

3D MODELLING OF OUTOKUMPU ASSEMBLAGE ROCKS – A GEOSTATISTICAL APPROACH

by

Eevaliisa Laine

Laine, E. 2016. 3D modelling of Outokumpu assemblage rocks – a geostatistical approach. *Geological Survey of Finland, Special Paper 59*, 139–162, 20 figures.

The targets of the present 3D modeling study are the middle part of the Outokumpu assemblage and Sola mineralization in the Outokumpu ore district in Eastern Finland – a metallogenic province about 100 km long x 60 km wide – hosting a Palaeoproterozoic sulfide deposit. Cu–Co–Zn–Ni–Ag–Au sulfide ores are associated with Palaeoproterozoic ophiolitic metaserpentinites derived from depleted mantle peridotites that were subsequently tectonically interleaved with allochthonous metaturbidites. The metaperidotites have been extensively altered to quartz–carbonate–calc–silicate rocks which are called as Outokumpu assemblage. The aim of the present study was to visualize, model and analyse structures related to Keretti, Vuonos and Sola sulphide mineralizations. The methods included 3D geological modelling and geostatistical simulation by using geological cross sections, drill core data, seismic profiles and the helicopter–borne Z-axis tipper electromagnetic (ZTEM) inversion results. 3D visualization of 3D inversion results of ZTEM measurements were used together with the earlier fault interpretations to define large crustal discontinuities of 10–30 km in length. Geological structures and lithological heterogeneity was studied by using geostatistical variogram analysis and turning bands and sequential indicator simulations. The unfolding of drill core data was done by flattening the gently folded geological layers. This unfolding process made it possible to model anisotropy parallel to layering. As a result, geostatistical simulations applied to metal contents and rock types as categorical variables indicate lithological heterogeneity and the elongation of rock units and mineralizations striking parallel to Outokumpu assemblage and very little continuity perpendicularly to the observed elongation. In addition, faulting and major shear zones divide the Outokumpu assemblage into separate blocks which differ structurally and geochemically from each other and with small relative displacements. However, these small displacements may affect thin (~10 m) ore bodies, and make the ore exploration in the Outokumpu area challenging.

Keywords: three–dimensional models, geostatistics, Finland

Geological Survey of Finland, P.O. Box 96, FI–02151 Espoo, Finland

E–mail: eevaliisa.laine@gtk.fi

INTRODUCTION

The target of the present 3D modelling study is the Outokumpu assemblage located in Eastern Finland (Fig. 1) in the Outokumpu ore district – a metallogenic province about 100 km long x 60 km wide – hosting a Palaeoproterozoic sulfide deposits (Cu-Co-Zn-Ni sulfide ores) characterized by an lithological association called Outokumpu assemblage. The aim of this study was to build regional (study area A; Fig. 1) and camp scale 3D geological models (study areas B-E; Fig. 2) using geological cross sections, drill core logs, structural geological observations and geological maps in order to analyse structural controls of sulphide mineralizations in the Outokumpu area. Geostatistical tools were tested to characterize and visualize the geological structures found surrounding the ore mineralizations. The traditional 3D modelling and visualization was combined with geostatistical simulations of subsurface rock type distributions. The present work uses the earlier built 3D geological models, and fault and shear zone interpretations by Saalman & Laine (2014) to unfold data and divide interpolation grids for geostatistical analysis and simulation. The resulted geostatistically simulated realizations of subsurface geology are not locally accurate but they

reproduce the modelled spatial correlation and data variability. Together with traditional 3D geological modelling, geostatistical simulations makes it possible to create and test several different alternative 3D voxel representations for subsurface geology. Hundreds of alternative voxel models representing the subsurface geology may be used to quantify the uncertainty. There are several different simulation approaches, such as turning bands (Mantoglou and Wilson 1982), sequential indicator (Journel & Alabert 1990, Journel & Gómez-Hernández 1993), multiple-point (Strebelle 2002), truncated Gaussian (e.g. Allard 1994) and plurigaussian (Armstrong et al. 2011) simulation. Geostatistical simulation can be applied to study lithofacies or rock type distributions of mine sites or mining camps (e.g. Schetselaar 2013).

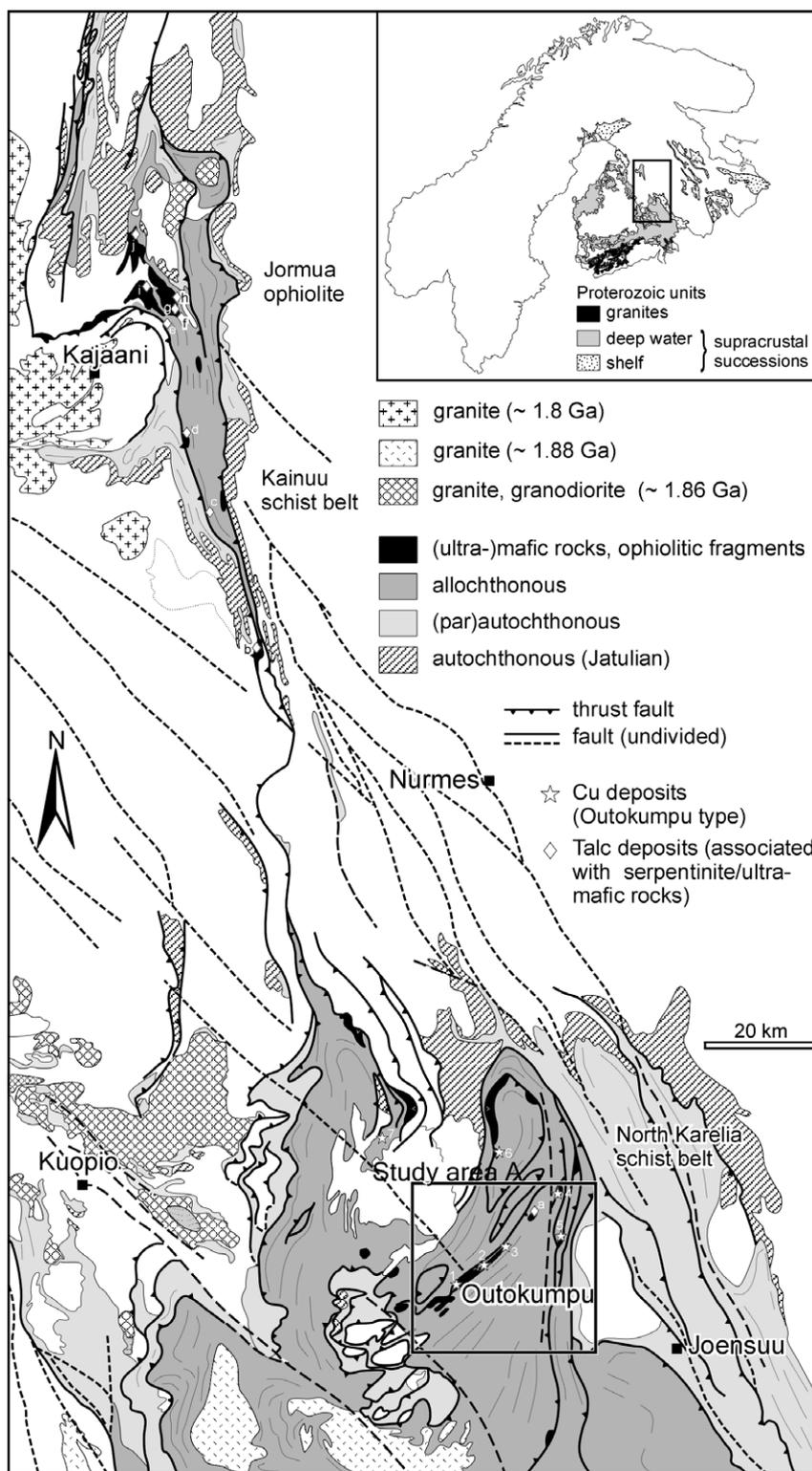
Despite of data sparsity and complex geology, geostatistical simulation techniques were tested with selected data sets from the Outokumpu area. The ZTEM (Z-axis tipper electromagnetic system) 3D inversion results (Kurimo et al., this volume) were used to model large fault zones in order to find new possible targets for ore exploration in the Outokumpu area.

GEOLOGICAL SETTING

Outokumpu assemblage comprises of lens-shaped serpentinized mafic and ultramafic bodies and their alteration association including tremolite- or diopside bearing calcite, dolomite and quartz rocks, fuchsite, tremolite and uvarovite (Peltonen et al. 2008). Outokumpu assemblage (Fig. 1) is located in the North Karelia Schist Belt, which was thrust on the late Archaean gneissic-granitoid basement of the Karelian craton during the early stages of the Svecofennian Orogeny between 1.92 and 1.87 Ga (Koistinen 1981). Two major tectono-stratigraphic units can be distinguished, a lower, parautochthonous ‘Lower Kaleva’ unit and an upper, allochthonous ‘Upper Kaleva’ unit or ‘Outokumpu allochthon’. The latter consists of tightly-folded deep marine turbiditic mica schists and metagraywackes containing intercalations of black schist, and the Outokumpu assemblage, which comprises ca. 1950 Ma old, serpentinized peridotites surrounded by carbonate-calc-silicate (‘skarn’)-quartz rocks. Late tectonic solid-state remobilisation, related to the duplexing of the ore

by isoclinal folding, upgraded the sulphides into economic deposits.

The studied Keretti and Vuonos orebodies, and Sola sulphide mineralisations are enclosed in the Outokumpu assemblage, which is thought to be one part of a disrupted and incomplete ophiolite complex (Vuollo & Piirainen 1989) that can be traced to the Kainuu schist belt (Fig. 1) further north where the well-preserved Jormua ophiolite is exposed (Kontinen 1987, Peltonen & Kontinen 2004). In general, ophiolites have been defined as “suites of temporarily and spatially associated ultramafic to felsic rocks related to separate melting episodes and processes of magmatic differentiation in particular oceanic tectonic environments” by Dilek & Furnes (2011). Their geochemical characteristics, internal structure, and thickness are strongly controlled by spreading rate, proximity to plumes or trenches, mantle temperature, mantle fertility, and the availability of fluids. The age distribution of ophiolites displays pronounced maxima during the time intervals 50–200 Ma, 450–1000 Ma,



Cu deposits: Outokumpu/Keretti (1), Vuonos (2), Perttilahti (3), Kylylahti (4), Sola (5), Saramäki (6), Luikonlahti (7).
Talc deposits: Horsmanaho (a), Alanen (b), Uutela (c), Lahnaslampi/Punasuo (d), Maailmankorppi (e), Tyyhelä (f), Jormua (g), Mieslahti/Pitkänperä (h), Tiittolanvaara (i), Vasikkakangas (j).

Fig. 1. Geological map of the Kainuu and North Karelia schist belts and location of the Jormua ophiolite and Outokumpu ore district and distribution of deposits. The box outlines the study area A for the regional 3D geological model (Fig. 4). Cu deposits: Outokumpu/Keretti (1), Vuonos (2), Perttilahti (3), Kylylahti (4), Sola (5), Saramäki (6), Luikonlahti (7). Talc deposits: Horsmanaho (a), Alanen (b), Uutela (c), Lahnaslampi/Punasuo (d), Maailmankorppi (e), Tyyhelä (f), Jormua (g), Mieslahti/Pitkänperä (h), Tiittolanvaara (i), Vasikkakangas (j). Modified after Säntti et al. (2006), Peltonen et al. (2008) and Saalman & Laine (2014).

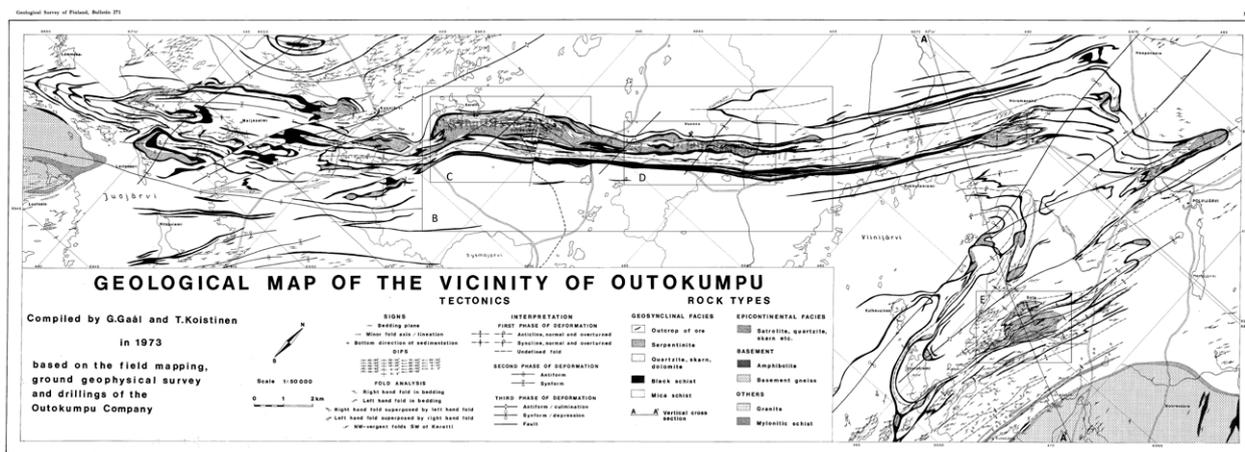


Fig. 2. The geological map after Gaál et al. (1975). Targets for 3D geological models: Outokumpu assemblage rocks (area B); Keretti ore body and surrounding rocks (area C); Vuonos ore body and surrounding rocks (area D); Sola serpentinite (area E).

and 2500–2750 Ma. Outokumpu assemblage rocks represent the rare occurrence of early Proterozoic ophiolites. In addition to Finland, early Proterozoic ophiolites have been reported from Canada (Scott et al. 1992).

The Keretti orebody was discovered in 1910 following a recognition, in 1908, of a large ice-borne boulder 50 km to the SE (Trüstedt 1921). It contained 28 million tons of ore of which 23 million tons was extracted by the end of 1980. The Keretti Cu orebody is lens-shaped, ca. 4000 m long, 250 to 300 m wide, and usually less than 10 m thick, but it may attain a thickness of 30–40 m. The ore averages 3.80 % Cu, 1.00 % Zn, 0.24 % Co, 0.12 % Ni, 28.10 % Fe and 25.30 % S. The Vuonos orebody, 10 km NE of Keretti, contained 6 million tons of ore of which 4 million tons was extracted. At Vuonos, Outokumpu-type ore body is ca. 3500 m long, 50–200 m wide and an average of 5 to 6 m thick. Characteristic average tenors of metals were 2.18 % Cu, 1.38 % Zn, 0.13 % Co, 0.12 % Ni, 14.76 % S, 10 ppm Ag and 12 ppm Se. Its discovery in 1965 followed the geochemical studies conducted by Huhma and Huhma (1970). In addition, the Ni ore above the main orebody was mined. Sola is a minor sulphide mineralization at ca. 0.1 Mt at 2 wt.% Cu, 1 wt.% Zn, 0.1 wt.% Co, 0.15 wt.% Ni and 17 wt.% S associated to skarn-quartz rocks within roundish Sola serpentinite formation to the east from the main Outokumpu ore field (Fig. 2).

Regional scale structural interpretations have been conducted by several geologists. Frosterus & Wilkman (1920) presented the emplacement of allochthonous Archaean basement gneisses over Lower Proterozoic cover sequences in Eastern Fin-

land. Wegmann (1928) and Väyrynen (1939) emphasized the significance of nappe tectonics during the Svecofennian orogeny. Bowes et al. (1984) and Koistinen (1981) made a structural geological interpretation of the polyphase deformation in the Outokumpu area while Ward (1987) proposed a model for the progressive deformational history of the Outokumpu area. Kohonen et al. (1991) constructed the regional structural geological model of North Karelia including the major Proterozoic shear zone – the Nunnanlahti-Holinmäki Shear zone as well as numerous related second order structures that traverse the Outokumpu area.

Even though Outokumpu assemblage rocks form a seemingly continuous formation (Fig. 2), it has been dissected by several crosscutting discontinuities. Faulting can be seen in different scales from outcrop scale to regional structures that divide the bedrock into large blocks when cutting the former shear zones. According to Saalman & Laine (2014) thrust stacking was followed by several stages of faulting that divided the ore belt into fault-bounded blocks with heterogeneous displacements: (i) NW-dipping faults with unresolved kinematics, (ii) reverse faults along c. 50 degrees–60 degrees SW-dipping faults, and (iii) SW-NE to SSW-NNE striking faults which may have formed at an earlier stage and have been reactivated. Figure 3a shows the faulting and fracturing of the Outokumpu assemblage rocks in the Horsmanaho open pit. Keretti ore body faults have been interpreted by Saalman & Laine (2014) by using the old mine sections from GTK archives (Laine et al. 2012) (Fig. 3b). Regional faulting and shearing is shown in the Figure 3c. Ore bodies were found to be located

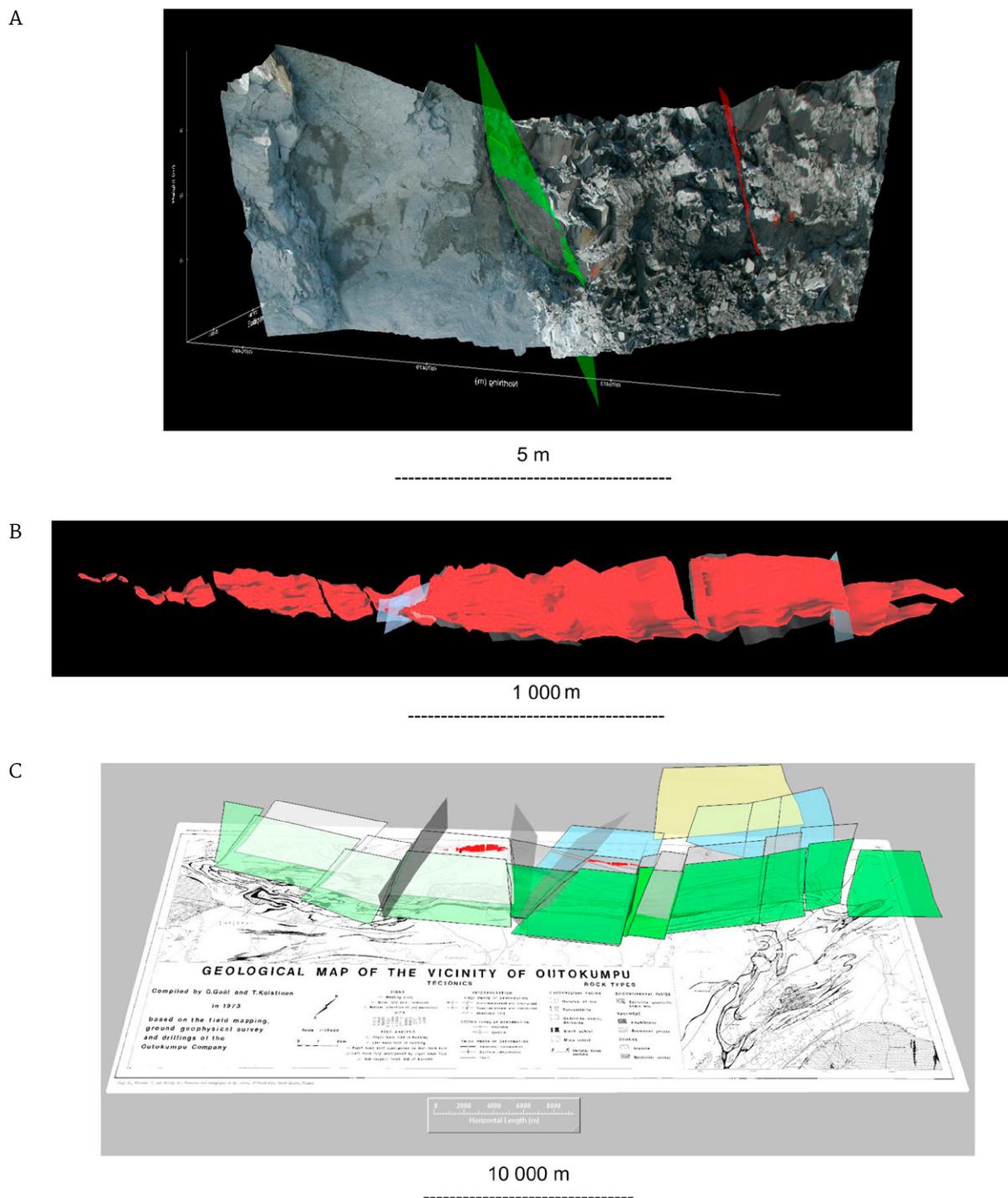


Fig. 3. Faulting in different scales. a) A Sirovision model from the Horsmanaho open pit. Photo and interpretation (Esko Koistinen in Laine et al. 2012); b) Faulting of the Keretti ore body after Saalman & Laine (2014) c) A geological map of the Outokumpu region after Gál et al. (1975) and faults and shear zones along the Outokumpu assemblage (Saalman & Laine 2014) colored according to the associated uncertainty with light colors for structures inferred solely from surface data and dark colors for structures inferred using seismic sections and surficial geological and geophysical data.

between two major shear zones and cut by several faults (Saalman & Laine 2014). According to Saalman & Laine 2014 there might have been uplift between Keretti and Vuonos orebodies, and a possible ore body has been eroded away. In addition,

the metamorphic grade of Outokumpu assemblage rocks change from high amphibolites facies in the southwest to lower amphibolite facies rocks in the Kylylahti area in the northeastern part of the Outokumpu area (Säntti et al. 2006).

DATA AND 3D MODELLING METHODS

Data

The applied structural geological framework was based on the structural observations derived from geological maps and structural geological interpretations (e.g. Gáal et al. 1975, Koistinen 1981, Saalman & Laine 2014). Lithological data were obtained from the drill core logs and mine sections (GTK database) and from the geological cross sections done by Koistinen (1981). Geochemical data consisted of Cu, Ni, Zn and Co contents along Outokumpu drill cores (GTK database).

The two geophysical data sets were used for geological interpretations and 3D visualisations,

ZTEM inversions (Kurimo et al., this volume) and seismic profiles. ZTEM is a variant of the electromagnetic (EM) airborne tipper AFMAG method (Ward 1959) for studying the electrical conductivity of bedrock in the depth range of 0–2 km. High resolution reflection seismic profiles in the Outokumpu area have been measured during the FIRE project (Kukkonen & Lahtinen 2006) and the HIRE project (Kukkonen et al. 2009). Seismic profiles have been interpreted by Saalman & Laine (2014) and the results were used in the present study.

3D modelling

The 3D modelling was done at three different scales:

1. *Regional 3D model* (study area A) was built for an interpretation of 3D ZTEM inversion results together with faults and shear zones (Saalman & Laine 2014). In addition, the regional features were investigated using schistosity (S_0 and S_1) digitized from the structural geological map of Koistinen (1981) and visualized by small discs in 3D (Mira Geoscience tools and Paradigm GO-CAD).
2. *3D model of the Outokumpu assemblage* (study area B) consisted of a fault block model and 3D visualization of the Outokumpu assemblage rocks together with ZTEM inversion results.
3. *Camp scale 3D models* were built for Keretti and Sola areas. Keretti camp scale 3D model

was built by using geological cross sections by Koistinen (1981) and Keretti ore model built by Esko Koistinen (Laine et al. 2012), and Saalman & Laine (2014). The lithological contacts were drawn using implicit approach by Geomodeller software. The implicit representation was done by isosurfaces of a 3D scalar field ($f(x,y,z)=\text{constant}$) (e.g. Calcagno et al. 2008, Lajaunie et al. 1997). The Sola serpentinite was modelled using similar approach with Geomodeller software. Geostatistical simulation was used to analyze the distribution of rock types and geochemical contents in the Vuonos and Keretti areas using ISATIS software. In the Vuonos case, geostatistical analysis was based on the earlier 3D geological model by Saalman & Laine (2014).

Geostatistical simulation methods

Different kind of geostatistical simulations were applied for metal grades and rock types as categorical variables. In general, the main task of geostatistics is to predict unknown values between known values using a spatial correlation model. Bedrock mineralogy and geochemistry are products of many interacting tectonic, physical and chemical processes. These processes are physically determined, but their interactions are so complex that the variation appears to be random. This complexity and incomplete understanding of the processes means that a deterministic or mathematical solution to quantify the variation is hardly possible. Accordingly, geostatistics applies a random model (Matheron 1965) for the estimation the unknown

values $Z(x)$ (called random function) constrained by known $z(x)$ values using a spatio-statistical variogram model.

Geostatistics is based on a spatial correlation model. If one single spatial model is applied on an entire domain, an assumption is made that random function Z is a stationary, which means that the statistical properties are assumed to be similar on the entire domain. For the strict stationarity, the random function satisfies the invariance of the statistical distributions under an arbitrary translation of the points by a vector h . The milder form is the second order stationarity when the mean is constant on the entire domain and the covariance function only depends on the separation h . In geo-

statistics, even milder hypothesis, so called intrinsic hypothesis is assumed so that for every vector h , the increment $Z(x+h)-Z(x)$ is second order stationary. The variance of the increment is

$$(1) \text{Var}[Z(x+h) - Z(x)] = 2\gamma(h)$$

and $\gamma(h)$ is called the variogram function which can be approximated by calculating the sample variogram:

$$(2) \gamma(h) = \frac{1}{N} \sum (z(x+h) - z(x))^2$$

where N is number of sample pairs having a distance h (approximately) between each other. Theoretically the sample variogram is zero for a zero distance. However, the sample variogram is calculated for distance classes, so that the smallest distance class reflects the nearby variation of sample values. Especially in the case of metal grades, this value, so called nugget effect, is often high. Usually, the sample variogram increases with increasing distance, i.e. the sample values are getting more and more dissimilar. The value or the distance h at which the variogram values stop increasing is called the range of the sample variogram. The maximum value of the sample variogram is called sill. The sample variogram is modelled by using these three parameters, nugget, range and sill, as a simple functions of h . The obtained variogram parameters are used in kriging interpolation, which is similar to inverse distance interpolation. Both methods weight the surrounding known values in order to predict values for unmeasured locations. The formula for these interpolators is a weighted sum of the known data surrounding the unknown value location:

$$(5) Z^*(x_0) = \sum_{i=1}^N \lambda_i Z(x_i)$$

where $Z(x_i)$ is the known value, λ_i is an unknown weight for the measured value at the i th location. x_0 is the location for the predictive value and N is the number of known variable values. In inverse distance interpolation the weight, λ_i , depend on the distance between the unknown and known values. In kriging, the weights λ_i are solved based on the

variogram model by minimizing estimation error under unbiasedness condition. Geostatistical simulations (e.g. Deutsch and Journel 1998, Chiles and Delfiner 1999) are based on the variogram model but values are estimated along the random path using known and earlier estimated values. Geostatistical simulations reproduce the original data variability and given spatial properties including spatial correlation modeled by the sample variogram. Based on summary statistics of several realizations, the probability distributions of ore grades and rock types can be calculated and visualized in 3D.

The main emphasis of the present study was to use variogram modeling in order to analyse spatial distribution of rock types and geochemical compositions relative to 3D modeled faults and shear zones. The simulated realizations were used to study probable 3D structural geological features. By geostatistical simulation several different realizations can be produced. The used geostatistical interpolation and simulation methods included:

- 1) **Ordinary kriging** (e.g. Chiles & Delfiner 1999) is used when the mean is not known. Ordinary kriging was applied to map the Co contents along the Outokumpu assemblage.
- 2) **Turning bands simulation** (Mantoglou & Wilson 1982), in which, at first, the data are kriged and then conditional simulations are created using a set of randomly distributed bands, or lines. Turning bands simulations were done using ISATIS-software to simulate Cu and Ni content distributions in the central Vuonos area.
- 3) **Sequential indicator simulation** (Deutsch & Journel 1998) was applied to rock types as categorical variables in the Vuonos area, and to Ni and Zn contents inside a small block bordered by faults and shearing within Vuonos area. Instead of original Ni- and Zn-grades, the indicator transforms were used. The sequential indicator simulation method was also used to visualize quartz rock distribution in the Keretti area.

Unfolding methods

Geostatistical methods are mainly using rectilinear coordinates and the Cartesian grid. However, geological formations are mostly at least gently folded. Different methods have been developed in order to be able to model spatial properties parallel to the naturally folded surfaces:

- 1) The unfolding can be done by a simple vertical translation of data (e.g. ISATIS), according to (or with) a flattened reference surface.
- 2) In the unfolding based on the coordinate transformation, two of the coordinate axes are rotated locally to be parallel and the third one to

be perpendicular to the reference surface. The coordinate transformation may be done using the reference surface in Paradigm GOCAD. Resulted grid, so called SGrid, is sophisticated in that the user can conform the SGrid to bounding surfaces and split the SGrid along fault Surfaces.

- 3) In the case of tectonically complicated terrains it would be ideal to use local orientations defined by a vector field. The problem is the lack of knowledge of subsurface orientations. In the present study, local orientations were derived from a piece of flat ore body using ISATIS software. In this way, the unfolding does not differ from the previous ones.

It is obvious that in the case of Outokumpu area there is very little information about exact

geometries of lithological contacts and shear zones. Hence, all the unfolding techniques described above are questionable and uncertain except for well-defined ore bodies. However, the geostatistical analysis can be used to validate the used geometries. If after unfolding process, the studied variable values show a clear spatial correlation, the reference surfaces, such as lithological contacts or shear zones, correspond probably the real subsurface structures. In the tectonically complicated areas, the best alternative could be to use local anisotropy orientations which may be obtained from the oriented drill cores. Even though almost all the rock properties follow the main layering, the shearing or intense faulting change the orientations to be oblique to the main orientation field. Moreover, very often partial melting may change the orientations of the rock units quite randomly in high grade terraines.

Discontinuity structures

Outokumpu assemblage is cut by several faults and shear zones. They were used to build a discontinuity model (or fault block model) based on the interpretation of faults and shear zones by Saalman & Laine (2014). The discontinuity model could be used

for geostatistical simulations and kriging to honour the the structural discontinuities. In the case of camp scale models, structurally different units were separated manually for geostatistical analysis.

3D MODELS

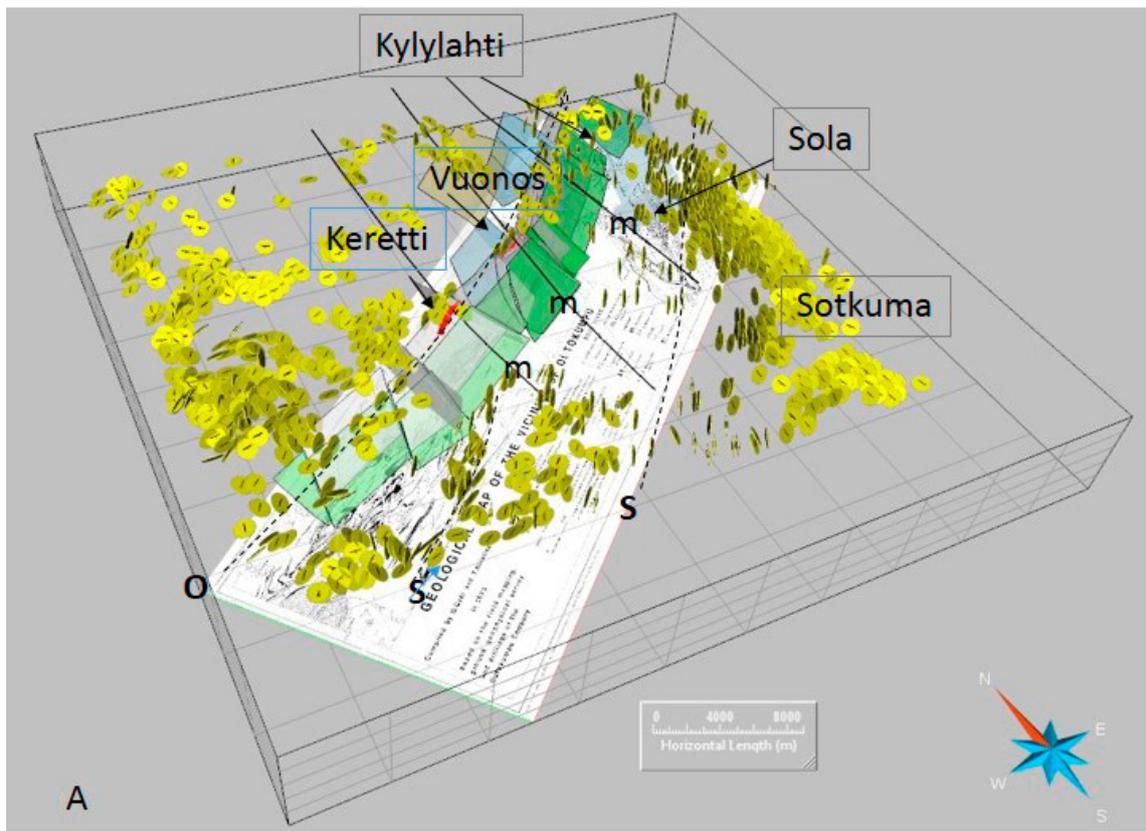
Regional 3D model

The area for the regional 3D geological model is shown in the Figure 1. The large scale structures were modeled using tectonic observations in 3D and ZTEM 3D inversion.

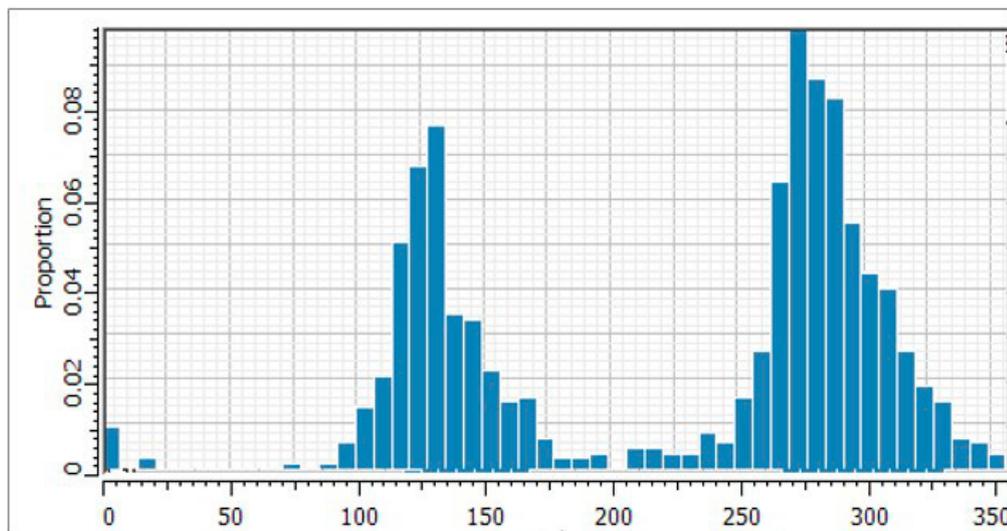
Planar structures (mostly S_1) were digitized from the geological map of Tapio Koistinen (Koistinen, 1981) and visualized in 3D using discs using Mira Geoscience tools for Paradigm GOCAD software (Fig. 15a). The schistosity strike mainly from southwest to northeast. Dip directions have bipolar distribution with two modes about 125 and 280 degrees from the north (Fig. 15b) i.e. to the southeast and northeast dipping planar structures. In the northwestern part of the Outokumpu area schistosity are mainly gently dipping (10–40 degrees). Ore bodies (Keretti, Vuonos and Kylylahti) are located in the narrow zone from southwest to northeast, along which there are also almost vertical schistosity. The area between this ore zone

(O) and Sotkuma dome seem to be divided by possible shear zones (S) along which the schistosity are steeply dipping (Fig. 4). Sola serpentinite hosting minor Cu-mineralization is located in the wide zone where the schistosity are steeply dipping.

Figure 5 shows resistivity values resulted by 3D inversion from the ZTEM measurements together with faults and shear zones (Saalman & Laine 2014). The high resistivity values (>3000 Ωm) are shown. SW dipping and S-N striking faults (S-N) could be continued as electrically conductive zones to probable faults of more than 20 km in length. The ore zone (O) is clearly visible and there seem to be several parallel high conductivity zones. The possible uplifted block interpreted by (Saalman & Laine 2014) is electrically resistive. The regional fault/shear zones seem to be form a clear pattern by two orientations. Ore mineralizations locate along these electrically conductive zones.



A



B

Dip directions

Fig. 4. a) Planar structures digitized from the geological map by Koistinen (1981) and visualized in 3D using Mira Geoscience and Paradigm GOCAD software. The ore zone (O) and a shear zone (S) from South to North are marked by arrows. Letter K is for the Keretti ore and letter V for the Vuonos ore. Black lines (m) mark the metamorphic zoning after Sääntti et al. 2006. b) A histogram of the dip directions of the digitized planar structures on the map.

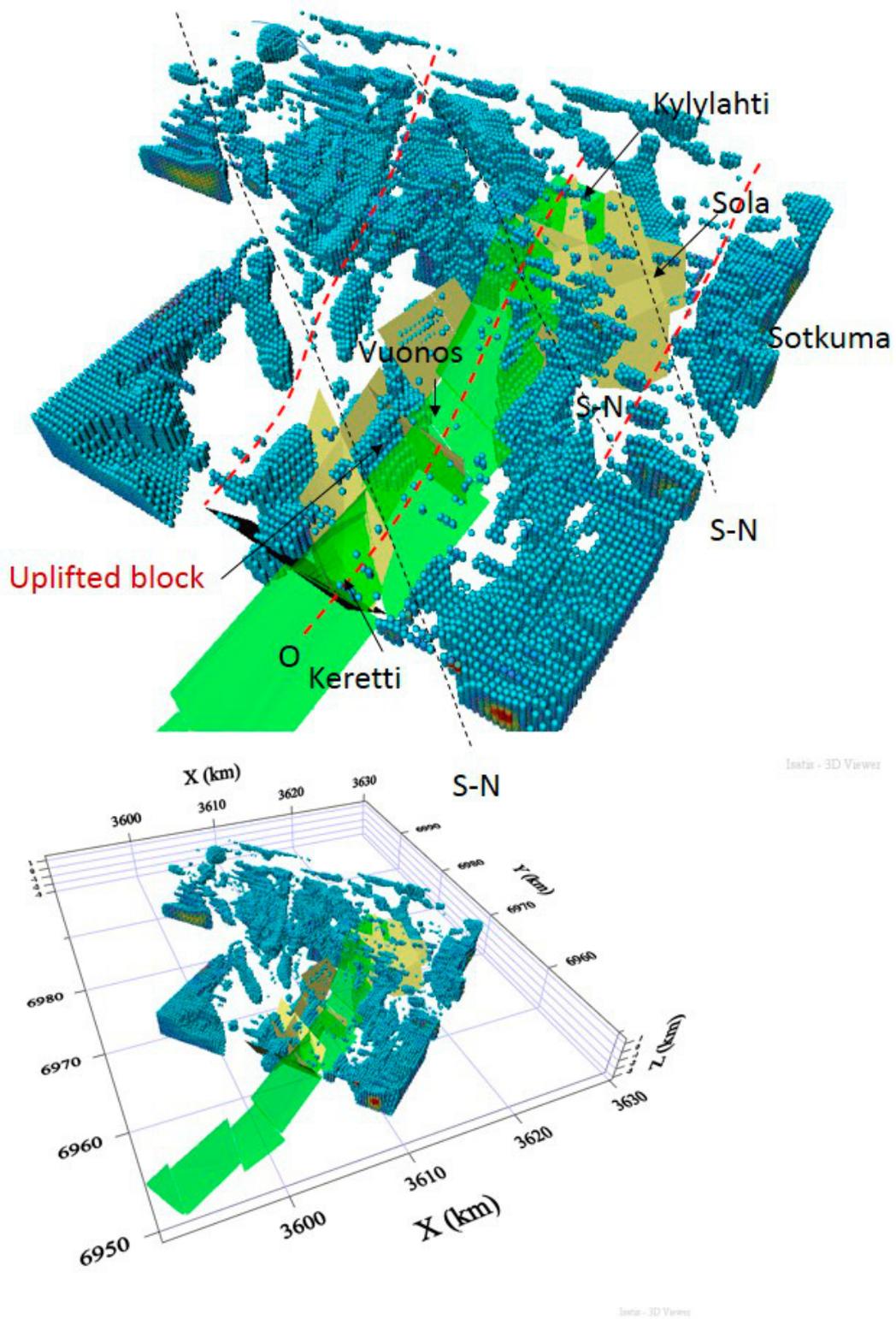


Fig. 5. Electrical resistivity (values larger than 3000 Ωm) resulted from the regional ZTEM 3D inversion together with Outokumpu shear and fault structures after Saalman & Laine (2014). Shear zones with a green color and faults with a light brown color. The black dashed lines are interpreted probable large fault/shear zones.

Outokumpu assemblage in 3D

Figure 6 shows the inversion done by ZTEM MT-3Dinv program with a grid with 72x61x74 cells (Kurimo et al., this volume). The cell size in the core area is 60x250x50 m. Six-frequency data (XIP, XQD, YIP, and YQD) were used in the 3D inversion topography and bird altitude effects considered. Electrical resistivity values less than 3000 Ωm were filtered from the visualization. The electrically resistive rocks locate as elongated bodies to the northwest from the electrically conductive Outokumpu assemblage rocks hosting thin and elongated ore bodies. Seismic reflections probably representing the Outokumpu assemblage rocks (Saalmann & Laine 2014) are visible as green points at locations with high reflectivity (the amplitude > 2.0).

The discontinuity models (Fig. 7) were used to constrain the kriging interpolation of the Co-content. Geochemical analyses were available mainly from the Vuonos area (Fig. 7a). Co, Cu, Ni and Zn contents have all skewed distributions. Because variogram modelling and kriging prerequisite nor-

mally distributed data, the normal score transformation was applied to Co, Cu, Ni and Zn contents. The resulted kriged section (Fig. 7b) shows the thin layer of Co-rich ore. Kriging was based on the exponential variogram with a nugget of 0.5, the sill of 0.47 and the range of 185 m (Fig. 7c). Very similar models were obtained for Cu and Zn contents. These results are in accordance with the ore model. In addition, structural features related to faulting and folding could be interpreted from this visualization (Fig. 7).

The Vuonos drill cores were composited, so that every sample had an equal length of 1 m. In case of a change in rock type, the sample was colored red. The resulted visualization of the drill cores, shows that at least Vuonos and Keretti are located in heterogeneous parts of the Outokumpu assemblage (Fig. 8). Lithologies such as serpentinite, soap stone, calc-silicate rocks, quartz rocks and ore were coded separately. Mica shists, gneisses and felsic volcanites were grouped together as well as felsic intrusive rocks.

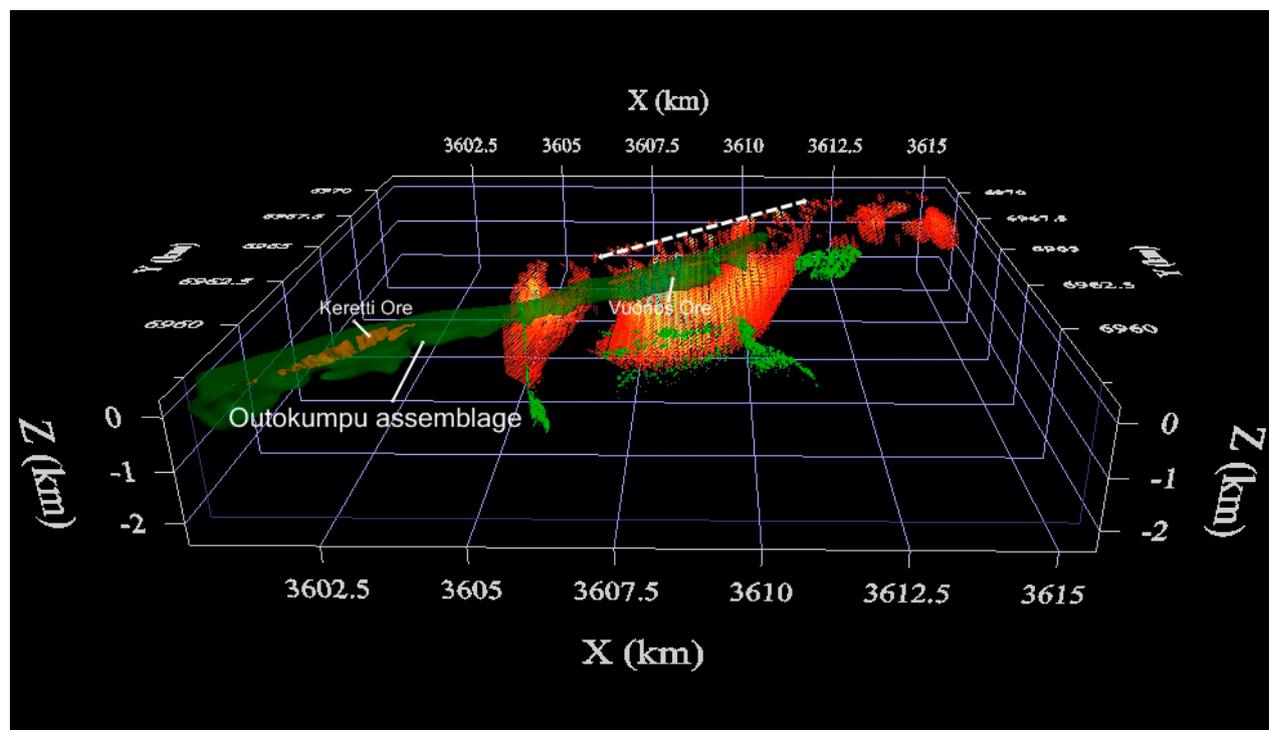


Fig. 6. Outokumpu assemblage, Keretti ore and Vuonos ore in 3D. Electrical resistivity (values larger than 3000 Ωm) resulted from the detail ZTEM 3D inversion along the Outokumpu assemblage with a red color and probable Outokumpu assemblage rocks along seismic sections with amplitudes greater than 2.0 (interpreted by Saalmann & Laine (2014)) with a green color. The direction of the elongation is marked by a dashed line.

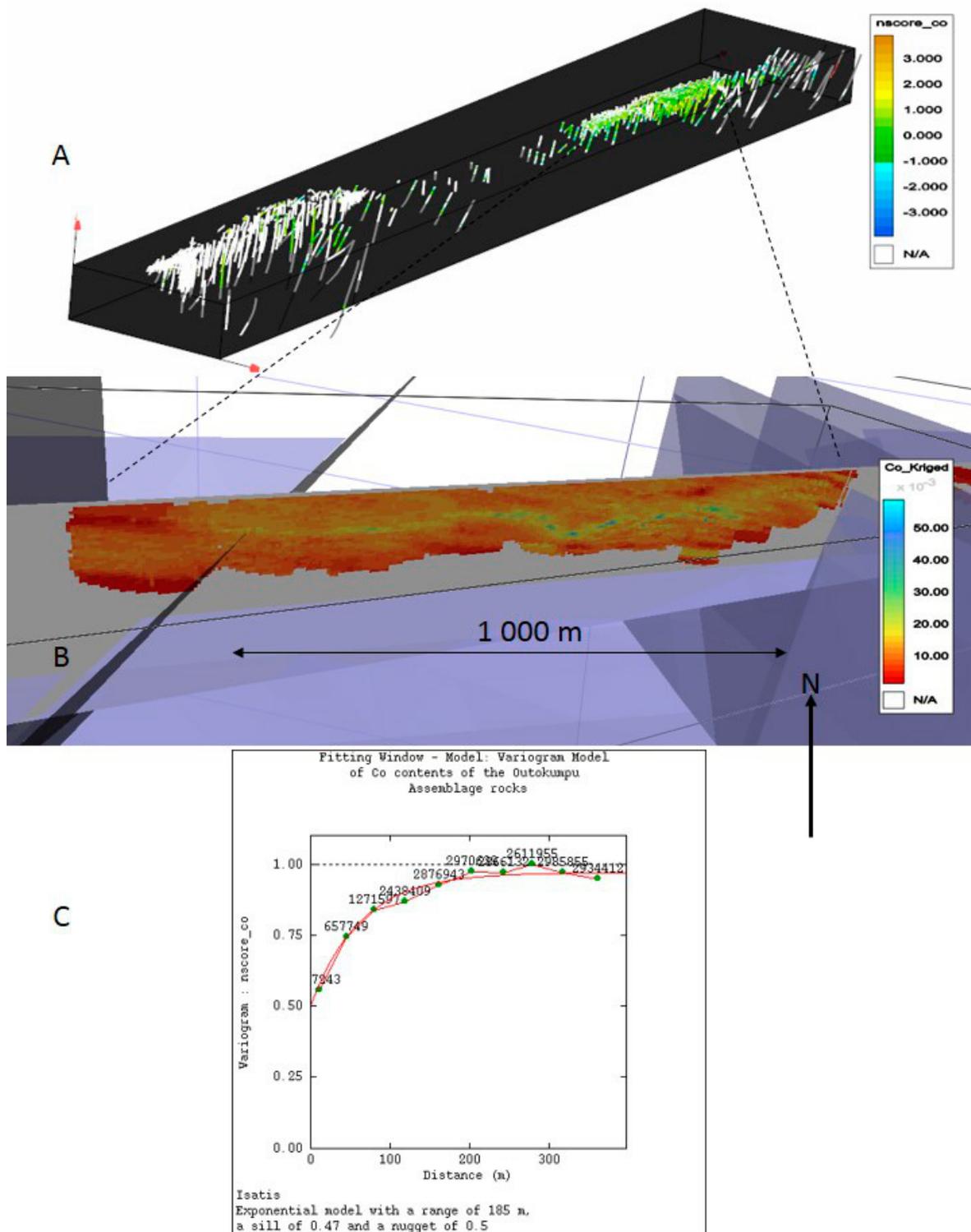


Fig. 7. a) Drill holes and Co contents along the drill holes in the Keretti and Vuonos areas. b) Kriged Co contents. c) The sample variogram (dashed line) and the corresponding variogram model (solid line) for normal score transformed Co contents.

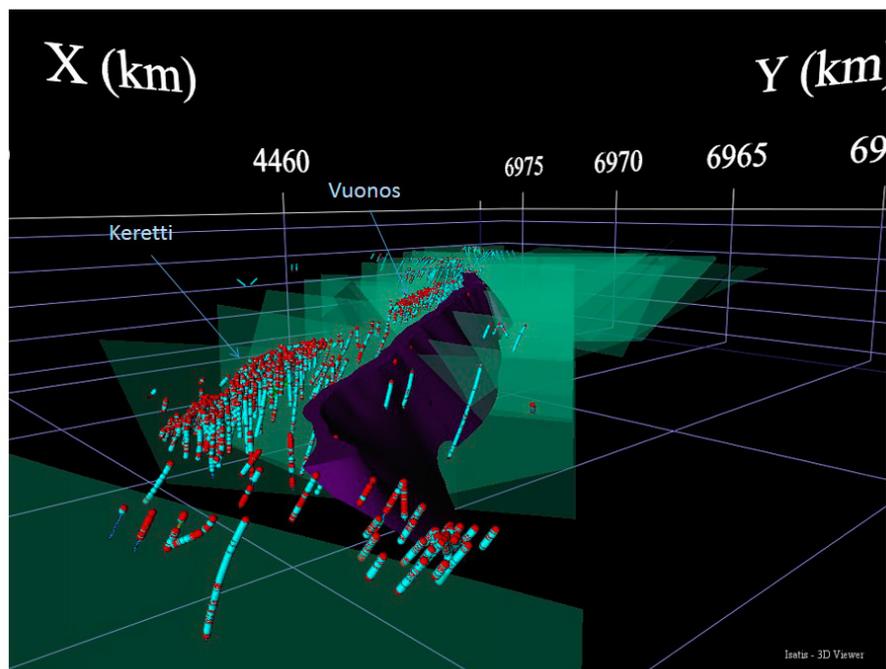


Fig. 8. Lithological contacts from the drill core data marked with a red color within the Outokumpu assemblage. Violet marks the black schist (Laine et al. 2012) and grey fault surfaces (Saalmann & Laine 2014).

Keretti

Keretti and Vuonos ore bodies were surrounded by Outokumpu assemblage rocks (Fig. 9). The Keretti 3D geological model shows how the Keretti ore was located on the southeast dipping shear zone (Fig. 10). In addition, it was cut by faults vertically and horizontally (Saalmann & Laine 2014). The ore was enclosed inside the Outokumpu assemblage which, in turn, is inside the black schist envelope. In detail, mine sections (e.g. Fig. 10) show that the thin ore was mainly associated thin layers of country rocks, such as calc-silicate rocks, quartz rocks and serpentinites. Contacts were sharp between the country rock and the Keretti ore, so the ore body

could be quite uniquely modeled from the mine sections.

Geostatistical simulation was tested on the distribution of altered rocks such as quartz rocks around the middle part of the Keretti ore body. Quartz rock has a density below 2600 kg/m³ and it forms a clear density contrast to the dense calc-silicate rocks containing pyroxenes (densities about 2800 kg/m³). Rock type data from drill cores were composited to samples of a length of 1 m and integer-coded for geostatistical analysis. In the present study, the rock type variable was transformed to an indicator variable for each rock

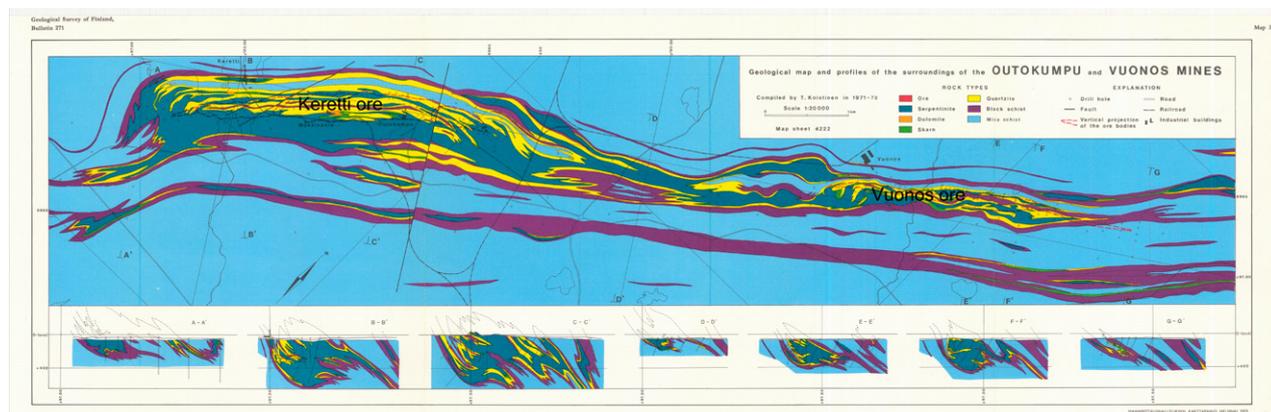


Fig. 9. Geological map and sections of the surroundings of the Keretti/Outokumpu and Vuonos ore mineralisations after Gaál et al. (1975).

type. For example, indicator variable for quartz rock gets a value of 1 if quartz rock is present and 0 else. Local orientations were derived from the geometry of the flat ore body (Fig. 12e) and copied to the voxel cells of a size of 5x5x5 m³ above and below the flat ore body. The sample variogram of the indicator transformation for quartz rocks was modelled with an exponential model (a nugget of

0.07, a range of 50–130 meters and a sill of 0.12) (Figs. 12a and 12b). The corresponding 2D simulation was used to visualize the variogram model (Fig. 12d). Search ellipsoids were oriented parallel to local orientations derived from the flat ore body. Summary statistics of 100 sequential indicator simulations was used to visualize the probable spatial distribution of quartz rocks below and above

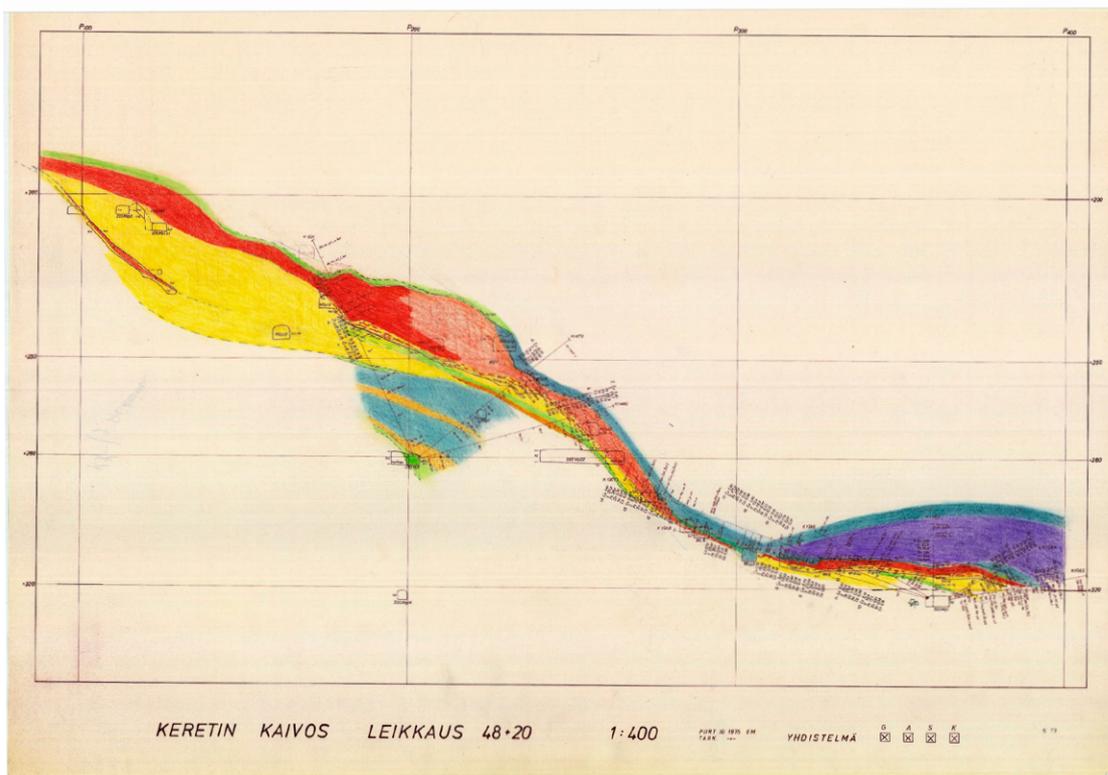


Fig. 10. Keretti/Outokumpu mine section 48 from GTK database.

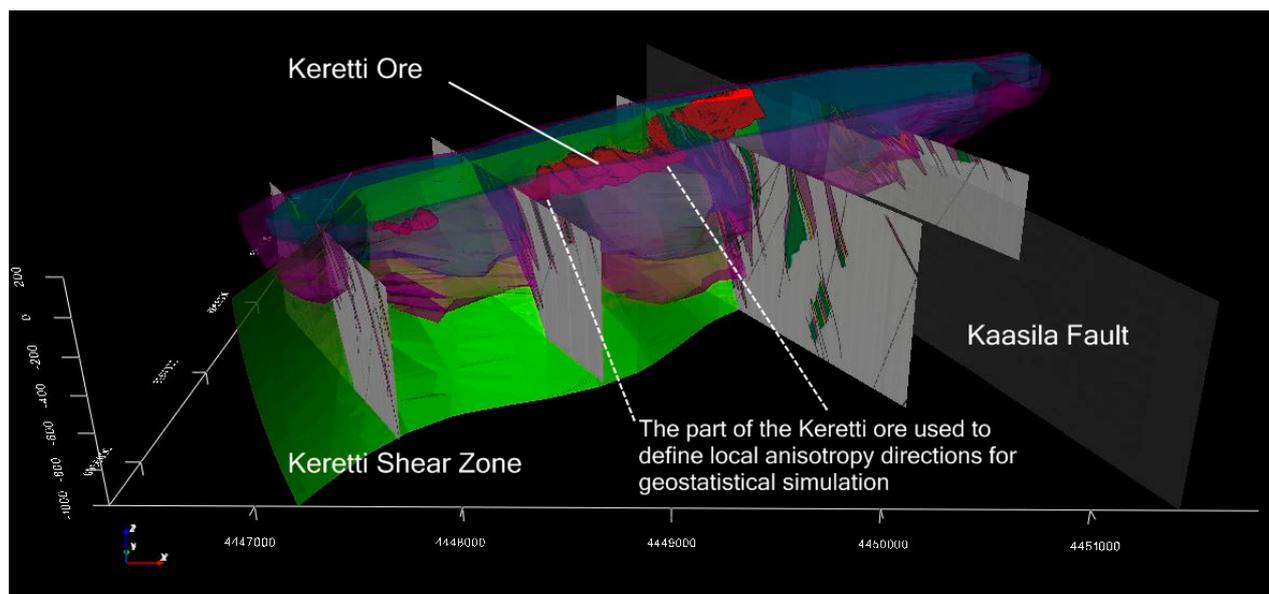


Fig. 11. Keretti 3D model. The lithological contact between black schist and mica gneisses have been colored with a violet color and between black schist and Outokumpu assemblage with a dark green color. The shear zone is colored using light green and Keretti ore using red.

Keretti orebody (Fig. 12e). The results indicate that quartz rocks might not occur as continuous, but rather as successive slightly elongated inclusions parallel to the main elongation of the ore body. The geological section drawn by Koistinen (1981)

(Fig. 12c) shows the similar distribution of quartz rocks but with a geological interpretation based on the structural geological analysis and drill core logs.

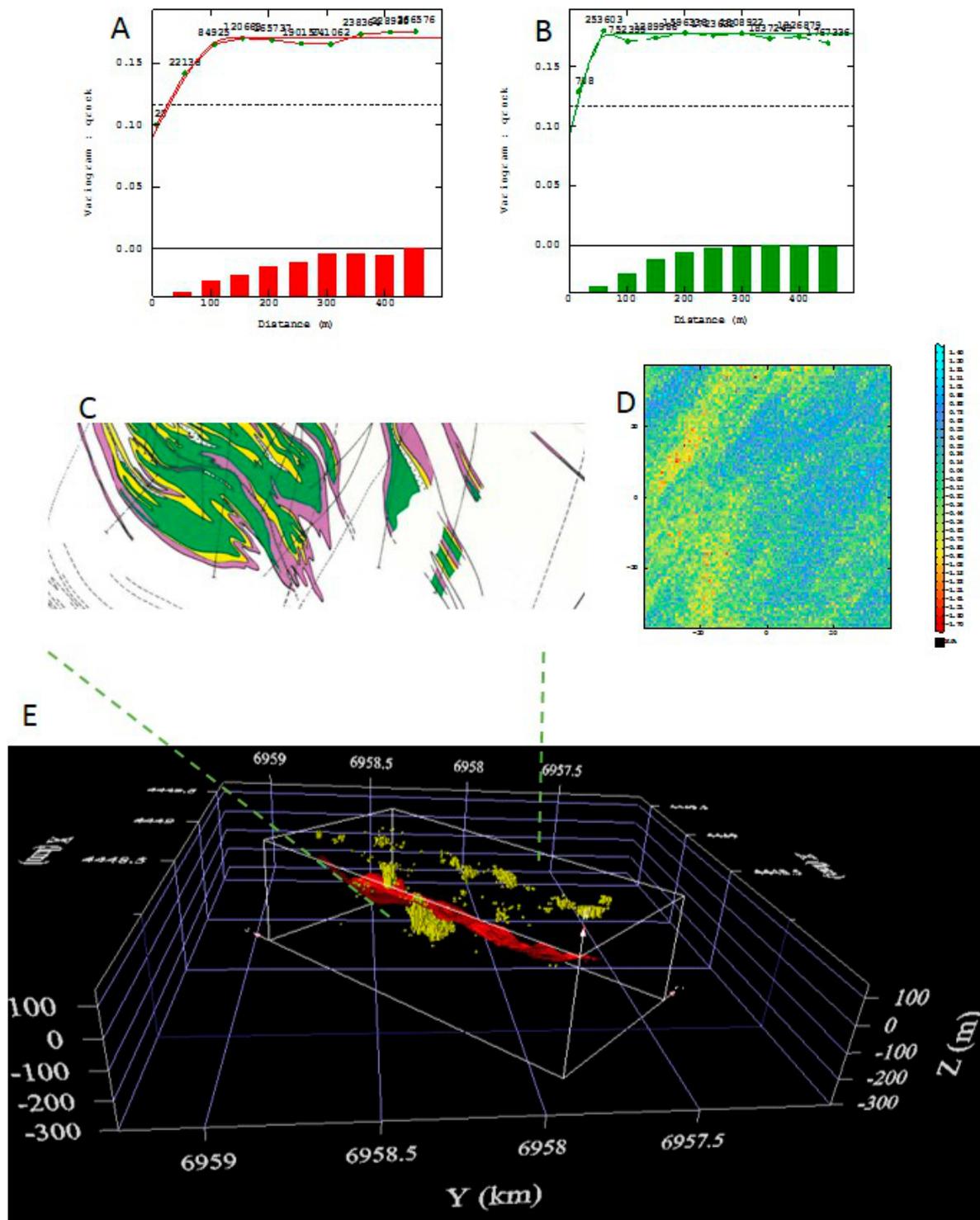


Fig. 12. The directed sample variogram and the corresponding model for the quartz rock as a categorical variable in the Keretti area a) 41 degrees and b) 131 degrees from the North; c) Geological Keretti cross section by Tapio Koistinen (1981); d) the 2D simulation based on the variogram model; e) A small part of the Keretti ore body in red and simulated 3D grid of the probability that quartz rock prevails at a certain certain location, grid cells with the probability of greater than 0.45 are colored with a yellow color.

Vuonos

The Vuonos Cu-orebody has been earlier modeled during the project “3D/4D modeling – Outokumpu area as a case study” (Laine et al. 2012) by using Paradigm GOCAD software and mine sections (Fig. 13). As in Keretti, also in Vuonos the ore body was located on the shear zone (Fig. 13b). In Vuonos, there is a clear difference between rocks below and above the shear zone. The rock unit above the shear zone was called the serpentinite zone and below it the transition zone according to Saalman & Laine (2014). Geostatistical variogram modeling and turning band simulation were used to study the differences between structures in these two rock units.

Gently folded Vuonos structures (Fig. 14) were used to transfer the drill core data parallel to flattened reference surface, in this case the boundary between the transition and serpentinite zones. The new simulation grid of a cell size of 5x5x5 m³ was created for the unfolded drill core data parallel to flattened reference surface. The same

boundary was used to divide the data and the simulation grid for the geostatistical analysis (Fig. 14). In the Vuonos case the used indicator variable represents the presence of the calc-silicate rock or serpentinite.

According to the sample variograms and the corresponding models for the calc-silicate rock as a categorical variable (Fig. 15) there are structural differences between the transition and serpentinite zones. In the transition zone the variogram range was 105 m in the direction of 41 degrees from north, 60 m in the perpendicular direction and only 40 m in the vertical direction. In the serpentinite zone the variogram ranges were almost the same (about 40 m) in all directions. However the variograms have high nugget effects implying that the calc-silicate rocks are nearly randomly distributed in space. This is visualized by the 2D unconditional simulation.

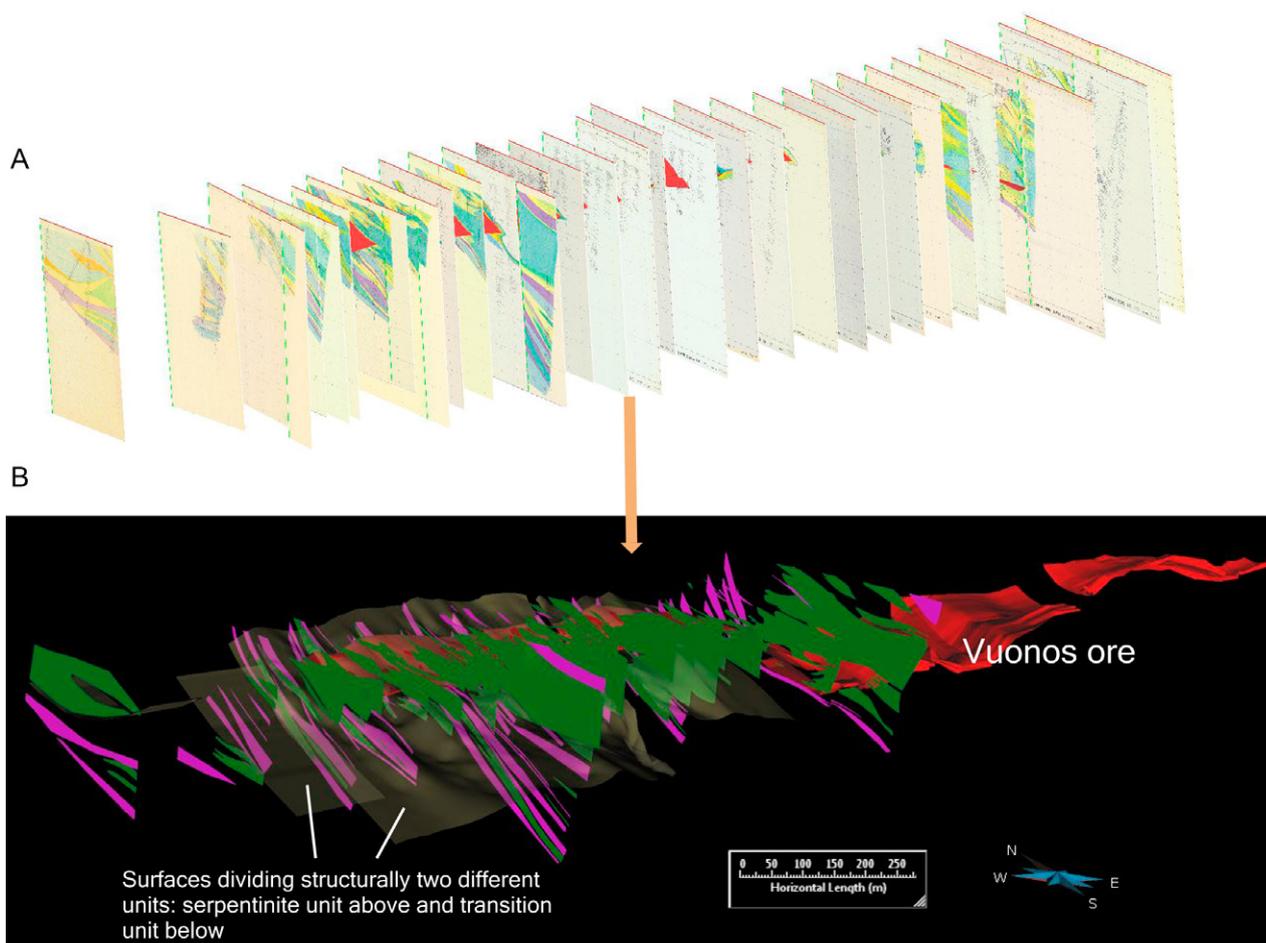


Fig. 13. a) Vuonos mine sections (GTK database) in 3D; b) Vuonos Cu-ore body (red) and serpentinites (green) and black schists (violet) after (Saalman & Laine 2014).

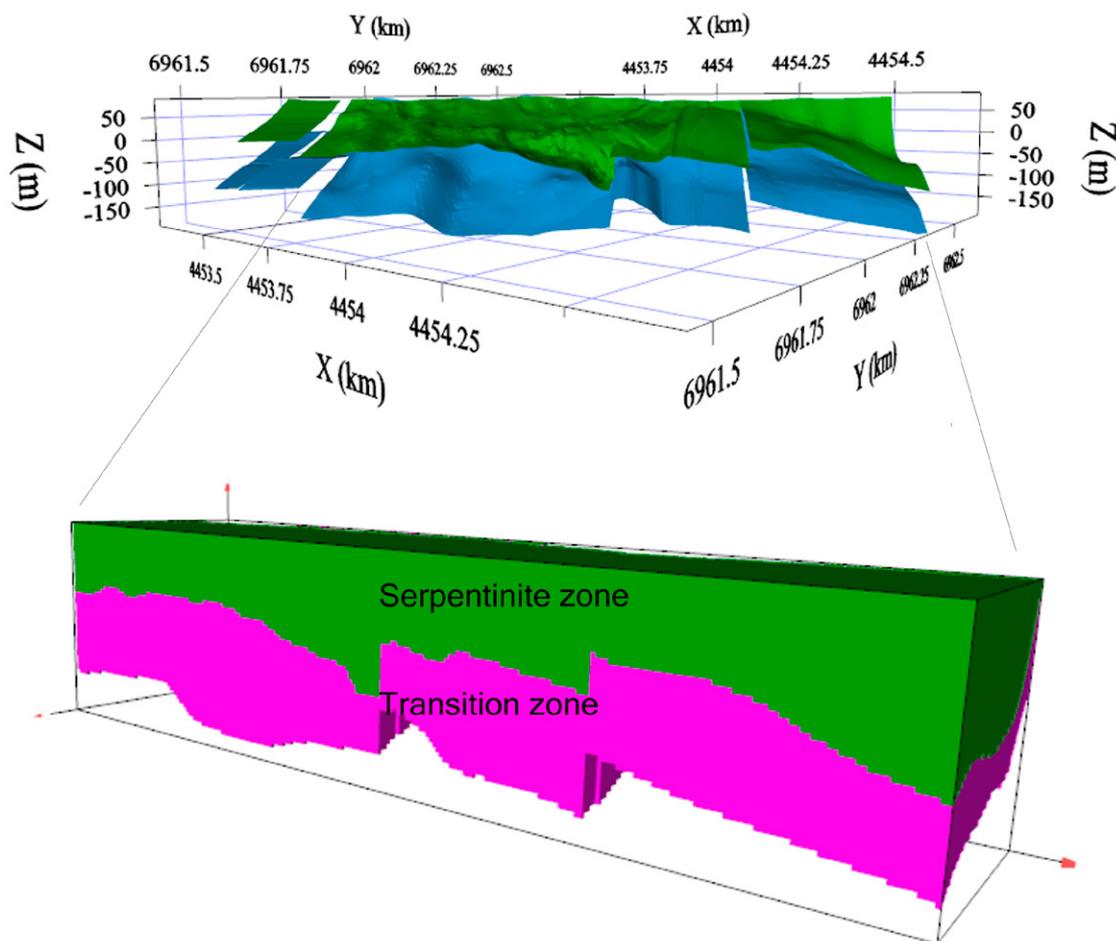
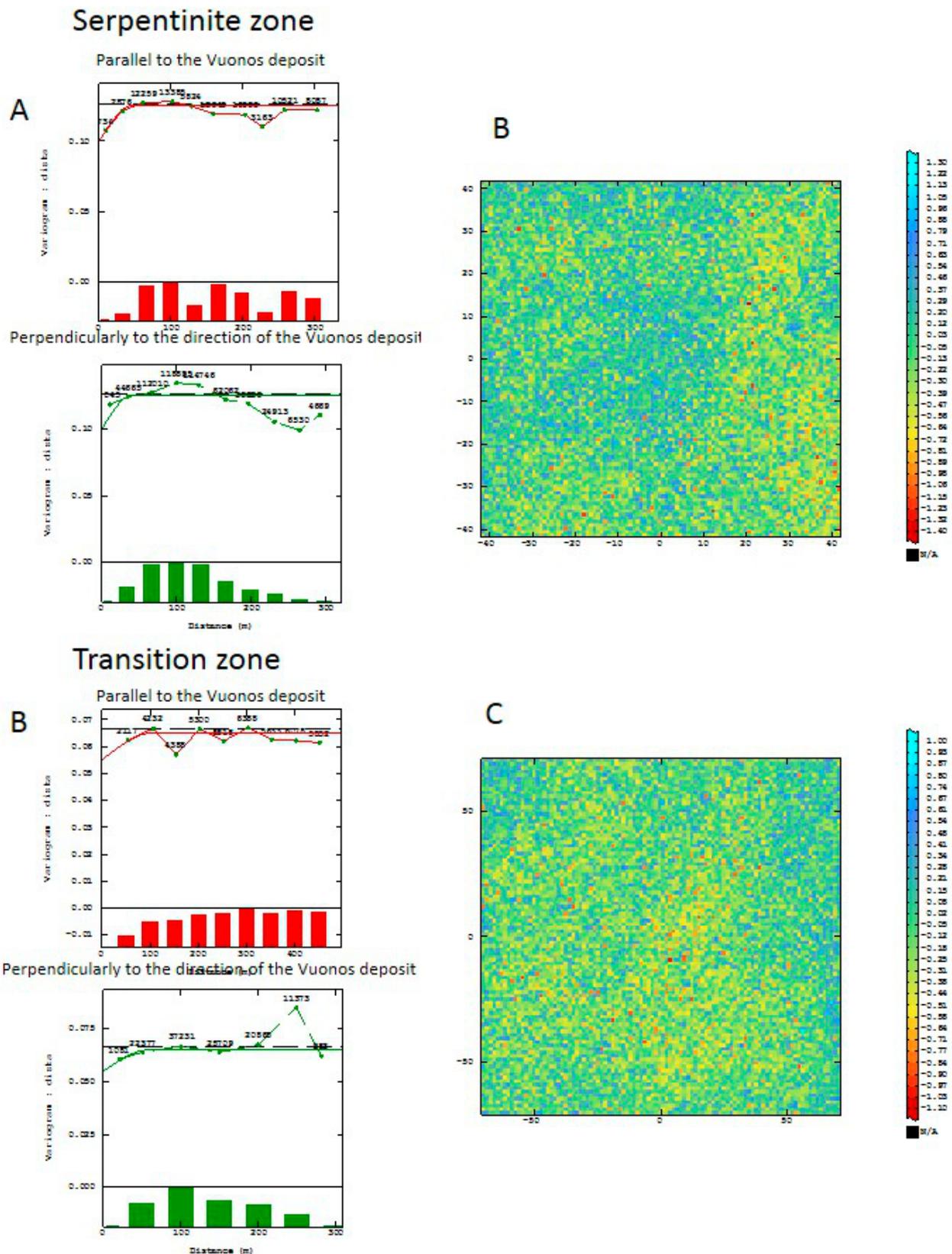


Fig. 14. The blue surface is a boundary between the paragneisses and Outokumpu assemblage rocks. The green surface is the boundary between serpentinite and transition zones. The 3D simulation grid was divided and bounded using these surfaces.

The spatial correlation of the indicator variables for the presence of serpentinites was tested using the same unfolded data set. In the serpentinite zone the sample variogram for the presence of serpentinite was modeled with a nugget of 0.03 and a spherical model having a range of 100 m in all directions, and a sill of 0.16 (Fig. 16a). Figure 16b shows the corresponding 2D simulation. In the transition zone the sample variograms for the presence of the serpentinite was modelled by a nugget 0.02 and a spherical model having, a range of 160 m parallel to the Vuonos deposit and 80 m perpendicular to this direction, a sill of 0.07 parallel to the Vuonos deposit and 0.15 perpendicular to this direction (Fig. 16 c). Figure 16d shows the corresponding 2D simulation. The result of 100 sequential indicator simulations were performed and the simulation grid was folded back to the original geometry (Fig. 17). These results are in accordance with the general idea of the roundish geometry of the serpentinite bodies along the Outokumpu assemblage.

In addition to structural differences, the serpentinite and transition zones differ geochemically. The turning bands simulation was tested for Cu and Ni contents in the Vuonos area (Fig. 18). Structural differences are apparent in both cases. Based on the variogram model and 100 simulations, the elevated Cu contents (greater than 0.5%) are more probable within the thin layers in the transition zone. Based on the variogram modelling and 100 simulations the Ni contents greater than 0.1% seem to occur in elongated zones in the transition zone. Cu and Ni contents show only weak spatial correlation in the serpentinite zone. In the small block in the Vuonos area, bordered by faults and shearing (Fig. 19), the sequential indicator simulation was applied to indicator variables for Ni greater than 0.03% and Zn greater than 0.01%. In this case the sequential indicator simulation was done into a SGrid built using the boundary between the serpentinite and the transition zone using Paradigm GOCAD. The results show a clear enrichment of the nickel in the serpentinite zone (Fig. 19a) and of the zinc in the transition zone (Fig. 19b).



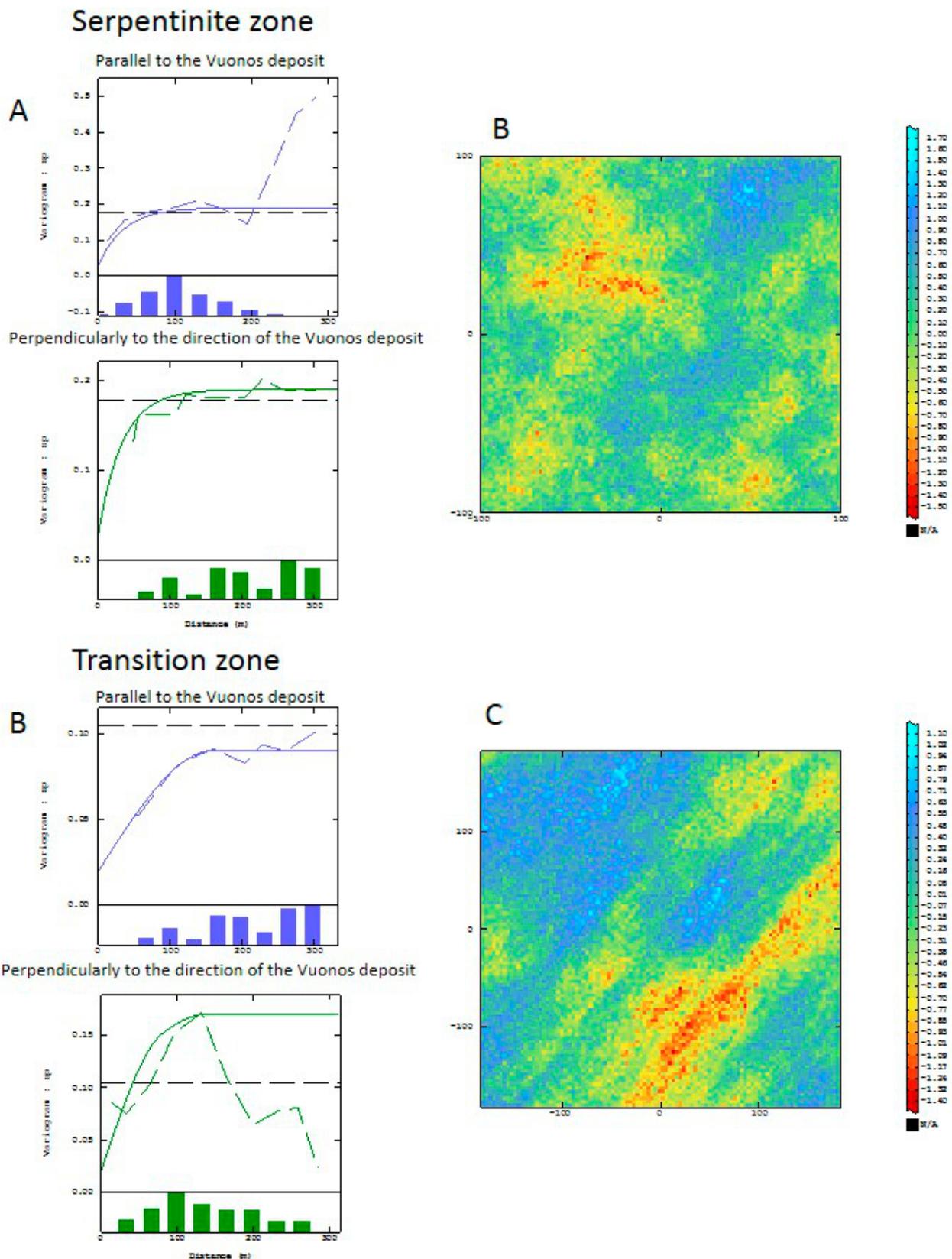


Fig. 16. a) Directed variograms and corresponding variogram models for the serpentinite as a categorical variable in the serpentinite zone, 41 degrees and 131 degrees from the North, and b) the unconditional simulation based on this variogram model; c) directed variograms and corresponding variogram models for the serpentinite as a categorical variable in the transition zone, 41 degrees and 131 degrees from the North, and d) the unconditional simulation based on this variogram model.

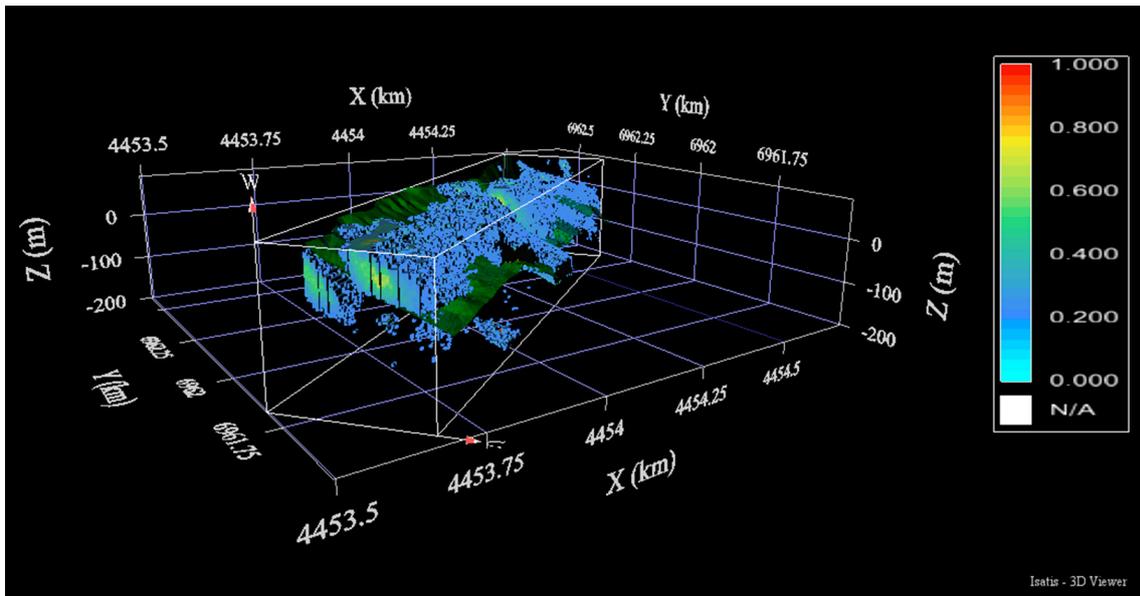


Fig. 17. Sequential indicator simulation of the serpentinite as a categorical variable. Simulation grid cells with the probability values greater than 0.1 are shown.

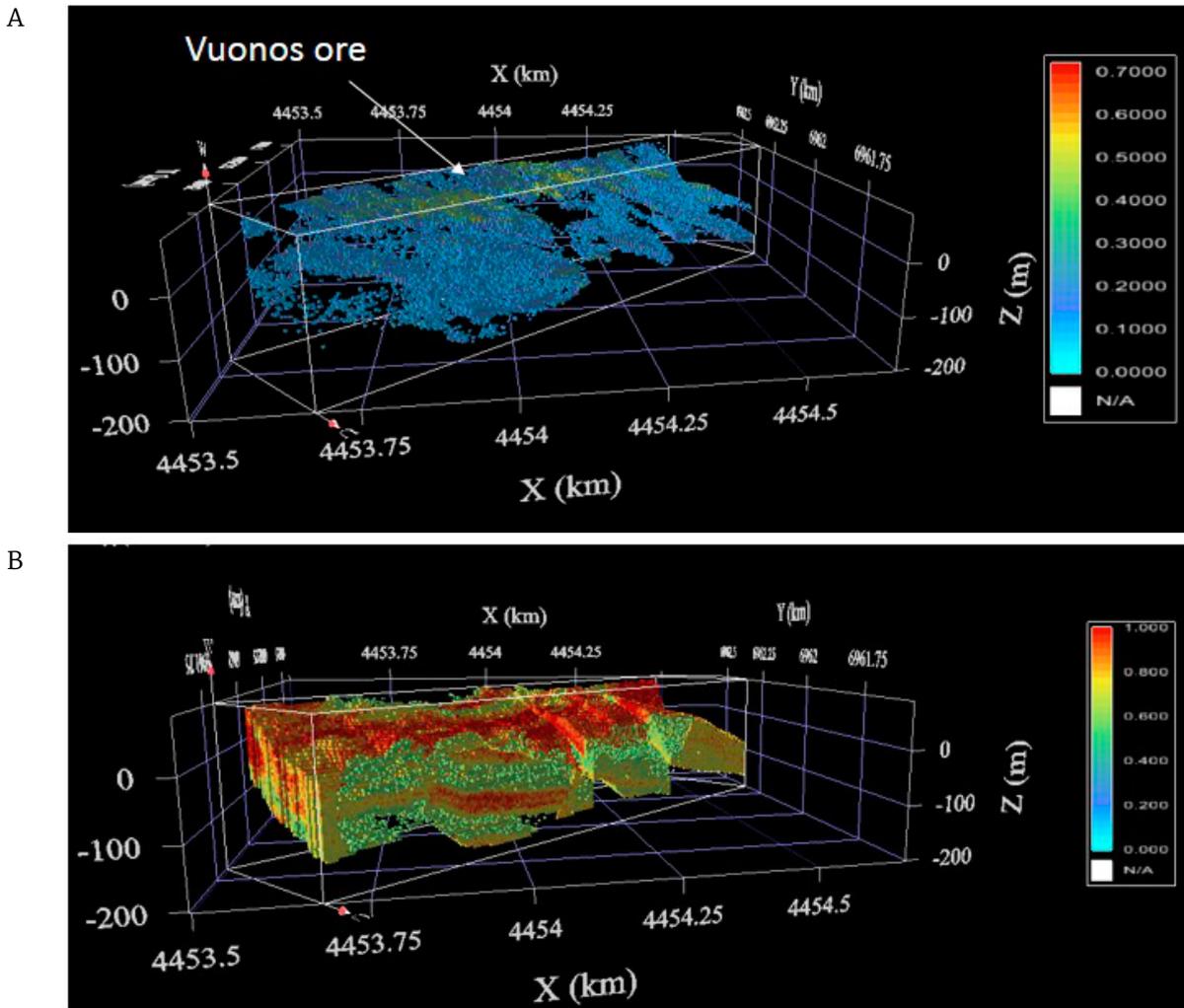


Fig. 18. Turning bands simulation of a) Cu contents in the transition zone, the probability that Cu content is greater than 0.5 %, simulation grid cells with values greater than 0.1 are shown; b) Ni contents in the transition zone, the probability that Ni content is greater than 0.1 %, simulation grid cells with values greater than 0.1 are shown.

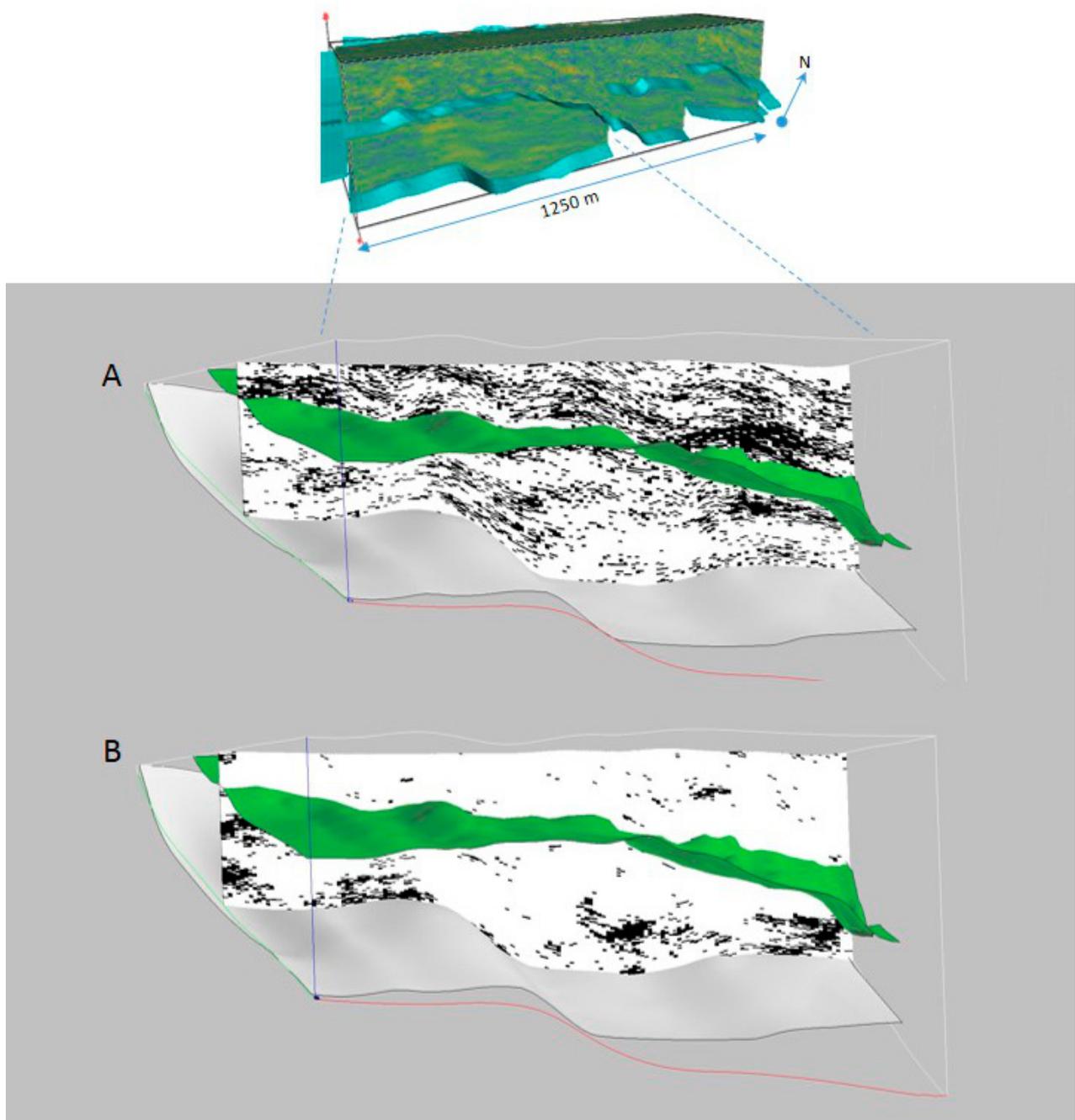


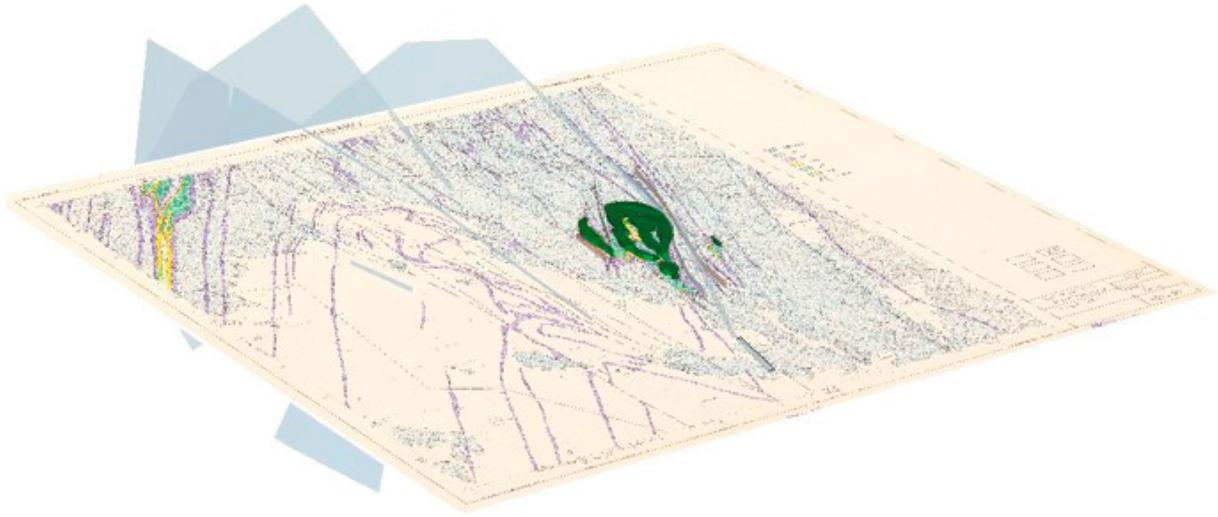
Fig. 19. Indicator sequential simulation, Sgrid cells are black when a) the Ni content is larger than 0.01 %; b) the Zn content is larger than 0.03 %.

Sola

At Sola area (Fig. 2) the Outokumpu assemblage rocks occur as a roundish body slightly elongated in the SW-NE direction. The 3D model of Sola serpentinite was built using geological cross sections and drill core data. The implicit approach (e.g. Lajaunie et al. 1997) was applied using Geomodeller software (Fig. 20a). Fig. 20a shows 3D geological model of Sola serpentinite on the old map (GTK database) of the Sola area between two to the west dipping large faults (Saalman & Laine 2014). The old map

by an unknown author (GTK database) (Fig. 18b) shows an interesting fault interpretations which are mostly in an agreement with the faults interpreted from the seismic sections by Saalman & Laine (2014). In addition, the interpreted fault zone is parallel with the ore zone (O) and the large structures (S) interpreted from the visualization of the planar structures by Koistinen (1981) and the ZTEM inversion results (Figs. 15a and 16).

A



B

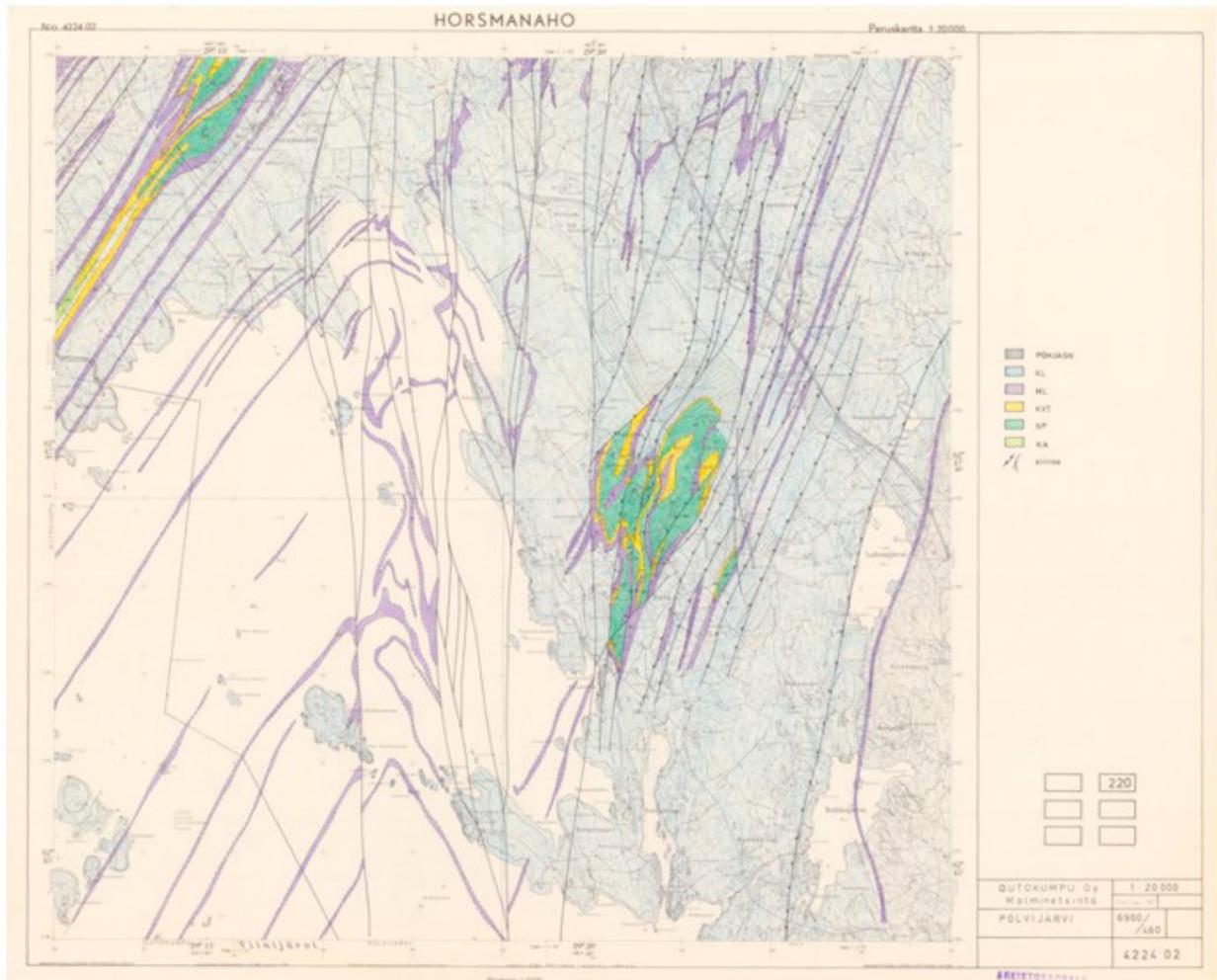


Fig. 20. a) Sola 3D model built using GeoModeller with the geological map of the Polvijärvi map sheet and three west dipping faults Saalman & Laine (2014). b) Polvijärvi map sheet 4224 02 (GTK database).

CONCLUSIONS

In the regional scale, large fault/shear zones could be interpreted from the subsurface electrical resistivity distribution obtained by 3D inversion of ZTEM data. The regional fault/shear zones seem to form a clear pattern by two orientations striking to the north and to the northwest. The similar structures could be interpreted by visualizing the planar structures (schistosity) in 3D. All the known ore mineralizations are located along these ore potential structures characterized by higher electric conductivity and near vertical planar structures (schistosity).

ZTEM inversion results along the Outokumpu assemblage show an elongation of electrically resistive rocks parallel to the Outokumpu assemblage. The kriged Co contents along the Outokumpu assemblage show discontinuities and gentle folding. Similar elongation could be modeled using geostatistical simulation. The structures surrounding the Keretti and Vuonos ore body show a clear elongation along the ore zone (O). In addition, using geostatistical simulation methods, it was found structural and geochemical differences between different fault blocks especially in the

Vuonos area. Moreover, geostatistical modelling results indicate elongated and planar structures below the Vuonos ore associated with shearing. This is in line with the ore body geometries and earlier interpretations. Geostatistical simulations reproduced geometries characteristic for different rock types within the Outokumpu assemblage. These alternative realizations may be useful in the future, especially in the numerical modelling.

Keretti, Vuonos and Sola mineralizations are mainly associated with sheared zones, which was demonstrated by 3D geological models. The ore bodies are thin and surrounded by altered and sheared rocks, hence the stochastic methods such as geostatistical kriging and simulation may be an alternative to explore this kind of ore bodies in the Outokumpu area. Because the drill cores are mostly about 300 m deep and the thickness of Outokumpu assemblage is in many places over 500 meters, there might be several undiscovered ore bodies at greater depths. Furthermore, the understanding of fault displacements could aid the ore exploration and also interpretation of ductile structures across the discontinuities.

REFERENCES

- Allard, D. 1994. Simulating a geological lithofacies with respect to connectivity information using the truncated Gaussian model. In: Armstrong, M. & Dowd, P. A. (eds) Geostatistical simulations. Kluwer, Dordrecht, Netherlands, 197–211.
- Armstrong, M., Galli, A., Beucher, H., Loc'h, G., Renard, D., Doligez, B., Eschard, R. & Geffroy, F. 2011. Pluri-gaussian Simulations in Geosciences. Berlin: Springer. 115 p.
- Bowes, D. R., Halden, N. M., Koistinen, T. J. & Park, A. F. 1984. Structural features of basement and cover rocks in the eastern Svecokareliides, Finland. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandl. (Naegle u. Obermiller)
- Calcagno, P., Chilès J. P., Courriouxa, G. & Guillen, A. 2008. Geological modelling from field data and geological knowledge Part I. Modelling method coupling 3D potential-field interpolation and geological rules. *Physics of the Earth and Planetary Interiors* 171, 147–157.
- Chiles, J. P. & Delfiner, P. 1999. Geostatistics, Modelling Spatial Uncertainty. Wiley-Interscience.
- Deutsch, C. V. & Journel, A. G. 1998. GSLIB: Geostatistical Software Library and User's Guide. Second Edition. Oxford University Press. 369 p.
- Dilek, Y. & Furnes, H. 2011. Ophiolite genesis and global tectonics; geochemical and tectonic fingerprinting of ancient oceanic lithosphere. *Geological Society of America Bulletin* 123, 387–411.
- Frosterus, B. & Wilkman, W. W. 1920. Suomen geologinen yleiskartta: vuorilajikartan selitys: Lehti D 3 Joensuu. Helsinki: Geologinen toimisto.
- Gáal, G., Koistinen, T. & Mattila, E. 1975. Tectonics and stratigraphy of the vicinity of Outokumpu, North Karelia, Finland: including a structural analysis of the Outokumpu ore deposit. *Geological Survey of Finland, Bulletin Geological Survey of Finland* 271. 67 p.
- Gómez-Hernández, J. J. & Journel, A. G. 1993. Joint sequential simulation of multi-Gaussian fields. In: Geostatistics. Netherlands: Kluwer Academic Publishers Dordrecht.
- Huhma, A. & Huhma, M. 1970. Contribution to the geology and geochemistry of the Outokumpu region. *Bulletin of the Geological Society of Finland* 42, 57–88.
- Journel, A. G. & Alabert, F. G. 1990. New method for reservoir mapping. *JPT Journal of Petroleum Technology* 42, 212–218.
- Journel, A. G. & Gómez-Hernández, J. J. 1993. Stochastic imaging of the Wilmington clastic sequence. *SPE Formation Evaluation* 8, 33–40.
- Kohonen, J., Luukkonen, E. & SorjonenWard, P. G. 1991. Nunnanlahti and Holinmaki shear zones in North Karelia; evidence for major early Proterozoic ductile deformation of Archaean basement and further discussion of regional kinematic evolution. In: Autio, S. (ed.) *Geological Survey of Finland, Current research 1989–1990*. Geological Survey of Finland, Special Paper 12, 11–16.
- Koistinen, T. J. 1981. Structural evolution of an early Proterozoic stratabound Cu-Co-Zn deposit, Outokumpu,

- Finland. Transactions of the Royal Society of Edinburgh: Earth Sciences 72 (2), 115–158.
- Kontinen, A. 1987.** An early Proterozoic ophiolite – the Jormua mafic-ultramafic complex, northeastern Finland. *Precambrian Res.* 35, 313–341.
- Kukkonen, I. 2009.** Reflection seismics in exploration. In: 7th Fennoscandian Exploration and Mining, 1–3 December 2009, Rovaniemi, Finland: final programme and abstracts, p. 47.
- Kukkonen, I. & Lahtinen, R. 2006.** Finnish Reflection Experiment FIRE 2001–2005. In: Kukkonen, I. T. & Lahtinen, R. (eds) Finnish Reflection Experiment FIRE 2001–2005. Geological Survey of Finland, Special Paper 43, 77–103.
- Kurimo, M., Lahti, I. & Nousiainen, M. 2016.** ZTEM survey in the Outokumpu region. In: Aatos, S. (ed.) Developing Mining Camp Exploration Concepts and Technologies – Brownfield Exploration Project 2013–2016. Geological Survey of Finland, Special Paper 59. (this volume)
- Laine, E. (ed.) 2012.** 3D modeling of polydeformed and metamorphosed rocks: the old Outokumpu Cu–Co–Zn mine area as a case study. Geological Survey of Finland, Report of Investigation 195. 77 p. (electronic publication)
- Lajaunie, C., Courrioux, G. & Manuel, L. 1997.** Foliation fields and 3D cartography in geology; principles of a method based on potential interpolation. *Mathematical Geology* 29, 571–584.
- Mantoglou, A. & Wilson, J. L. 1982.** The turning bands method for simulation of random fields using line generation by a spectral method. *Water Resources Research* 18 (5), 1379–1394.
- Matheron, G. 1965.** *Le variables régionalisées et leur estimation.* Paris: Editions Technip.
- Peltonen, P. & Kontinen, A. 2004.** The Jormua Ophiolite; a mafic-ultramafic complex from an ancient ocean-continent transition zone. *Developments in Precambrian Geology* 13, 35–71.
- Peltonen, P., Kontinen, A., Huhma, H. & Kuronen, U. 2008.** Outokumpu revisited; new mineral deposit model for the mantle peridotite-associated Cu–Co–Zn–Ni–Ag–Au sulphide deposits. *Ore Geology Reviews* 33, 559–617.
- Saalmann, K. & Laine, E. L. 2014.** Structure of the Outokumpu ore district and ophiolite-hosted Cu–Co–Zn–Ni–Ag–Au sulfide deposits revealed from 3D modeling and 2D high-resolution seismic reflection data. *Ore Geology Reviews* 62, 156–180.
- Säntti, J., Kontinen, A., Sorjonen-Ward, P., Johanson, B. & Pakkanen, L. 2006.** Metamorphism and Chromite in Serpentinized and Carbonate–Silica-Altered Peridotites of the Paleoproterozoic Outokumpu–Jormua Ophiolite Belt, eastern Finland. *International Geology Review*, 48:6, 494–546.
- Schetselaar, E. M. 2013.** Mapping the 3D lithofacies architecture of a VMS ore system on a curvilinear-faulted grid; a case study from the Flin Flon mining camp, Canada. *Ore Geology Reviews* 53, 261–275.
- Scott, D. J., Helmstaedt, H. & Bickle, M. J. 1992.** Purtuniqu Ophiolite, Cape Smith Belt, northern Quebec, Canada; a reconstructed section of early Proterozoic oceanic crust. *Geology Boulder* 20, 173–176.
- Strebelle, S. 2002.** Conditional simulation of complex geological structures using multiple-point statistics. *Mathematical Geology* 34, 1–21.
- Trüstedt, O. 1921.** Över geologin inom Outokumpu området, diskussion. *Medd. Geol. Fören. Helsingfors* 1919–1920, p. 16.
- Väyrynen, H. 1939.** On the geology and tectonics of the Outokumpu ore field and region. *Bulletin de la Commission géologique de Finlande* 124. 91 p.
- Vuollo, J. & Piirainen, T. A. 1989.** Mineralogical evidence for an ophiolite from the Outokumpu serpentinites in North Karelia, Finland. *Bulletin of the Geological Society of Finland* 61 (1), 95–112.
- Ward, P. 1987.** Early Proterozoic deposition and deformation at the Karelian craton margin in southeastern Finland. *Precambrian Research* 35, 71–93.
- Ward, S. H. 1959.** AFMAG; airborne and ground. *Geophysics* 24 (4), 761–789.
- Wegmann, C. E. 1928.** Über die Tektonik der jüngeren Faltung in Ostfinnland. *Fennia* 50, 1–22.