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REGIONAL ANALYSIS OF HYDROTHERMAL NICKEL PROSPECTIVITY IN THE OUTOKUMPU MINERAL DISTRICT

by

Soile Aatos

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This paper describes the methodology and analysis of the regional prospectivity of hydrothermal nickel in the Outokumpu Mineral District.This forms a case study which is part of the Developing Mining Camp Exploration Concepts and Technologies – Brownfield Exploration project that focused on developing deep exploration concepts and technologies for Outokumpu-type metal deposits in crystalline bedrock areas.

Although the focus in future metal exploration and mining is gradually concentrated in greater depths, the key to understanding deep ore potential is still grounded on a good understanding of the geology of the Earth's surface. Evolving mineral deposit concepts, good geophysical and geochemical data coverage and modern GIS modelling tools enable us to identify and evaluate regional geological characteristics and the related metal potential of brownfield areas.

In this semi-quantitative study, pseudo-lithological features of the Outokumpu Mineral District were mapped from airborne electromagnetic and magnetic data using GIS technology and tools. Geochemical data were also used to delineate the regional to target scale prospective areas for follow-up exploration of Outokumpu-type hydrothermal nickel deposits using GIS fuzzy modelling techniques.

Keywords: nickel, prospectivity mapping, GIS, models, geophysical data, geochemical data, Outokumpu, Miihkali, Maarianvaara, Eastern Finland, Finland

Geological Survey of Finland, P.O. Box 1237, FI-70211 Kuopio, Finland

E-mail: soile.aatos@gtk.fi

INTRODUCTION

After a century of exploration and mining activities, the regional Outokumpu-type metal potential of Northern Karelia, Finland (Fig. 1), has recently been quantitatively assessed by Rasilainen et al. (2014). They focused on the still undiscovered resources of copper, zinc, cobalt and nickel a permissive tract area of ca. 9800 km^2 to the depth of one kilometre and estimated a median tonnage of 580,000 t Cu, 220,000 t Zn, 53,000 t Co and 41,000 t Ni in one Outokumpu-type permissive tract area.

Genetic models of Outokumpu-type deposits in tectonized and metasomatized serpentinites have previously been described by Kontinen et al. (2006) and Peltonen et al. (2008) for the period from 1921 to 1999. Saalmann & Laine (2014) pointed out the significance of deep structural controls on the ore deposit settings after Kontinen et al. (2006), Peltonen et al. (2008) and Kukkonen et al. (2012). Zhang et al. (2006) concluded, based on their fluid flow modelling results, that multiphase regional structural processes affected hydrothermal events at Kylylahti, Polvijärvi, and thus also the metal enrichment and remobilization in the Outokumpu nappe area (Fig. 2). Peltonen et al. (2008) described Outokumpu as a Red Sea-type ophiolitic ore deposit originating from a tectonic setting resembling Phanerozoic passive margins.

Due to the ongoing active exploration and mining in the Outokumpu Mineral District (Fig. 2), GIS-based raster calculation and knowledge-driven fuzzy logic prospectivity modelling techniques were here used to identify tectonized Palaeoproterozoic mantle peridotites associated with Outokumpu-type nickel metallogeny that were described in Kontinen et al. (2006) and Peltonen et al. (2008) as having potential for hydrothermal nickel sulphides.

The concept for producing an Outokumpu-type ore deposit model was initially developed in the GEOMEX J.V. project operating in Finland in 1998–2003 (Kuronen et al. 2004, Kontinen et al. 2006, Peltonen et al. 2008), and later modified by Kontinen (2014). Their conceptual model of Outokumpu-type mineralization consists of two sub-concepts, the Cu-rich proto ore and the secondary Ni-Co sulphide disseminations. During the course of this study work, an interesting report on the hydrothermal nickel-(PGE) potential related to accretionary environments was published (González-Álvarez et al. 2010, 2013), leading to a need to explore for similar nickel-(PGE) deposits in the Outokumpu region. In this study, supplementary exploration vectors are added to the previous concept of the Outokumpu-type Cu-Co-Zn mineral deposit model based on new exploration knowledge of accretionary ophiolitic environments. These include the role of chromium, lithium and PGE as possible indicators of hydrothermal nickel-PGE and lithium deposits in the Outokumpu-type geological settings.

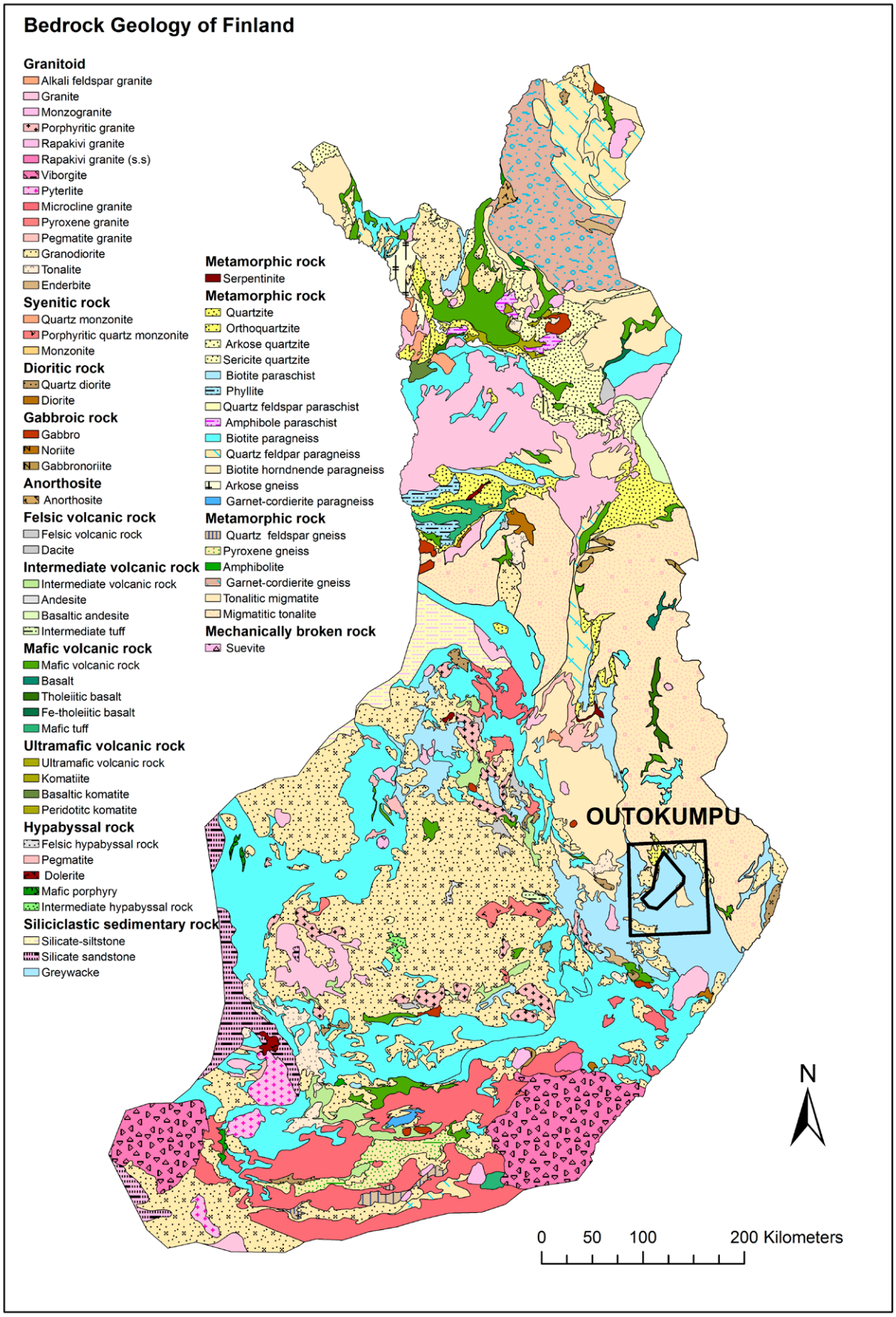

Fig. 1. The Outokumpu Mineral District (black quadrangle) is located in the Karelian metasedimentary border zone (light blue) partly thrust during the Svecofennian orogeny on the Archaean basement (beige) of the Karelian craton (Lahtinen et al. 2009). The Outokumpu Mining Camp area of the present project, also coinciding the ZTEM flight survey area (Kurimo et al. 2016), is outlined as a black octagon inside the Outokumpu Mineral District area. Bedrock map: Digital Bedrock Map Database of Finland (Bedrock of Finland - DigiKP).

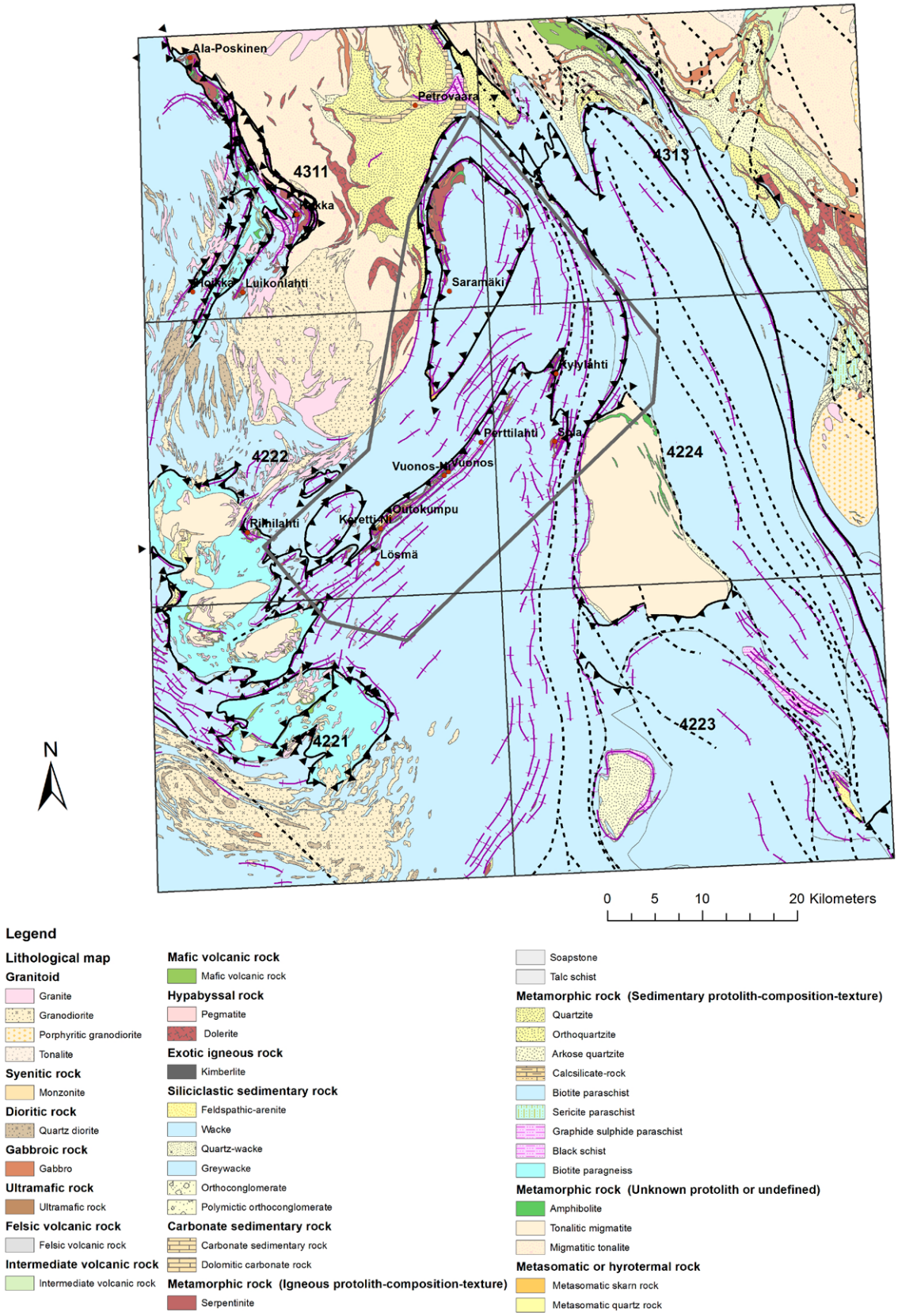

Fig. 2. Lithology of the Outokumpu Mineral District modified from the 1:200 000 scaled Bedrock of Finland – DigiKP showing the main Outokumpu ore deposits. The modelling study area covers the Finnish 1:100 000 map sheet areas 4221 Heinävesi, 4222 Outokumpu, 4223 Joensuu, 4224 Kontiolahti, 4311 Luikonlahti (Sivakkavaara) and 4313 Koli (framed by black lines), coinciding with the area of the GEOMEX project (Kuronen et al. 2004). The Outokumpu Mining Camp area is outlined as a grey octagon inside the Outokumpu Mineral District area. Geological line features: thrust faulting (triangulated), major faulting (black), a minor fault (dashed) and black shales (purple). The spatial reference of the study was Finland zone 3 (KKJ 3). Ore deposits: GTK digital archives (see FODD 2015).

MATERIALS AND METHODS

GIS-based tools and integrative computational analyses have been used in predicting regional metal prospectivity for over 20 years (e.g. Harris et al. 2000, Bonham-Carter & Cheng 2008, Nykänen 2008, Porwal & Kreuzer 2010, Leväniemi 2013, Torppa et al. 2015). However, recent developments in proxy setting and prospectivity analysis in regional nickel prospectivity mapping has been undertaken also, for example, in Zimbabwe by Markwitz et al. (2010), and for Avebury-style hydrothermal-remobilized nickel mineral systems in Australia by González-Álvarez (2010) and Lisitsin et al. (2013).

In this study the conceptualization modelling approaches presented in the above papers were integrated with the model of Outokumpu-type mineral deposits by Peltonen et al. (2008) and summarized in Rasilainen et al. (2014). The vectors used for producing prospectivity analysis of the nickel sulphide prospectivity map for Outokumpu Mineral District are listed and described in Table 1. This study concentrated on outlining the practical features and constraints (Tables 1–3) revealed by geophysical and geochemical GIS data related to the prospectivity of secondary Ni sulphides originating along with serpentinization processes in the Outokumpu nappe complex. Visualization and enhancement techniques used by Airo (2015) were applied to Outokumpu-type geophysical anomalies for enhancing prospective areas and for the selection of additional geophysical vectors for modelling within the GIS. The study area was extended to match the previous GEOMEX project area delineation and was not restricted to the present mining camp project covering just the ZTEM flight area. This provides a wider area to explore (Fig. 2), and also matches the area in which a regional 3D geological interpretation of the mineral district was undertaken (see Aatos et al., this volume). The maximum depth of this prospectivity analysis data varies from surficial to shallow, according to the airborne electromagnetic (EM, 70-100 m depth at its best) and surface gamma-ray spectrometry data (Airo et al. 2014) used. The prospectivity model would primarily be considered a 2D model.

The presented 2D prospectivity analysis was based on existing geological, geochemical or geophysical data as summarized in Table 1. Airo (2015) has established the high magnetic susceptibility and some other characteristic geophysical features of Outokumpu ore (e.g. density, conductivity and Königsberger ratio) and Outokumpu-type anomalies (classified regional airborne conductivity and magnetic anomaly maps). Kontny & Dietze (2014) noted that magnetite and monoclinic pyrrhotite of ferromagnetic metaperidotite result in the high magnetic susceptibility of the Outokumpu assemblage. GTK's in-house interpreted airborne electromagnetic (EM), magnetic and radiometric uranium data (Airo et al. 2014, Airo 2015) along with regional till geochemical (Salminen 1995) and lithogeochemical data (Rasilainen et al. 2007, 2008) were used to produce the Ni mineral prospectivity maps of the Outokumpu region (Tables 1 and 2).

A geoprocessing tool for spatial data modelling using fuzzy logic was used to build experimental models to produce prospectivity maps (Sawatzky et al. 2009) based on Outokumpu-type exploration vectors. Figure 3 presents an example of a built fuzzy logic model to produce a preliminary Ni prospectivity map based on Outokumpu-type exploration vectors (Table 2).

In the data conditioning phase, the point geochemical data were interpolated using a nearest neighbor algorithm for the till data and an inversed distance weighting algorithm for the lithogeochemical data due to the irregular or scattered sample points grid and non-normal distribution of the data values (Table 2). Whole-rock analyses in the Finnish lithogeochemical rock geochemistry database (RGDB) data (Rasilainen et al. 2007, 2008) were used to compute CIPW norms with the R application Geochemical Data Toolkit (GCDkit) (Janoušek et al. 2006) to test whether there were any differences in Mg-bearing mineralogical distributions in the region (Tables 1 and 2).

As an intermediate product in the GIS prospectivity analysis process a 2D pseudo-lithological interpretation (Fig. 4) based on airborne magnetic and apparent resistivity data (Airo et al. 2014) was also used in the modelling.

For the basis of this work, I compiled a set of exploration proxies conducted from the available geophysical and geochemical data and a prospectivity analysis workflow for the Outokumpu-type secondary Ni sulphide disseminations (Tables 1 and 2). As a result of applying the methodology and tools described in the previous sections, I produced a 2D computational GIS interpretation process for the Outokumpu-type secondary Ni potential occurring in or in relation to the serpentinized

Table 1. A simplified conceptual mineral system model for Outokumpu-type hydrothermal Ni deposits modified after Peltonen et al. (2008), Markwitz et al. (2010) and Lisitsin et al. (2013), and exploration vectors used for Outokumpu Mineral District prospectivity modelling.

Mineral systems concept	**Exploration vector**	**Signature or response for modelling**
Availability of Ni source	Presence of ultramafic rocks containing ophiolitic packages, ultramafic rocks (picritic basalts >12% MgO)	Regional: Ultramafics detected in the area of interest Targeting: Olivine or hypersthene in CIPW norm (Cross et al. 1902), lithogeochemical data
Mobility of Ni (endogenous hydrothermal processes caused by regional metamorphism)	Magnetite and Mg-bearing minerals formed after disintegration of olivine Serpentinization Skarnification	Regional: Positive airborne magnetic anomalies associated with massive magnetite occurrences within ultramafic rocks Regional: High simultaneous airborne EM imaginary (quadrature) component and magnetic anomalies associated with serpentinites and skarns Regional to site-specific targeting: High acid (aq. reg.) leachable Mg concentrations in till (reflecting the presence of serpentine and/or magnesite)
Mobility of Ni (introduced by hydrothermal activity)	Introduction of U Introduction of Cr (secondary), Li and B	Regional: Airborne U anomalies Targeting: High U concentration in lithogeochemical data Regional to site specific targeting: High acid (aq. reg.) leachable Cr and Li anomalies in till. Detected boron-bearing minerals in bedrock
Deposition of Ni	Deposition of sulphides (black schists) vs. trap (tectonic contacts) Deposition of sulpharsenides, sulphosalts (granitoids, black schists) vs. trap (tectonic contacts)	Regional: High conductivity due to possible pyrrhotite and other conductive metal sulphides, mainly in black schists Regional to site-specific targeting: Identification of suitable nappes, thrust zones, shear zones and faults Regional to site-specific targeting: High lithogeochemical concentrations of Cu and Pd Regional to site-specific targeting: High acid leachable Cu, Co and Ni anomalies in till Site-specific targets: Identification of podiform chromitites (stratigraphic constraint) Site-specific targets: Identification of boron minerals related to high-strain zones

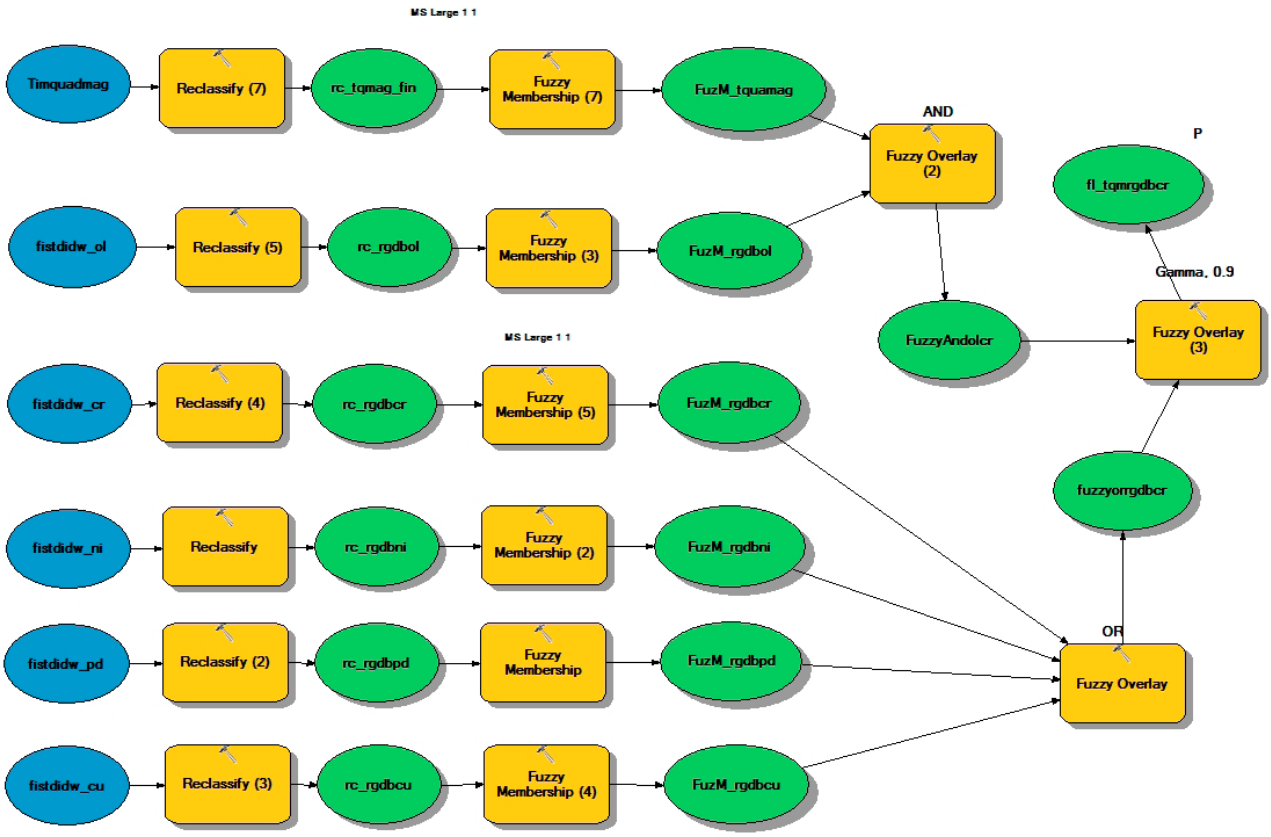

Fig. 3. An example of a fuzzy logic model built in this study. The model was built in a graphic user interphase of an object-oriented spatial data model builder (Sawatzky et al. 2009). Fuzzy membership function algorithms based on the mean and standard deviation of the input data where either small or large values of data have high memberships (Sawatzky et al. 2009) were used. Mean multiplier and standard deviation multipliers were defined as 1. The application-specific methods used to combine two or more membership data were overlay types AND, OR or GAMMA (Sawatzky et al. 2009).

peridotites of the ophiolite bodies. Some of the most interesting of the produced prospectivity maps are reported in this study (Figs. 4–10).

In the case of brownfield exploration in mining camps, suitable bedrock maps that can be used for validating 2D GIS prospectivity maps are often more abundant than in the greenfield areas, depending on the scope, number and quality of previous surface exploration programmes or observations. In this study area the Outokumpu hydrothermal nickel prospectivity maps produced were validated based on expert knowledge and qualitative field-based observations.

The regional pseudo-lithological model (Table 2, Fig. 4) was validated in discussions with experienced geologists having expertise in regional bedrock and structural mapping of the Outokumpu Mineral District. The geophysical anomaly mapping based on pseudo-lithological composite geodatasets with cut-offs (Table 2, Figs. 5 and 6) were validated using data available from known ore deposits and mineral showings from the Outokumpu Mineral District (FODD 2015, layman's samples and observations archived in the GTK database). Geochemical metal anomalies in till were validated visually together with boulder data (Table 2, Fig. 8).

Table 2. Regional data used for prospectivity modelling. The pixel size of each raster was 50 m x 50 m. The electrical conductivity and radiation of bedrock is dependent not only on the mineral composition but as well as, for instance, on the texture and water content of the mineral material of the glacigenic overburden (Airo 2015). Local anthropogenic anomalies have been visually screened out in the expert validation phase, especially in the interpretation of radiometric U results, as there are anomalous spots because of some human land construction activities, such as mining waste dumps.

Modelling data	Reference	Data provider	Data domain	Subject	Spatial data type or geometry	Modelling parameters [range of raster value]
KKJ map sheet areas, 1:100 000		National Land Survey of Finland (NLS)	Land survey	Geographical spatial data	Vector	Study area (Fig. 2)
Digital Bedrock Map Database, 1:200 000	Bedrock of Finland – DigiKP	Geological Survey of Finland (GTK)	Geology	Bedrock geology	Vector	Background data for comparison (bedrock types, faults)
Apparent resistivity, real (in phase) and imaginary (quadrature) conductivity	Airo et al. (2014)	GTK	Geophysics	Airborne EM	Raster	Electromagnetic anomalies: apparent resistivity = [0,5178], real (3 kHz) = [-2223,17144] and imaginary (3 kHz) = [-1856,11569]
Magnetic	Airo et al. (2014)	GTK	Geophysics	Airborne magnetics	Raster	Magnetic anomalies (DGRF-65) = [-3240,9769]
Natural radioactivity	Airo et al. (2014)	GTK	Geophysics	Airborne radiometrics	Raster	U anomalies of the Earth's surface: U (eq.) = [-1.84,11.08]
Rock geochemistry database	(Rasilainen et al. 2007, 2008)	GTK	Geochemistry	Regional lithogeochemistry	Interpolated point data (raster)	Ni, Cr, Cu and Pd anomalies of bedrock (ppm): Ni = [14,2722], Cr = [19,3138], Cu =[17,579], and Pd = [5,26]
Till geochemistry database	Salminen (1995)	GTK	Geochemistry	Regional geochemistry of till	Interpolated point data (raster)	Mg, Ni, Cr, Cu, Co, Li anomalies of till (ppm): Mg = [836,41956],Ni = [3.1,859], Cr = [7.5,208], Cu = [5.8,303], Co = [1.9,90], Li = [0-95.9]
CIPW norm mineralogy	In preparation (Aatos)	S. Aatos, unpublished computational model evidence layer data	Petrology	Inferred regional ultramafic-mafic mineralogy	Interpolated point data (raster)	Computationally interpreted olivine anomalies of rocks (%): ol = [0,68]
Pseudolithology	This study	This study, computational model evidence layer data	Geophysics	Inferred regional bedrock geology	Multiplication of the values of two rasters on a cell-by-cell basis (raster)	Classified composite geodatasets: 1) apparent resistivity (EM) * magnetic anomalies = [-6958404, 17964170] 2) quadrature component (EM) * magnetic anomalies = [-2311669.25, 11987580] 3) in-phase component (EM) * magnetic anomalies = [-13671361, 50215728]

RESULTS

The pseudo-lithological map (Fig. 4) was found to be useful for not only as inclusion in the prospectivity modelling but also as an information source for bedrock mapping in places where geological information was sparse. For example, regional pseudo-lithological map provided indications that the airborne geophysical anomalies probably caused by 2.2 Ga old diabase sills originating from low-Al or karjalitic magma (Nykänen et al. 1994), ultramafic rocks and Maarianvaara granitoid can be visually separated from Lower and Upper Kalevian metasedimentary rocks, or that Outokumpu and Miihkali nappes can be clearly mapped (Figs. 1, 2 and 4).

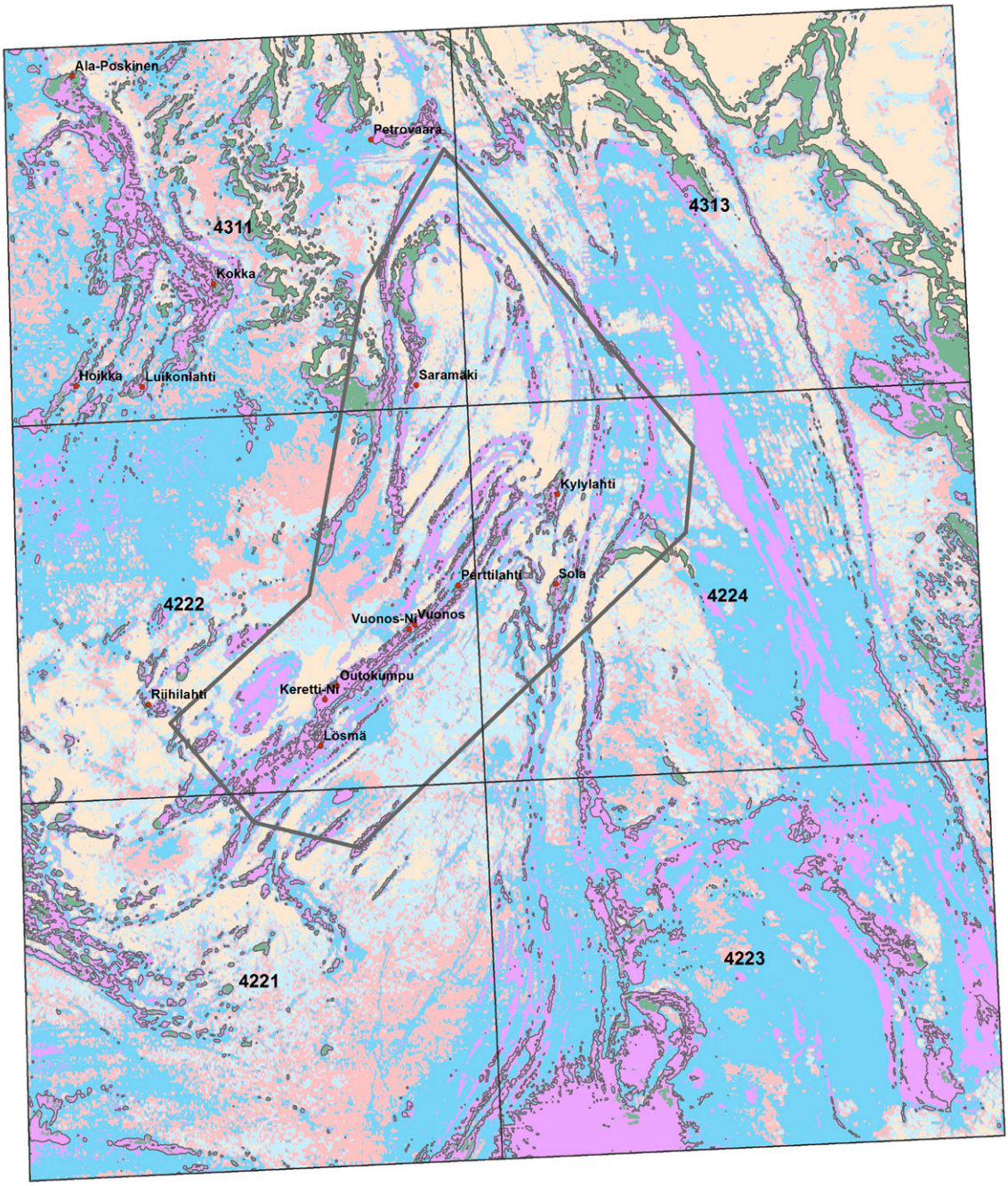

Fig. 4. Pseudo-lithological map of the study area based on airborne geophysical apparent resistivity and magnetic GIS raster data. The model area comprises six 1:100 000 map sheets (grey outline), an area about 7200 km^2 in total. Colours of the model: purple = conductive and magnetic rock units (e.g. black schists), green = magnetic and resistive ground (karjalites, soapstone, Outokumpu-type talc rocks), blue = Lower Kalevian rock units, pale blue = Upper Kalevian rock units, and red = granitoids (e.g. Maarianvaara granite north-west of Vuonos). Raster data source: GTK (see e.g. Airo et al. 2014). Ore deposits: GTK digital archives (see FODD 2015).

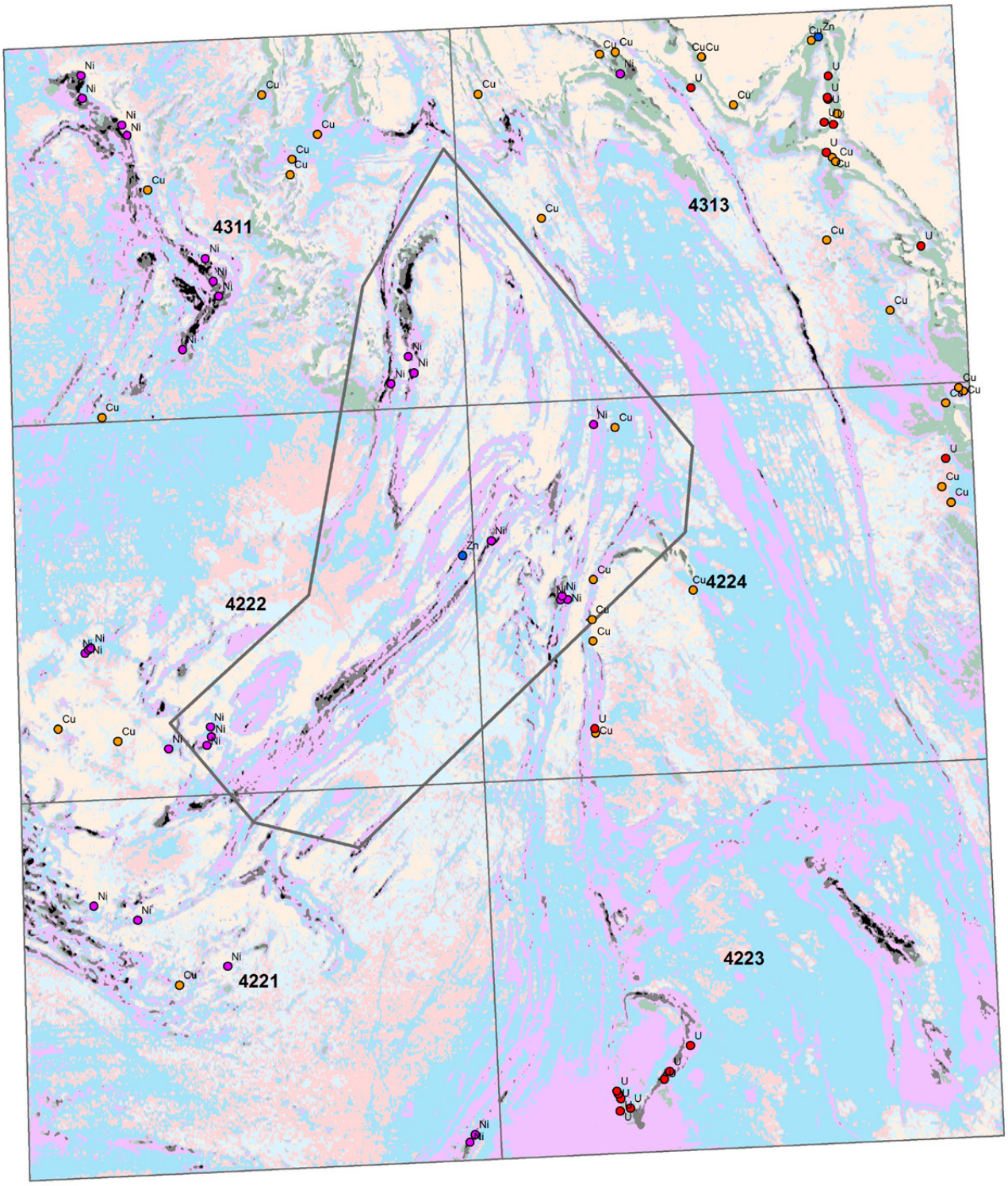

Fig. 5. A pseudo-lithological map based on a composite quadrature and magnetic aerogeophysical GIS raster data (Table 2) with a model cut-off value coincide well with Outokumpu assemblage-type rock areas (e.g. serpentinites, skarns) or features having simultaneous high-electric imaginary (quadrature) and magnetic anomalies (grey to black areas). Metals reported from the layman's bedrock observation database: Cu, Ni, Zn and U (GTK digital archives). Raster data source: GTK (see e.g. Airo et al. 2014). Base map: pseudolithological map from Figure 4.

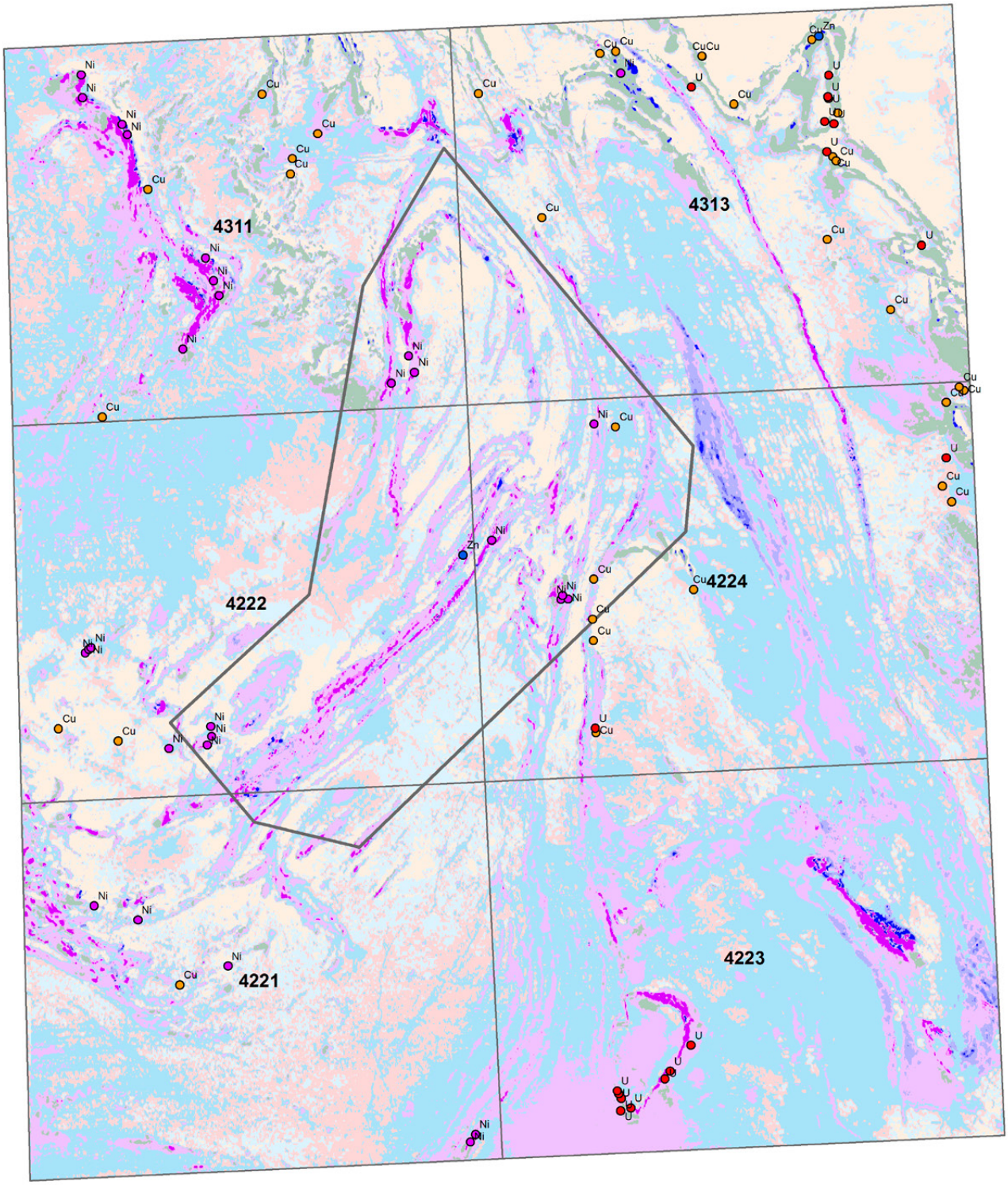

Fig. 6. A pseudo-lithological map based on a composite in-phase EM and magnetic aerogeophysical GIS raster data (Table 2). The model delineates the conductive and magnetic pyrrhotite and other sulphides containing zones as overlapping high-electric EM real (in phase) component and magnetic anomalies (red purple). Low-magnetic, high-conductive anomalies (blue violet) may correlate, for example, with highly graphitic schists, low-sulphide or pyrite-only black schists. Besides Outokumpu assemblage-type rocks, copper anomalies may be originated also from karjalitic rocks. Metals reported from the layman's bedrock observation data: Cu, Ni, Zn and U (GTK digital archives). Raster data source: GTK (see e.g. Airo et al. 2014). Base map: pseudo-lithological map from Figure 4.

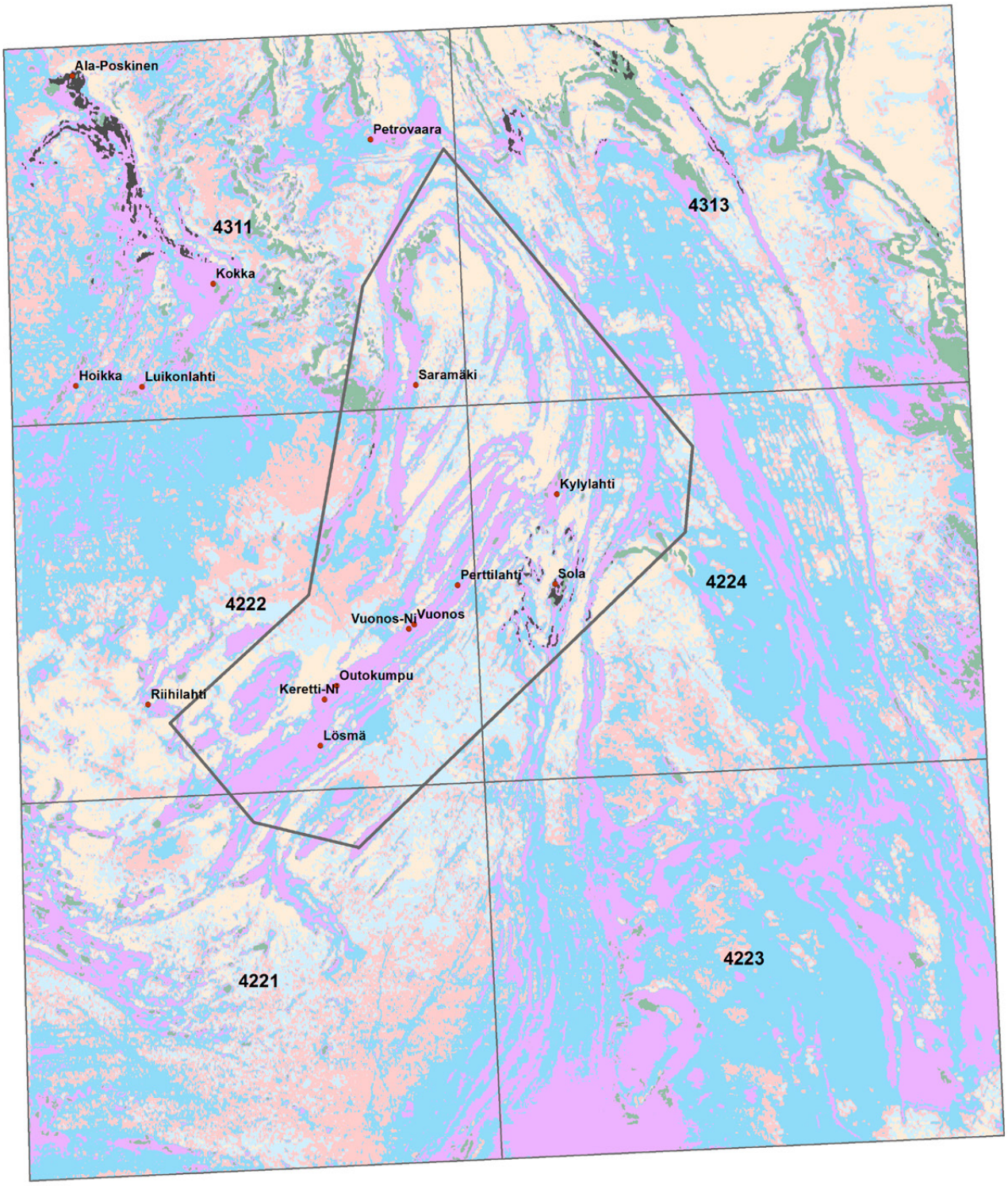

Fig. 7. A lithogeochemistry-based fuzzy logic prospectivity model of the Outokumpu Mineral District suggesting areas of the most primitive ultramafic rocks with hydrothermal Ni (± PGE) potential (dark grey shading). The possible indications of chromitites (± related PGE minerals) as modelled based on the pseudo-lithological indications of serpentinite or ultramafic rock (Fig. 5), computed normative olivine in ultramafic rocks, and concentration of Cr, Ni, Cu or Pd in lithogeochemical data from the RGDB by Rasilainen et al. (2007, 2008) as conceptualized in Tables 1 and 2 (dark grey shading). Ore deposits: GTK digital archives (see FODD 2015). Base map: pseudo-lithological map from Figure 4.

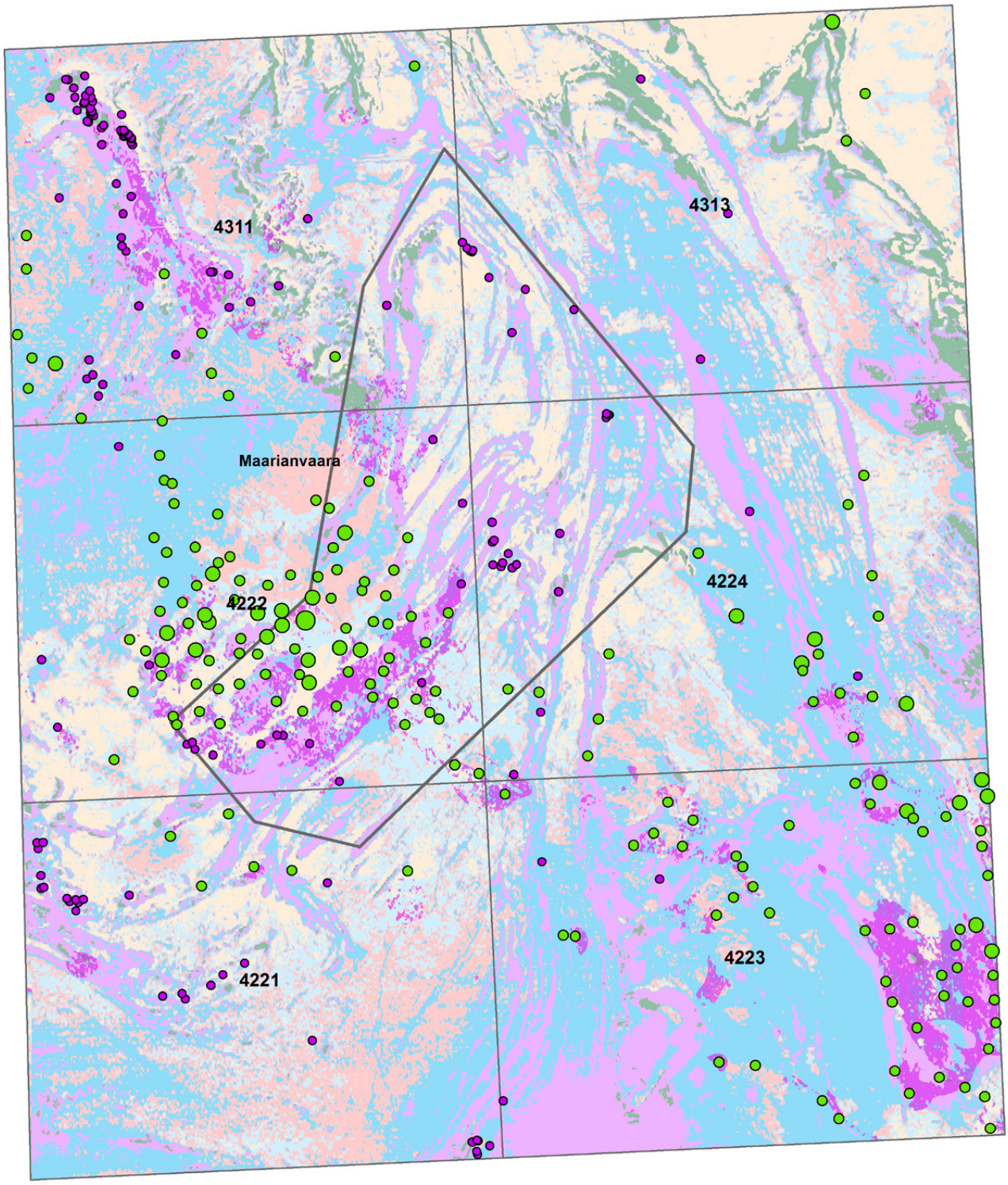

Fig. 8. A till geochemistry-based fuzzy logic prospectivity model (deep purple) of the Outokumpu Mineral District suggesting areas having potential for remobilized hydrothermal Ni (± PGE). During the GIS visualization experiments of regional metal anomalies (e.g. Cu, Co, Ni, Zn, Cr) in till before constructing Outokumpu-type prospectivity models, anomalies of other than base metals, e.g. lithium, were also recognized. In the Paakkila-Kuusjärvi area, south-southwest of Maarianvaara granitoid, there exists a regional lithium anomaly (green dots) in till over an area of granite pegmatites related to a shear zone, which may indicate younger or more differentiated magmatic hydrothermal activity in the area compared to Maarianvaara granitoid. The lithium anomaly (24-95.9 ppm) appears to be in the close vicinity of maximum values of Outokumpu-type combined geophysical (pseudo-lithological serpentinite interpretation in Figure 5, airborne U) and till (Mg, Ni, Cr, Cu, Co) anomaly models (deep purple) (see model concepts in Tables 1 and 2). Purple circles mark nickel-mineralized boulders in the layman's sample database of GTK. Base map: pseudo-lithological map from Figure 4.

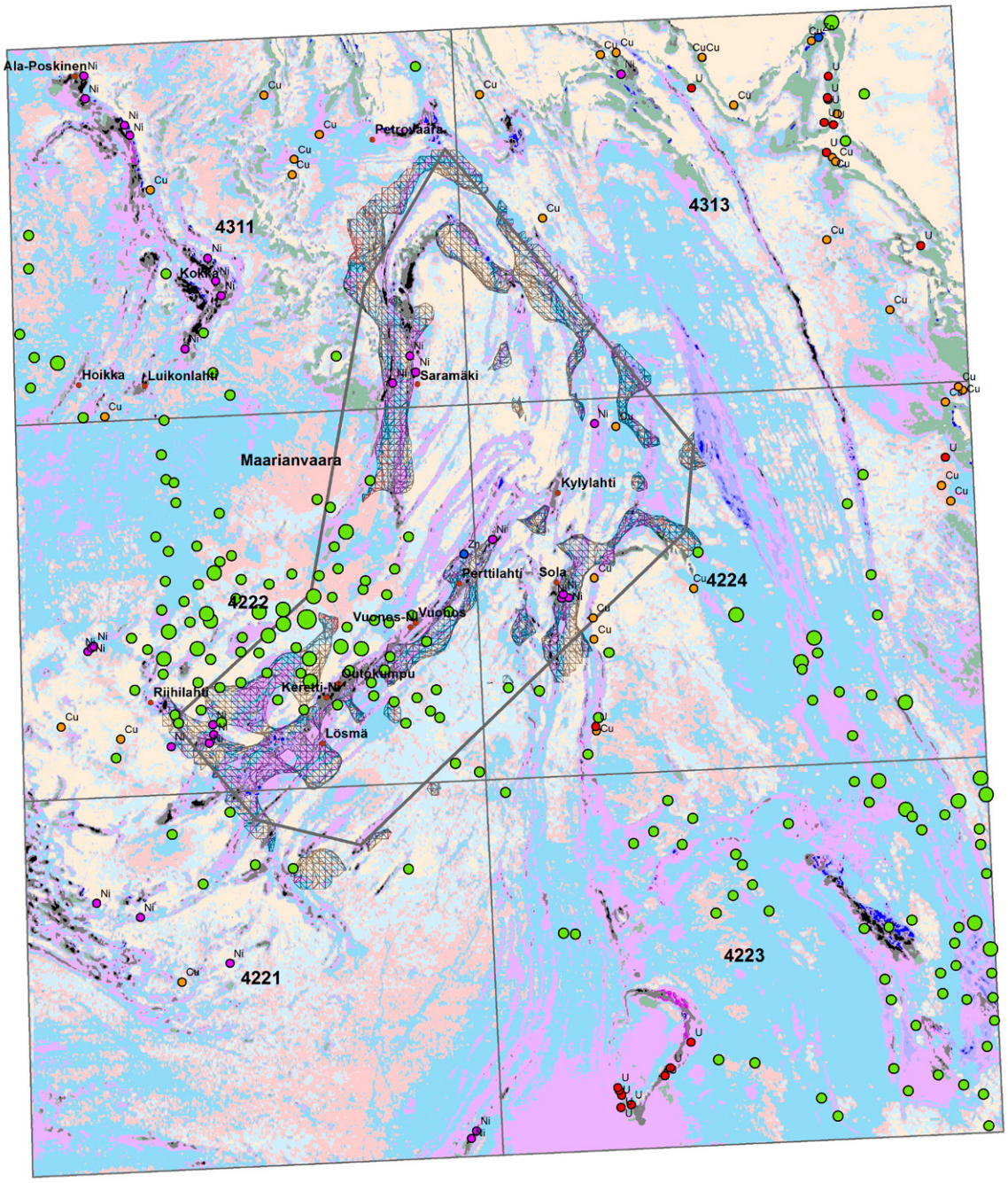

Fig. 9. A 2D GIS view combining the two 2D geophysical GIS raster models from Figures 5 and 6, 2D GIS data on lithium anomalies in till within a range of 24 to 95.9 ppm from Figure 8, and 3D ZTEM inversion results (Kurimo et al. 2016, Lahti et al. 2016) interpolated with a cut-off value of 750 Ωm in a 3D grid (grey mesh), see also Figure 11. Base map: pseudo-lithological map from Figure 4.

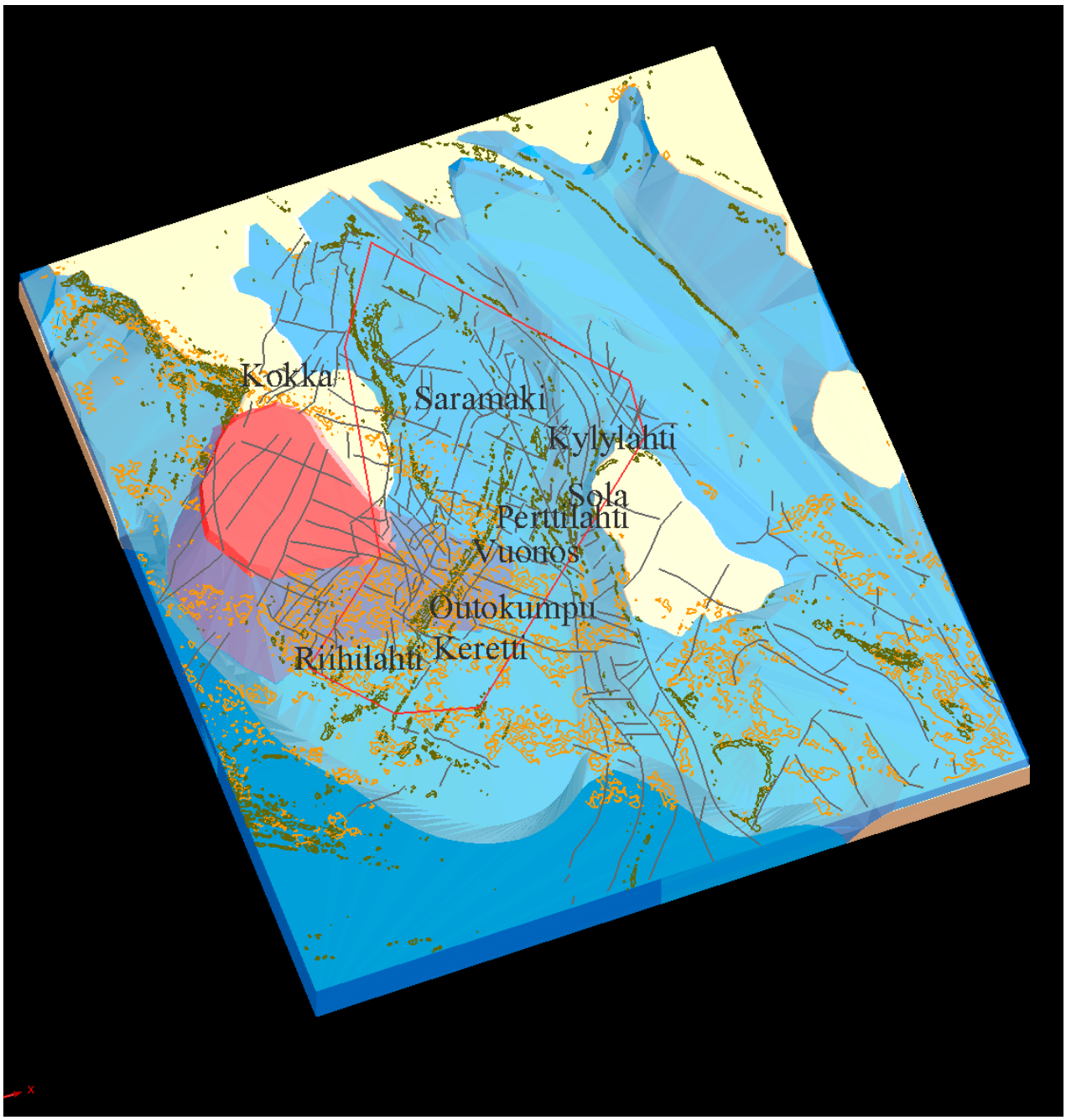

Fig. 10. Regional 2D GIS prospectivity models with cut-off contours can be presented in same space, for example, with 3D geological models to further visualize the prospectivity scenarios in a 3D geology and mine planning software application. In this example, the main bedrock geological units of the Outokumpu Mineral District were visualized as 3D solid models (beige = Archaean basement, transparent blue = Palaeoproterozoic metasedimentary rocks and red = Maarianvaara granitoid). An example of an Outokumpu-type fuzzy logic GIS prospectivity model (orange contour = model cut-off value) based on geophysical and geochemical data of the Outokumpu Mineral District is visualized on top of the 3D geological solid model. The bedrock geological and fault interpretation were based on digital bedrock map of Finland (Bedrock of Finland - DigiKP), gravity map of GEOMEX project (Ruotoistenmäki 2006), pseudo-lithological interpretations of this study, and aerogeophysical raster data (Airo et al. 2014). The dimensions of the 3D solid model in this figure caption are about 80 km x 120 km x 5 km, corresponding to the 2D prospectivity modelling area of this article.

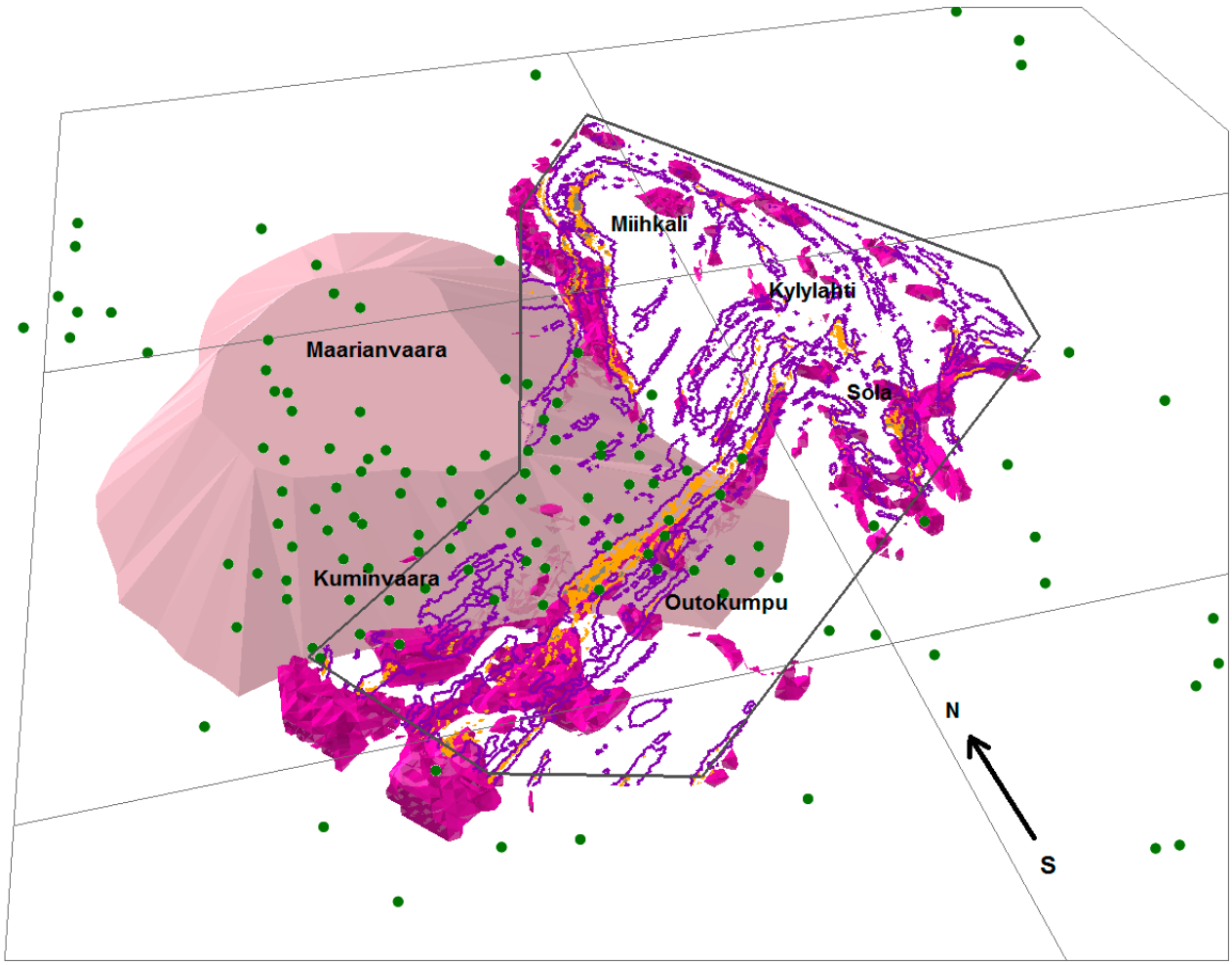

Fig. 11. A figure caption of Outokumpu-type serpentinite-skarn model (grey-orange pixels), interpolated ZTEM 3D inversion (Kurimo et al. 2016) results with with a cut-off value (deep purple), and lithium in till visualized in a common 3D GIS scenery with a solid model of Maariavaara granite (pink). The ZTEM model data reveal some unknown zones of deep conductivity beneath the Earth's surface, e.g. the anomalous belt in Kuminvaara between the main Outokumpu Belt and Maarianvaara granitoid. Outlining of the research area as in Figure 2. Depth extent of the model ca. 2 km.

DISCUSSION

Underexplored hydrothermal nickel-(± PGE) prospectivity of the Palaeoproterozoic Outokumpu ophiolite regime

Global context of hydrothermal nickel-(PGE) deposits

Interest in hydrothermal-remobilized type nickel-(PGE) deposits and systems has increased in recent years (González-Álvarez et al. 2013). The hydrothermal multi-metallic nickel ore type potential in collisional or accretionary environments of different ages related to mafic-ultramafic magmatic and ophiolitic rocks has been identified, for example in North and South Africa (Ghorfi et al. 2008, Markwitz et al. 2010), Canada (Chen et al. 1993, Heaman et al. 2009, Laznicka 2010), Western Australia (Pirajno et al. 2016) and in Russia (Grokhovskaya et al. 2009). Proterozoic Ni-PGE remobilizing hydrothermal processes and mineralization have also been detected in sediment-hosted environments (Distler et al. 2004), such as unconformities having U-Au potential (McCready et al. 2004, Cuzens 2010). Many of these deposits have world-class mineral potential.

According to the composite data, updated regional exploration vectors of remobilized hydrothermal Ni-(±PGE) deposits and the preliminary spatial modelling results of this study imply that many of these global features can be identified from Outokumpu-type deposits (e.g. Kokka, Vuonos, Horsmanaho and Vasarakangas at Kylylahti, too.

Table 3. Hydrothermal Ni–Cr–(±PGE) deposits detected from Proterozoic to Palaeozoic collisional or accretionary environments. This particular branch of mineral occurrences has a variety of ages and deposition environments.

Mineral system	Location	Ore type	Age (ca. Ma)	Domain	Reference
Avebury	McIvor Hill Complex	Low Cu, Ni with W, Pb, Bi, Mo, Sn, Sb and Au, Cr-spinels	510-390	Collision between a passive continental margin and intra-oceanic arc, later granitic intrusions. Ultramafic body, local skarns, contact aureole of a granite	Lisitsin et al. 2013
Sukhoi Log	Lena Goldfield, Boidabo Synclinorium	Multi-stage origin with a late metamorphic overprint	516–320	Thrusted passive margin sequence connected with ophiolites	Distler et al. (2004), Pirajno (2009)
Bou Azzer	Anti-Atlas, Morocco	Chromitite alteration, Co-Ni-As sulphide, low in PGE	788–305	Ophiolite under sedimentary cover	Ghorfi et al. (2008)
Coronation Hill, Rum Jungle Mineral Field	Pine Creek, Northern Territory, Australia	U-Au-PGE, Ni-Co pyrite	1607	Unconformity, mafic magmatism, reduced basement lithologies	Mernagh et al. (1998), McCready et al. (2004), Cuzens (2010), Orth et al. (2014)
Thompson Mine, Ospwagan Group	Thompson Nickel Belt, Manitoba, Canada	Ni-Cu-PGE sulphide mineralizations, PGE-Au sulphosalts	1880	Ultramafic sill – sediment complexes, intensive remobilization	Chen (1993), Heaman et al. (2009)
Kokka (Figs. 2, 4 and 7)	Outokumpu Mineral District, Eastern Finland	Co-bearing, weak Ni mineralization (PGE?) in skarn or contact of serpentinite, black schist	1970	Allochthonous ophiolite	Inkinen (1969), Koistinen (1976), Jokela (2012)
Sikomäki open pit, Vuonos Ni Mine (Figs. 2, 4 and 7)	Outokumpu Mining Camp, Eastern Finland	Ni ore (PGE?), Co-bearing Ni sulphides-arsenides, chromite, U-bearing minerals	1970	Allochthonous ophiolite	Rauhamäki (1975), Kauppinen (1976), Hänninen (1978)
Horsmanaho	Outokumpu Mining Camp, Eastern Finland	Ni mineralization (PGE?), Co-bearing Ni sulphides-arsenides in concentration of talc mine	1970	Allochthonous ophiolite	Hänninen (1983)
Vasarakangas at Kylylahti (Figs. 2, 4 and 7)	Outokumpu Mining Camp, Eastern Finland	Chromitite, PGM, laurite, irarsite, osarsite in euhedral matrix gersdorffites	1970	Allochthonous ophiolite	Liipo (1999)
Raglan, Delta (Povungnituk Group, Chukotat Group), Purtuniq Ophiolite	Cape Smith Belt, Canada	Fe-Ni-Cu-PGE mineralization	1999	Ultramafic-mafic differentiated bodies, sedimentary rocks	St-Onge & Lucas (1994), Scott et al. (1998)
DeGrussa, Red Bore, Doolgunna (?)	Narracoota-Karalundi, Bryah-Yerrida, Australia	Cu and Au mining and exploration (PGE potential not reported, but possible?)	2020	Ophiolite under sedimentary cover, thrusted	Enterprise Metals Limited (2015), Pirajno et al. (2016)
Monchetundra	Pechenga-Imandra-Varzuga Rift System	Hydrothermal complex and multiphased secondary PGE	2495	Tectonized, intense and long magmatic activity, layered ultramafic rocks	Grokhovskaya et al. (2009)

Some of the potential mineral systems are related to the marginal hydrothermal mineralization processes of primary Ni deposits (e.g. Thompson, Purtuniq and Monchetundra). (Table 3).

During rifting and in accretionary orogens of Palaeoproterozoic age, existing or forming metal deposits were affected by complex processes related to deformation, metamorphism or even partial melting, causing various types of hydrothermal activity (Bierlein et al. 2009, Sharma 2009, Singh et al. 2016). Hydrothermal processes related to Palaeoproterozoic continental growth and cyclicity of shearing-controlled remobilization of chromium and PGE of chromites have been described, for example, from the Archaean Singhbhum craton – Palaeoproterozoic Singhbhum Mobile Belt, India (Mondal 2009).

In Finland, the role of structural processes in Ni-PGE remobilization was already identified in the 1970s at the Hitura nickel sulphide mine, Nivala, where PGE mineralization in the Palaeoproterozoic, originally sill-like ultramafic intrusive cumulate nickel ore deposit was detected to be controlled by hydrothermal processes, and shearing or contacting structures in sulphide enriched layers and veins (Häkli et al. 1976, Makkonen et al. 2011), with secondary PGM (Kojonen et al. 2004).

The role of chromium in the Outokumpu-type mineral concept

Mozier et al. (2012) have thoroughly described the USGS concept of global podiform chromitite metallogeny and potential and according to their work, podiform chromitites in ophiolites mainly occur within ultramafic rocks near cumulate contacts or tectonic zones, and they may indicate enrichment of PGEs (Table 4).

Palaeoproterozoic continental passive margins and accretionary orogens (Condie 2002, LIP Commission 2016) related to the Cr-(Ni)-PGE potential in podiform chromitites in 2.2 Ga highly differentiated karjalitic sills occur worldwide. Karjalites of the same age range also exist in the Outokumpu Mineral District (Vuollo et al. 1995, LIP Commission 2006, Knauf et al. 1999, Pekkarinen et al. 2006). Their origination may have a resemblance, for example, with the conditions in the Palaeoproterozoic margins of Singhbhum Craton (Singh et al. 2016). Hanski (2015) has described the primary metallogeny of the Outokumpu Palaeoproterozoic ophiolites from formation to the final breakup of the Kenorland supercontinent. Later Palaeoproterozoic multi-phased Cr-Ni-(PGE) alteration, remobilization or accumulating processes in mafic-ultramafic Outokumpu-type ophiolites have been described and conceptualized by Knauf et al. (1999), Kuronen et al. (2004), Kontinen et al. (2006), Säntti et al. (2006) and Peltonen et al. (2008).

Hydrothermal remobilization of the original PGE mineralogy of Outokumpu chromitites by PGE-gersdorffites is suggested to be linked with regional metamorphism after the formation of chromitites (Knauf et al. 1999). Regional thermal activity is also supported by the metasomatic alteration or even breakdown of chromite described by Säntti et al. (2006). Later hydrothermal replacement of the original PGE minerals reveals that PGE-related cobaltoan gersdorffite ((Ni,Co)AsS) could be an interesting pathfinder mineral for PGE prospectivity in the Outokumpu region. However, the economic value of the PGE in the Outokumpu region remains unknown due to insufficient information (Knauf et al. 1999).

In this study, at least two or three different kinds of chromium-bearing, structure-controlled PGE mineralization-favouring processes could be identified in the Outokumpu region that are presently intermingled in the same geological space (Figs. 7 and 8). Firstly, karjalites may include some PGE minerals (Srivastava et al. 2014). Secondly, ophiolite complexes may have chromitite pods enriched in PGE when they are sulphide-bearing (Prichard & Brough 2009). Chromitite pods with PGE minerals have been detected in the Outokumpu ophiolite complex by Vuollo et al. (1995), Liipo et al. (1998), and Liipo (1999) at Vasarakangas. The ophiolite bodies also contain Outokumpu-type massive or semi-massive Cu-Co-Zn-Ni±Au sulphide potential in ophiolite assemblages, which have been identified to belong to this geological context (Peltonen et al. 2008, Hanski 2015). Thirdly, later nickel-PGE remobilization connected with the disintegration of podiform chromites in cobalt-bearing hydrothermal mineralization processes has been identified near Outokumpu by Knauf et al. (1999).

The Outokumpu-type polymetallic sulphide ores are strongly remobilized and tectonized, and they seem to have received their metals from ultramafic rocks, and a minor part of the sulphur from black schists (Peltonen et al. 2008, Saalmann & Laine 2014). Hydrothermal alteration in the

Outokumpu Mineral District may have been related to regional metamorphism or late orogenic magmatic activity during the Svecokarelian orogeny, represented by ca. 1.86 Ga old Maarianvaara granitoid (Huhma 1986, Peltonen et al. 2008) and possibly Kitee-type granite pegmatites (Figs. 8–11). These magmatic events may have impacted on the podiform chromitites, chromites or chromium-bearing magnetites, also altering or remobilizing the possible PGE in them.

Additional pathfinder proxies for targeting the exploration of hydrothermal Ni-(PGE) in the Outokumpu Mineral District

Although zones and locations prospective for Outokumpu-type mineralization can be traced quite easily with geophysical anomalies at the regional scale, unfortunately they do not help in distinguishing or targeting the individual trace metal potential in them without geochemical or mineralogical parameters. For targeting trace metal mineralizations, lithogeochemistry or geochemistry of till may provide more detailed characteristics of the prospective spots (Tables 1 and 4). The regional till geochemistry data may reveal the presence of regional hydrothermal alteration more clearly than lithogeochemistry of less altered bedrock *in situ*. It is likely that metal anomalies of till generally originate from fragmented and weathered boulder material dispersed geographically and topographically by glaciogene forces (Fig. 8). Some of the weathered or secondary mineral material in till originating from the exotic mineralogy of bedrock may dissolve more easily with acids than fresh rock samples.

A few additions to the conceptual exploration model of Outokumpu-type hydrothermal-remobilised multi-metallic Ni-Cr-(PGE) mineral systems in the Outokumpu Mineral District can be made based on the features of analogous deposits elsewhere. Some of these exploration vectors (Table 4) resemble quite closely those developed for younger analogies (e.g. Grapes & Palmer 1996, Lisitsin et al. 2013, Rajendran & Nasir 2014, Cooper & Ireland 2015). As podiform chromitites are known to occur in Vasarakangas (Tables 3 and 4), in the Outokumpu case a surface or zone of chromitite pods could be used as a structural constraint in interpreting the boundaries of the ophiolite complex, as was predicted in the model presented in Figure 7. Nikkarinen & Salminen (1982) have developed a heavy mineralogical exploration proxy for till material connected to Outokumpu serpentinites. According to them, the abundance of tremolite and iron sulphides together with uvarovite can be used as pathfinder minerals in the bottom till material tracing the Outokumpu serpentinites. It should be noted that uvarovite is lacking from lower amphibolites facies environments, such as Kylylahti, Sola and the northern part of Miihkali (pers. comm. Asko Kontinen). Cameron & Hattori (2005) have compiled specifications for exploring PGE in surface environments, e.g. with Quaternary cover materials. Mernagh et al. (1998) have suggested the U^2/Th ratio of airborne radiometrics to regionally uncover the unconformity type U-mineral sources caused by hydrothermal remobilization by metamorphism or granitic magmatism. Recently, Lehtonen et al. (2015) have developed new laboratory technologies and procedures for more cost-effective indicator mineral (e.g. PGM) exploration.

Regionally and, in places, in connection with some of the Outokumpu-type ore deposits, secondary chromium and boron have both been concentrated enough to form, for example, dravite-elbaite-type Cr-bearing tourmalines (Outokumpu dravite and Kaavi Cr tourmaline (Peltola et al. 1968, Hytönen 1999)). Maarianvaara granitoid or later pegmatites related to the shear zone in Outokumpu show complex geochemical characteristics in places, e.g. chromian Na-Mg tourmaline dravite, and hydrothermal or otherwise secondary Cr minerals in Outokumpu-type skarns (Peltola et al. 1968). The presence of high chromium in high-grade silicate minerals in the Outokumpu mining area implies derivation from the original chromites and the migration of the released chromium into new minerals either in regional or contact metamorphic processes. Further disintegration of possible secondary chromium minerals can be witnessed, for instance, as anomalies of easily leachable (aq. reg.) chromium possibly of silicate origin in till (Fig. 8) or as overprinting of remobilized Cr-bearing hydrothermal minerals on the walls of underground museum tunnels of the closed Outokumpu mine (Fig. 12).

The role of Maarianvaara granitoid in the Outokumpu-type ore deposition style has once again come under discussion after a few decades of silence (pers. comm. Urpo Kuronen and Jarmo Vesanto). After the formation of the mineralized

Table 4. Some complementary suggestions of features that could be useful as exploration vectors for the Ni-Cr-(PGE) potential mapping of Outokumpu-type deposits.

Mineralization style	Pathfinder mineralogy	Significance in the concept	Study material	Exploration proxy for prospectivity modelling	Reference
Outokumpu assemblage	Pentlandite, cobaltoan minerals	Significant at the targeting scale	Ni-Co anomaly in till	Ni/Co ratio in heavy mineral fraction of till	Nikkarinen & Salminen (1982), Kontinen et al. (2006)
(Podiform) chromite > remnants and secondary Cr minerals due to hydrothermal alteration > strain-related Cr-Ni-(PGE?)	Chromite, uvarovite, Cr-bearing mica etc. Hydrothermally altered Cr minerals and Ni-sulphides in tectonized quartz rocks of the Outokumpu assemblage	Original deposit style minor. It would be indicative in targeting or deposit-scale exploration of altered zones	Cr anomaly in till	Acid-soluble Cr	Vuollo et al. (1995), Knauf et al. (1999), Aatos et al. (2006), Säntti et al. (2006), Prichard & Brought (2009), Mosier et al. (2012)
Remobilized Ni-PGE	Co-gersdorffite, Ni-arsenides	Original deposit style minor, but indicative on the regional to deposit scale	Ni-As anomaly in till, Pd in humus	Identification of potential minerals, metal distributions in them	Knauf et al. (1999), Cameron & Hattori (2005)
Primary and secondary Ni deposits	Secondary magnetites depleted of Ni and Cr	Detection of eroded Ni–Cu–PGE deposits under e.g. Quaternary sedimentary coverage	Differentiated or altered composition of magnetite in surficial sediments	Trace element distribution of magnetites	Boutroy et al. (2014)
Strain-related Cr-Li-B, can also be found in the Outokumpu Mineral District	Dravite, Cr-Li-bearing mica, corundum	Structural-genetic interest in case of serpentinites. In case of pegmatites, may indicate economic Li deposits	Cr-Li anomaly in till	Acid-soluble Cr, Li	Peltola et al. (1968), Grapes & Palmer (1996), Hytönen (1999), Cooper & Ireland (2015)

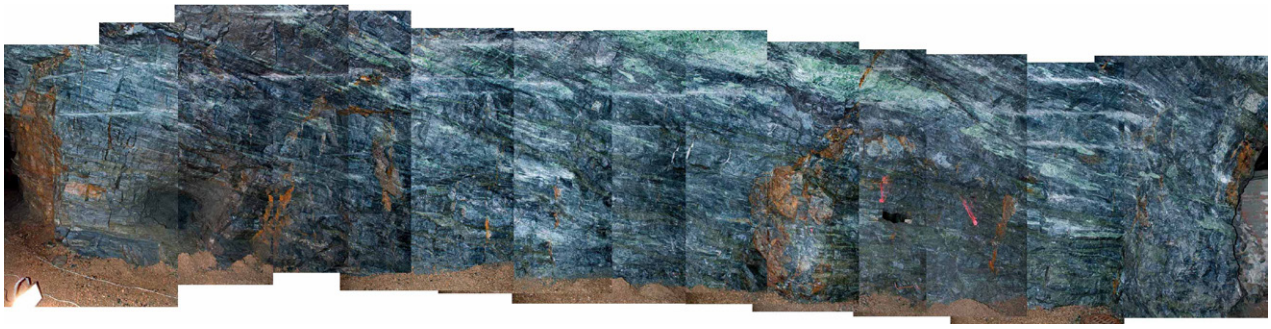

Fig. 12. Remobilization of chromium can be observed, for example, in the barren rock walls of a driven tunnel in the Outokumpu mine museum, Outokumpu, Finland. The green wedge-shaped bodies dipping gently from left to right on the upper right edge of the image set contain abundant secondary chromium minerals other than chromite (photo collage by Esko Koistinen, GTK).

protolithic mafic-ultramafic – sedimentary sequences, later Paleoproterozoic orogens may have involved granitic – alkaline magmatism enriched with REE, Th and U, and having economic potential for lithium (LCT-type pegmatite dykes containing, for example, tourmaline). One example is the Trans-Hudsonian Wekusko Lake pegmatite field in the Flin-Flon domain, Manitoba, Western Canada. (Manitoba Geological Survey 2015)

According to young metasomatic Cr-Li-B analogies from the Pounamu Ultramafic Belt in New Zealand, Cr-Li-bearing minerals can be encountered in collisional metamorphic fault zones of LIP plateau-originated allochthonous ultramafics, although the mobility of Cr and introduction of external B and Li by granitic alkaline fluids from continent-derived sources may be needed to explain the abundance of, for instance, chromian minerals in this zone. (Grapes & Palmer 1996, Cooper & Ireland 2015)

The Tohmajärvi region further southeast of the Outokumpu Mineral District is known for its Li pegmatites, being part of the Kitee granite (Alviola 1974). Li-bearing minerals found in till in the Tohmajärvi region are mostly biotites rich in lithium (Nikkarinen & Wennerström 1982). Outside this study's scope and without any further investigations, these ideas concerning metamorphic lithium enrichment or potential complex pegmatites in the Paakkila-Kuusjärvi area of the Outokumpu Mineral District remain untested.

Outokumpu and Miihkali nappes involve differences in lithology

The GIS fuzzy logic prospectivity models presented in this study (Figs. 7 and 8), based on regional till (Salminen et al. 1995) and bedrock lithogeochemistry (Rasilainen et al. 2007, 2008), indicate that Ni and Cr anomalies do not fully correlate with each other geographically, e.g. between Outokumpu and Miihkali nappes. According to the pseudolithological model presented here (Figs. 4 and 13), the metasedimentary rocks of the Miihkali and Outokumpu nappes have differing geophysical characteristics compared with each other, also implying differences in geology. The main cause for this may be different geological settings with diverging physico-chemical conditions of sedimentation or metamorphosis of metasedimentary rock units, probably caused by tectonic effects on the present stratigraphic positioning. In addition, some later tectono-magmatic events with complex hydrothermal activities after deposition following proto-ore may also have caused or enhanced the incoherent spatial distribution of chemical elements regionally (Figs. 2, 7-13).

Miihkali could have reserved more of its original ultramafic Ni-(PGE) potential and integrity towards the thermo-chemical effects caused by the granitic - alkaline magmatic or metamorphic fluids containing differentiated or dissolved base metals and U compared to the ultramafic bodies in contact with graphite schists in the Outokumpu nappe. The surface part of the Miihkali nappe area may have been stratigraphically or spatially more distant than the Outokumpu nappe, or weakly or not affected, for instance, by the regional metamorphic fluids or the Maarianvaara granitoid or younger pegmatite granite fluid fluxes, unless these dynamics could be evidenced in deeper parts of the Miihkali lithodeme.

If the Outokumpu and Miihkali nappes were of the same lithological origin, the Outokumpu ore belt could have been similar to the Miihkali type ultramafic formation, until it was exposed to the end phase of the collision-related thermal sources (Maarianvaara granitoid and younger pegmatites) or surficial fluids (fluxing agents, noble elements, Co, U, Li, B and others) (mobile Cr, Ni and possibly PGE), but at present it could be tectonically dislocated compared to the Miihkali basin. If the Miihkali basin showed fewer indications of hydrothermal remobilization of the original nickel and chromium, it could be considered as being more of an original mantle formation and a less tectonized upper thrust slice of the Outokumpu allochthon than the Outokumpu nappe.

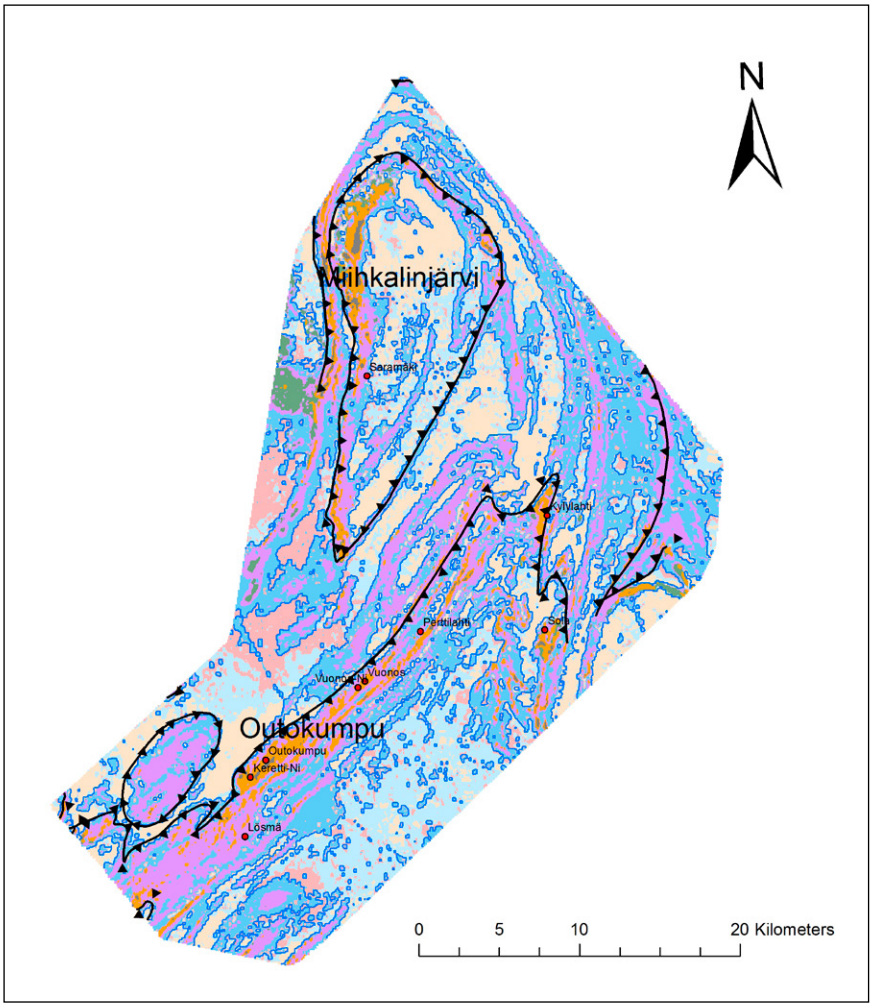

Fig. 13. The interpreted metasedimentary units of Outokumpu (dominated by blue) and Miihkali nappes (more beige than blue) differ from each other in geophysical characteristics, as indicated in this excerpt of a pseudo-lithological map of inferred Outokumpu assemblage (Fig. 5) of the Outokumpu Mineral District coinciding with the Outokumpu Mining Camp and the ZTEM flight area. Interpreted thrust faults are shown by triangulated lines (Bedrock of Finland - DigiKP). Inside the nappes, Outokumpu-type anomalies of ultramafic rocks and skarns are indicated by grey and orange colours, respectively. Base map: pseudo-lithological map from Figure 4.

CONCLUSIONS

In this study, supplementary exploration vectors were added to the previous concept of the Outokumpu-type Cu-Co-Zn mineral deposit model based on new exploration knowledge of collisional or accretionary ophiolitic environments. These include the role of remobilized chromium, lithium and PGE as possible indicators of hydrothermal nickel (±PGE) and lithium deposits in the Outokumpu-type geological setting.

The Palaeoproterozoic regime of the dismembered ophiolitic Outokumpu nappe complex, consisting of Outokumpu and Miihkali nappes piled up on each other, includes potential for Red Sea-Oman-type Cu-Co-Zn-Ni metallogeny in a highly tectonized and remobilized environment. Olivine in the ophiolites was hydrated to serpentines, which in turn may have disintegrated and donated their nickel in the regional metamorphic processes to form conductive sulphidic minerals with external sulphur from sedimentary sources. In the serpentinization process, magnetite was also formed, making the ultramafic rocks magnetic in their present form in their regional tectonic setting. Regional metamorphic and later granitic – alkaline magmatic fluid activity launched by accretionary or collisional tectonic events may have remobilized and enriched parts of the nickel- and cobalt-bearing sulphides to form secondary

multi-metallic hydrothermal nickel type sulphide deposits, in which elevated PGE may or may not also occasionally be met. Zones enriched in sometimes exotic, hydrothermal or metamorphosed secondary chromium minerals originating from altered or decomposed chromites formed in the highly sheared footwalls of the Upper Kalevian Outokumpu nappe complex, which was thrust onto the Archaean basement covered by Lower Kalevian metasedimentary rocks. The existing Outokumpu-type mineral deposit model could be slightly updated with a hydrothermal nickel-(±PGE) deposit concept, developed based on its essential characteristics as identified worldwide. Structural proxies to delineate the boundaries of the Outokumpu nappe complex units in exploration were introduced by taking into account the chromite-bearing rock units as a structural constraint. Exotic secondary chromium minerals originating from chromite, such as dravite or other Cr-bearing silicates, could perhaps be used as indicators of tectonic high strain zones related to Outokumpu-type ophiolite constraining structures. Remobilized hydrothermal nickel-(±PGE) mineralizations may provide a complementary pathfinder feature to the structural boundary controls of the Outokumpu-type ophiolitic units. In addition to this, a regional-scale Li-anomaly detected around Maarianvaara granitoid in the western part of the research area was tentatively hypothesised as being related to younger pegmatite granites.

Interpretation of the metal prospectivity of the Outokumpu region was replenished by using GIS fuzzy logic modelling to compile and further develop conceptual and GIS prospectivity analysis of the region based on the electric, magnetic, radiation and geochemical properties of the geological surface materials, such as bedrock and till. A GIS fuzzy logic approach and other GIS tools were used in geophysical and geochemical data processing and in integrating computational mineralogy and modelling-based geological inference data with more conventional exploration data. Computational interpretation was used to help improve the surficial geological and ore prospectivity interpretation for deep exploration purposes.

Computational GIS analysis tools integrating aerogeophysical and surface geochemical data can also be used as delineating aids in the orienting phase of deep exploration of hydrothermal multi-metallic nickel-(±PGE) potential in brownfields at the regional scale. Computational pseudo-lithological interpretation may serve as one additional source of distinguishing information for geological and structural mapping in regions where an abundance of a seemingly monotonous single rock type dominates the geological interpretation, like the Palaeoproterozoic schists and gneisses do in the Outokumpu Mineral District. Pseudo-lithological and prospectivity interpretation layers can be used as surface faces of 3D exploration cuboids for further 3D prospectivity modelling or integrative visualization of different earth model data elements in 3D.

According to the prospectivity analysis of this study and the available regional GIS data, interesting metal-bearing geochemical anomalies were detected related to Outokumpu-type geophysical conductive and magnetic, as well as U anomalies in compliance with the regional 3D geological and exploration interpretations modelled in this project. The pseudo-lithology approach may provide some aid in locating mafic-ultramafic rocks and interpreting lithological variation in abundant, monotonous-looking schist areas in the Outokumpu Mineral District.

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