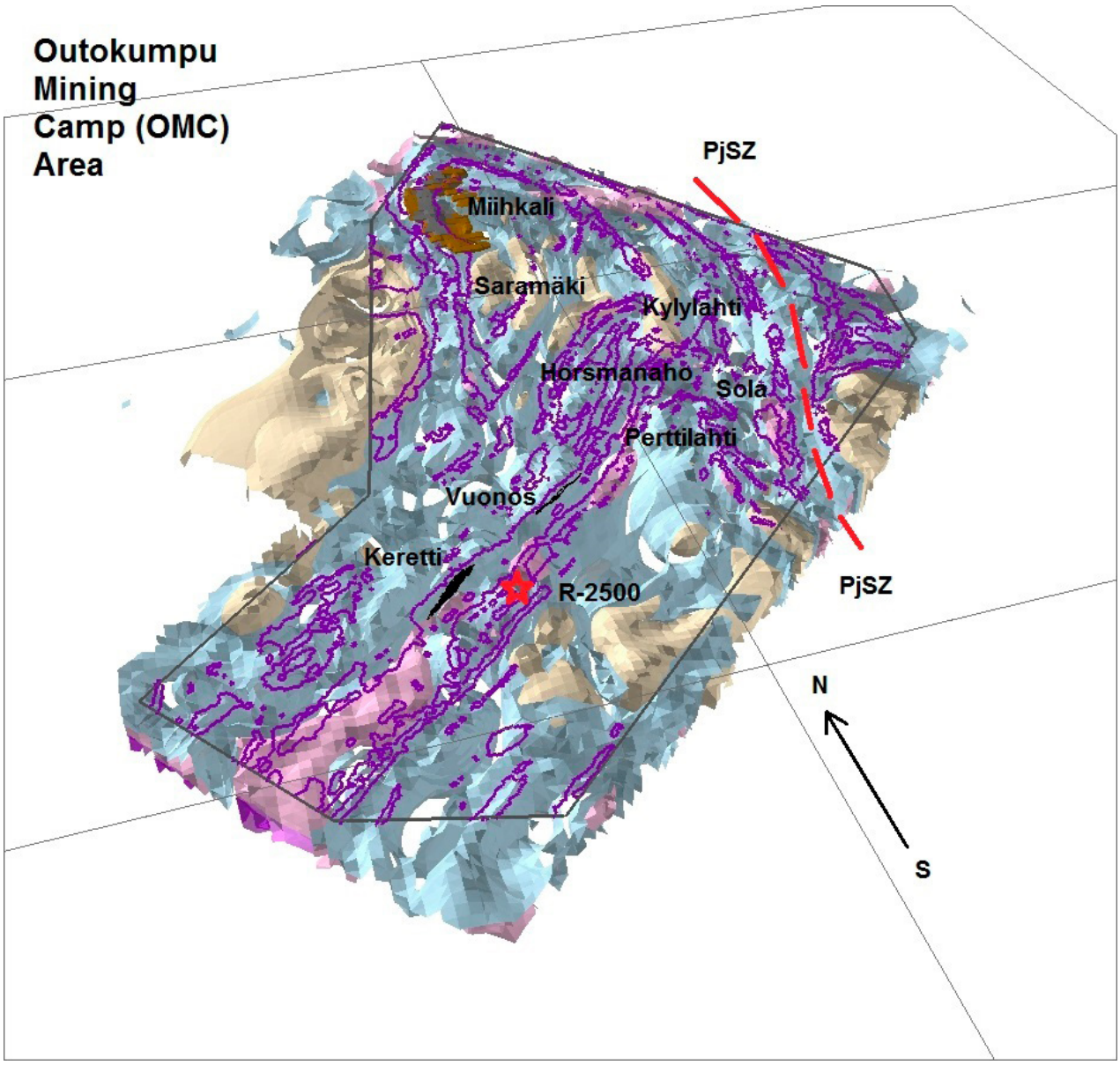

Fig. 4. An example of integrating geophysical and geological 3D model data from the Outokumpu Mining Camp (OMC) area illustrated in 3D GIS scenery. Classified low-altitude airborne conductivity data by GTK (purple contours); interpolated surfaces based on regional ZTEM inversion data described by Kurimo et al. (2016) (beige, blue and pink surfaces); targeting density model data by Leväniemi (Lahti et al. 2016, Leväniemi 2016) (brown and grey bodies); geological model geometries of Keretti and Vuonos ore deposits by Laine et al. (2012) (black bodies). Outokumpu Deep Hole R-2500 (Kukkonen 2011, red asterisk). PjSZ = Polvijärvi Shear Zone (red dashed line). The extent of the model scenery is about 25 km x 45 km x 2 km.

RESULTS

The OMC turned out to be a highly suitable target area for developing deep exploration concepts and technologies on a mining camp scale. All the geophysical methods applied in this project were of use in achieving the main result of the project, i.e. the Outokumpu deep exploration concept (OKUDEX concept) (Table 1). The results suggest that reprocessed and modelled reflection seismic survey data, potential field models based on petrophysical parameters, together with geological interpretations could be used to constrain other, geophysical data having a more robust resolution, such as deep EM (ZTEM and AMT). The chosen deep exploration methods of the project generally responded to different petrophysical properties of the rock mass (elastic properties, conductivity, density, magnetic properties) and complemented each other (Heinonen et al. 2016, Komminaho et al. 2016, Kurimo et al.

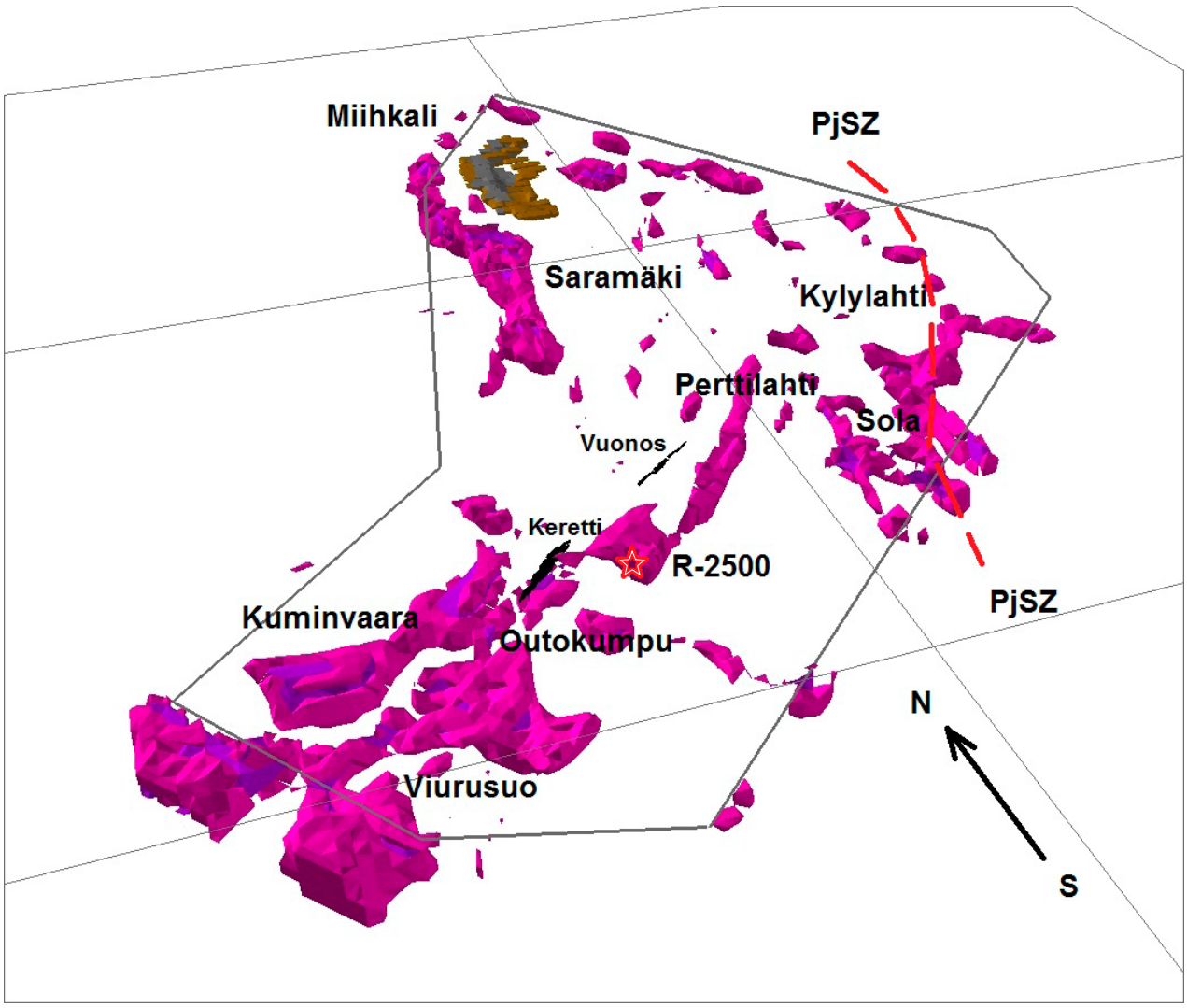

Fig. 5. Indications of deep conductive anomalies (purple interpolated surface) based on regional ZTEM 3D inversion model data described in Kurimo et al. (2016) featured with Miihkali, Keretti and Vuonos 3D models. Miihkali density model data by Leväniemi (Lahti et al. 2016, Leväniemi 2016) (brown and grey bodies). Geological earth models of Keretti and Vuonos ore deposits by Laine et al. (2012) (black bodies). Outokumpu Deep Hole R-2500 (Kukkonen 2011, red asterisk). PjSZ = Polvijärvi Shear Zone (red dashed line). Extent of the model scenery is about 25 km x 45 km x 2 km.

2016, Lahti et al. 2016, Leväniemi 2016, Maitituerdi 2016, Nousiainen & Leväniemi 2016, Tuomi 2016).

The project interpreted the regional geology of the OMD and OMC as concepts and earth models compiled from geological and geophysical interpretations (Aatos 2016, Lahti et al. 2016) and as regional structural geological models based on geostatistics, simulations, and common earth modelling (Laine 2016).

The project established the Sukkulansalo National Test Line (SNTL), following the location of high-resolution reflection seismic profile V7 (Kukkonen et al. 2011) and encompassing a versatile set of geophysical and geological deep exploration data and interpretations to facilitate the development and testing of new deep exploration methodology in the future (Heinonen et al. 2016).

The project was able to reach the main goals of the project, i.e. to develop deep (2–5 km) mineral exploration concepts and methods suitable for Outokumpu-type ore deposits and to build a general framework for common earth modelling and an integratable set of various types of earth models and CEMs of the OMC and surrounding areas. With integrated sceneries of state-of-the-art congruent geo-referenced field and model data and interpretations, the project was able to characterize the main regional bedrock formations and structures of the research area to a depth of 2 km and potentially to 5 km, possibly constraining the Outokumpu-type mineral potential below the relatively well known uppermost 300 m of the bed-

Table 1. A generalized characterisation of the pre-competitive phase of the Outokumpu deep exploration concept (OKUDEX concept), comprising a combination of some equally important parts of the exploration process useful in predicting favourable deep features indicating the existence of Outokumpu assemblage rocks or Outokumpu-type mineral potential.

	Controlling feature	**Deep exploration proxies**	**Geological data and methods**	**Geophysical data and methods**	**Verification of concepts and modelling**
I	Tectono-stratigraphic units and their history	Constraining unit boundaries and positioning favourable sequences of strata included in the Outokumpu nappe complex	Regional to targeting bedrock geological inference by expert knowledge or by modelling	Systematically collected surface and deep geophysical airborne or field measurement data. Forward modelling of reflection seismics, inversion modelling of regional ZTEM, AMT data	Reviewing strategic targets with deep drilling, possibly complemented by shallow diamond drill coring, and with targeted field geophysical measurements and down-hole geophysics
II	Structures	Continuation of structural controls related to favourable unit boundaries and remobilized zones related to mineral deposits in Outokumpu assemblage rock sequences	Structural geological mapping and expert knowledge, predictions and simulations based on structures	CEM modelling of deep EM and other deep geophysical survey data, constraining e.g. with reflection seismic data	Reviewing strategic structures with structural geological mapping, oriented structural observations while deep drilling, analysis of whole rock and metal concentrations of drill-core samples, down-hole geophysics
III	Properties of the ore or ore-hosting rock assemblages	Mineralogy-bound, ore potential differentiating signatures and pathfinders in mineralized parts of Outokumpu assemblage rocks	Geochemical whole-rock drill core analysis data, mineralogy	Petrophysical properties, potential field modelling, seismic forward modelling. Identifying coinciding anomalies e.g. high-amplitude reflectors vs. ZTEM data.	Reviewing strategic targets by deep drilling with whole rock and metal concentration analyses, down-hole geophysics

rock in the OMC area. The optimal operating depth for the exploration and mining industry in Finland would probably be above 1.5 km. The main mineralized deep indications of Outokumpu-type mineral deposition revealed by this project are situated in known conductive and reflective anomaly zones in Viurusuo-Outokumpu-Perttilahti (Outokumpu Belt), Kylylahti-Sola (Polvijärvi Shear Zone), and the Saramäki Belt plunging due south (Miihkali Basin). The deep EM model data revealed a previously undescribed regional SW–NE-trending deep conductor belt between Lake Viitajärvi and Lake Juojärvi (Kuminvaara Belt) at a depth of about 1–2 km. The width of the Kuminvaara Belt equals that of the Outokumpu Belt (Fig. 5).

The project developed new technologies and competence in the field of common earth modelling for deep exploration in Finland. The project is expected to have an impact on future business opportunities and society, with new expert services and data. The future continuation of research and competence development were ensured by inviting experienced and junior geophysicists and geologists to work together in order to extend the common knowledge base of deep exploration, common earth modelling and Outokumpu-type ore deposits during the project.

Being able to visualize integrated data, earth models and CEM results consistently in commonly used 3D applications and environments is crucial when enhancing the communication between science branches or academia and industry. The project collected existing or digitized 3D datasets that allowed the development of integrated georeferenced 3D data and model sceneries, e.g. for further multidisciplinary spatial orientation and queries on a mining camp scale. The data files of the project, e.g. observation, measurement, interpretation and model data and their metadata, will be stored in the GIS databases of GTK. They will become publically available for further use and development according to the usual data product conventions of GTK, after the project qualifying period has expired.

SUMMARY

Long-term exploration and mining activities in brownfield areas related to specific type(s) of mineral systems have an increasing need to develop cost-efficient and informative predicting methods for deep exploration reaching depths extending 500 m. This is due to the exhausting of near surface deposits and high cost of deep data collection. Exploration in brownfield areas also requires technologies that avoid unnecessary disturbance of inhabitants and the environment. One solution fulfilling these demands is the efficient integration of existing, and if necessary, diversely optimised new geo-data with interpretation and modelling for deducing the deep characteristics of geological features indicative of the mineral deposit styles in focus.

Most of the methods applied and developed in this project are suitable for regional deep exploration projects in the orienting work phase, before the targeting phase with complementary field observations and measurements. One geological key for focusing the deep exploration of a brownfield region more cost-efficiently is understanding of the mineral system context of the sought ore type, as well as thorough knowledge of the surficial geology of the explored region. Modelling results should always be evaluated and validated with field data (e.g. by drilling) and interpretations updated in an iterative way. Brownfield areas usually have advantages on their side when compared to greenfield areas, such as plentiful data. In many cases, however, there may be a lack of specific data and knowledge needed for CEM or 3D earth model purposes (e.g. geological, geophysical and geochemical deep drilling data combined with reflection seismic profiles) from a location of interest, and in such cases, the gathering of new complementary data cannot be avoided.

The geological environments hosting the Outokumpu-type ores are known for difficulties in interpreting the confusing or disguising effects of black schist interbeds or other conductive rock types typical of these regions. All of the used EM methods are sensitive to the masking effects caused by multiple layers of conductive rocks, emphasizing the need to develop complementary deep EM measurements and modelling methods (e.g. joint inversion with other relevant geophysical data) to resolve these issues. The results of seismic modelling, other geophysical interpretation and CEM can mostly be verified inside a measurement profile where geological interpretation of deep drilling data is available. Potential field modelling provides multi-disciplinary perceivable

geometries for constraining the ore potential of rock formations. Expanding geophysical interpretation to greater depths increases the uncertainty of the results as a function of depth and the detectability of the deposit. The uncertainty of the results generally increases as a function of distance from the observation points or measurement lines, unless the observation or measurement density in the area of interest is increased. The uncertainty of the results can be diminished by using multi-sourced data and integrated interpretations. Systematic observations of surficial and subsurface structural geological data and interpretations are indispensable in constructing geological earth models constraining geophysical CEM.

As a whole, the project was able to delineate geophysical anomalies and geological constraints, probably indicating the main deep-reaching zones of Outokumpu assemblage rocks in the OMC area. At the end of the project, the present compiled versions of the project earth and common earth models represent the best available geophysical interpretations backed up by bedrock and structural geological and geochemical expert knowledge of the OMC. Eventually, the main outcome of the project, the OKUDEX concept, will provide suggestions for general concepts, experience and guidance for novel applications of such datasets in modelling the bedrock at mining camps and exploration in analogous areas resembling the OMD. The most strategic targets of the project are proposed to be reviewed, or undergo deep drilling (1000 m), possibly complemented with shallow diamond coring of the surface (300 m).

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