

3D structure and physical properties of the Kuhmo Greenstone Belt (eastern Finland): Constraints from gravity modelling and seismic data and implications for the tectonic setting

Hanna Silvennoinen^{a,*}, Elena Kozlovskaya^b

^a Department of Physics, Division of Geophysics, POB 3000, FIN-90014 University of Oulu, Finland

^b Sodankylä Geophysical Observatory/Oulu Unit, POB 3000, FIN-90014 University of Oulu, Finland

Received 7 February 2006; received in revised form 30 August 2006; accepted 12 September 2006

Abstract

In our paper we study 3D structure of the Kuhmo Greenstone Belt (2800–2760 Ma) located in the Finnish part of the Archean Karelian craton in the Fennoscandian Shield. Although the surface position of the belt is relatively well constrained by geological studies, its 3D structure is poorly known. Previously, two groups of competing geodynamic models have been proposed to explain formation and stabilization of the belt. The first group suggest that the belt may be formed in intracratonic, extensional rift environment with igneous rocks being derived from hot, upwelling mantle plume. In this case one would expect that the belt has a diapiric shape with deep root. The other suggests that the belt may be formed by collision and subduction processes, resulting in thin elongated shape and shallow root. Thus the knowledge of the 3D structure of the belt is essential to distinguish between two groups of models. The belt is marked by a regional-scale positive Bouguer anomaly, indicating strong density contrast between the belt and surrounding bedrock. In spite of that, previous seismic studies (SVEKA'81 wide-angle reflection and refraction profile and FIRE1 near-vertical reflection profile) revealed pronounced change in the crust–mantle boundary beneath the belt (from almost 60 to 40 km), but no any velocity or sharp reflectivity contrasts between the belt and its surrounding. In order to explain this apparent disagreement, we estimated seismic velocities and density of the main rock types of the belt from modal mineralogy. The result of the modelling suggests that the main rocks types of the belt have low seismic velocities and high densities due to high content of amphibole, biotite and muscovite. This explains why the belt is not seen in the seismic data, in spite of the gravity high. Thus we applied 3D gravity modelling and inversion in order to obtain the 3D density structure of the belt. Our result demonstrated that the Kuhmo Greenstone Belt is a surface structure that is 10–12 km wide with depth less than 7 km and average density of $2.84 \times 10^3 \text{ kg/m}^3$. The belt has no deep “root” in the middle crust and lower crust. The difference in Bouguer anomaly west and east of the belt is explained by the regional trend produced by the Moho uplift. Our model implies that the belt was formed as a result of plate-tectonics like processes rather than mantle diapirism, although these processes not directly comparable to the Phanerozoic ones due to the higher heat flux in Late Archean.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: 3D gravity modelling; Archean; Fennoscandian Shield; Greenstones; Density

* Corresponding author. Tel.: +358 44 336 7298; fax: +358 8 553 1414.

E-mail address: hanna.silvennoinen@oulu.fi (H. Silvennoinen).

1. Introduction

Archean greenstone belts around the world are of great interest for geologists as they often host gold and other valuable metal deposits. However, the origin and development of these belts is still strongly debated, particularly with regard to the role of plate tectonic (e.g. collision and subduction) processes and magmatic (e.g. diapirism, plume magmatism) processes in evolution of the Archean lithosphere (Benn et al., 2006; de Wit, 1998; Hamilton, 2003). As studies of greenstone belts in the Precambrian areas demonstrated, the belts may be formed by strongly contrasting tectonic processes. As a result, the 3D structure and physical properties of the greenstone belts may differ significantly from each other. For example, large diapiric batholiths and synclinal greenstone keels may suggest that diapirism was an important tectonic process in the Achaean Slave Province (Bleeker, 2002); whereas in the Superior Province the linear distribution of belts suggests that accretion tectonics (i.e. plate tectonics) may have dominated (cf. Stott, 1997). Therefore, studying of the 3D structure of the greenstone belts is important not only for the purpose of ore exploration, but for understanding the early history of the Earth as well.

In our paper we study the 3D structure and elastic properties of the Archean Kuhmo Greenstone Belt (2800–2760 Ma) in eastern Finland trending over 100 km in the north-south direction (Fig. 1a). Although the surface position of the belt is relatively well constrained by geological studies, its 3D structure is poorly known and it is not clear to what depth the belt extends. As a result, there is still no basis for defining large-scale crustal elements within a geodynamic context (Eilu et al., 2003).

The belt is marked by a regional-scale positive Bouguer anomaly (Fig. 1b), indicating that strong density contrast exists between the belt and the surrounding bedrock. However, the laboratory measurements of the bulk density of the rocks sampled at the surface do not indicate presence of large amounts of high density rocks within the belt (Fig. 1c).

In 1981 the belt was crossed by the SVEKA'81 wide-angle reflection and refraction profile (Fig. 1a). However, seismic velocity models of the SVEKA'81 profile by Luosto et al. (1984) and Kozlovskaya and Yliniemi (1999) did not show any V_p or V_s velocity contrasts between the belt and its surrounding, as would be expected basing on the visual analysis of the gravity field. In 2001 the belt was crossed by a new reflection profile FIRE1 made by Vibroseis technique (Kukkonen et al., 2006). The profile revealed a very detailed structure of the uppermost crust in the vicinity of the belt. The contact of the Kuhmo Greenstone Belt with the surrounding rocks is not marked by any clear reflecting pattern in the cross-section of the FIRE1 profile either.

In our study we use a 3D gravity modelling and inversion to evaluate 3D structure and density of the belt. The results of the laboratory measurements of the bulk density of the main rock types of the belt are used as constraints in order to decrease the fundamental non-uniqueness of gravity data interpretation. In addition, seismic velocities and the density of the rocks of the belt are estimated from modal mineralogy using Monte Carlo simulation in order to investigate the influence of the main rock forming minerals on density and seismic velocities.

2. Regional geology

The Kuhmo Greenstone Belt is located in the Fennoscandian Shield in the northern Europe. The Archean Karelian craton forms the core of the shield. It is flanked by Proterozoic orogens, from southwest by Svecofennian domain and from north by Lapland-Kola orogeny (Korsman et al., 1999). Our research area is situated in the Finnish part of the Karelian province (Fig. 1a).

The Karelian province is a typical granite-greenstone domain (Gaál and Gorbatshev, 1987). Its bedrock is comprised mainly of granodiorites and quartz diorites. The greenstone belts including the Kuhmo Greenstone Belt are sheared into narrow, almost N-S-trending zones. They are comprised of calc-alkaline felsic to mafic volcanic rocks, tholeiitic basalts, komatiites and komatiitic cumulate rocks, komatiitic basalts, chromium-rich basalts, intermediate to mafic pyroclastic volcanic rocks and heterogeneous sedimentary rocks (Luukkonen, 1992). The Kuhmo Greenstone Belt separates the bedrock into two distinct domains with different geological and geophysical properties. The rocks east of the belt have protolith ages older than 2800 Ma. To the west of the belt the rocks are mainly about 2740 and 2690 Ma old (Korsman et al., 1999).

The migmatic tonalite-trondhjemites containing the amphibolitic enclaves on the area around the belt represent the remnants of the formerly more extensive, about 3000 Ma old, protocrust. This crust was first deformed ca. 2843 ± 18 Ma ago with amphibolite-granulite facies metamorphism and the accompanying plutonic event. The next major plutonic period spanned between ca. 2740 and 2690 Ma. The greenstones of the belt were deposited between these two plutonic

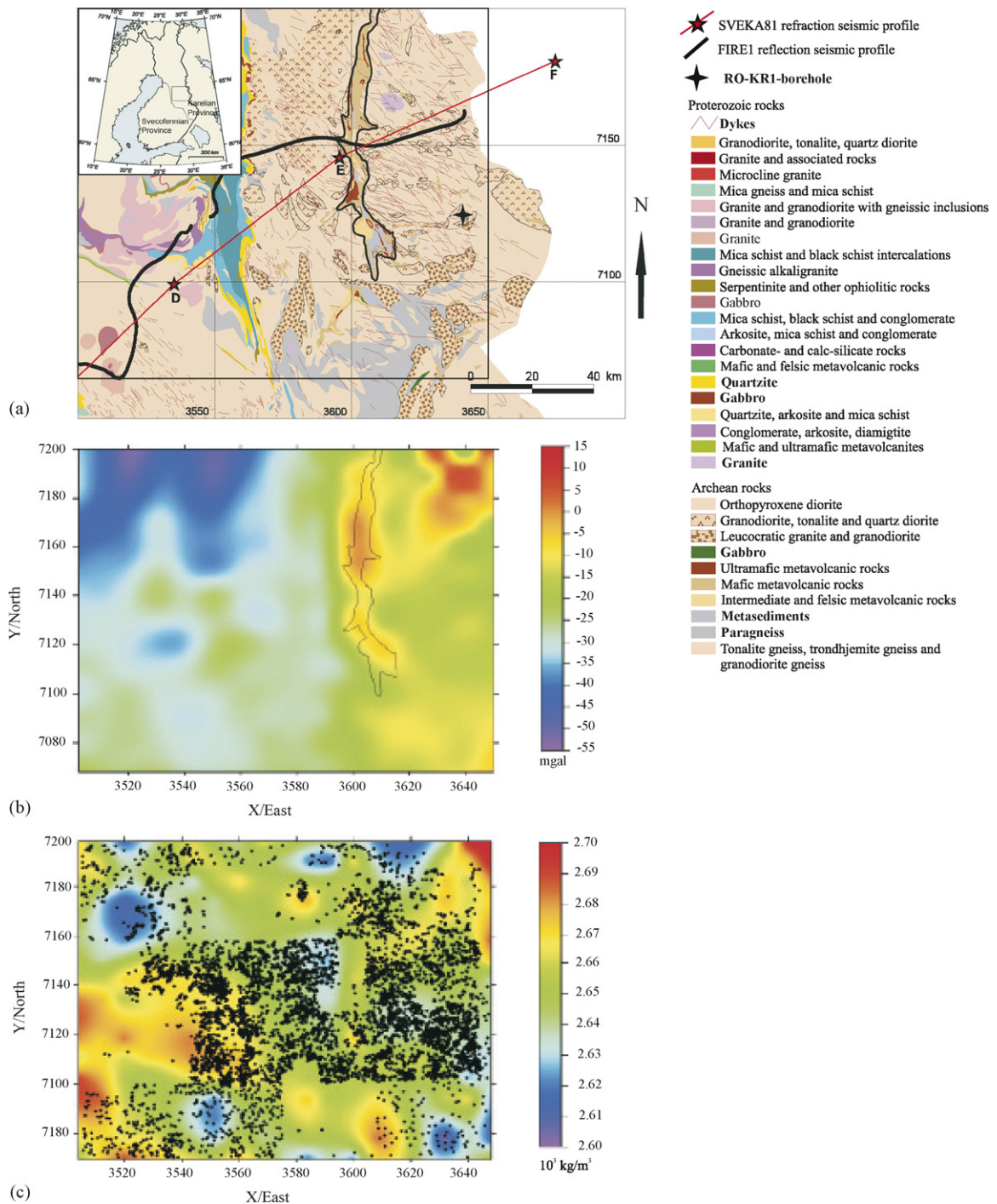


Fig. 1. (a) Position of the SVEKA'81 and FIRE1 profiles on 1:1 000 000 geological map of Finland (after Korsman et al., 1997). Geographical location of the selected area is shown in the upper left corner. The research area of the gravimetric modelling is bordered with black rectangle. Also Kuhmo Greenstone Belt is bordered with black line. (b) The Bouguer-anomaly map of the research area (Korhonen et al., 2002) with the borders of the Kuhmo Greenstone Belt. The average linear spacing of the gravity observations stations was 5 km and the Bouguer anomaly map used in this study is defined on 10 km $\times$ 10 km regular grid (Korhonen et al., 2002). (c) The bulk density map of the research area (Pirttijärvi, 2005) with the sampling stations for the density measurements.

events (2800–2790 Ma ago). The major lithostatic units exposed at present erosion level are submarine lava plains, submarine to subaerial central volcanic complexes, and submarine to subaerial fault-bounded basin fill. After its deposition the belt has been deformed in multiple deformation phases during Archean and early Proterozoic. Proterozoic mafic dykes crosscut both greenstones and granitoids (Luukkonen, 1992; Vaasjoki et al., 1993, 1999).

There are multiple theories to explain the geodynamic environment during the deposition of the Kuhmo Greenstone Belt. The main theories include subduction-related magmatic arc or marginal basin settings (Piirainen, 1988; Taipale, 1983, 1988), crustal downsagging (Martin et al., 1984) and intracontinental rift model (Luukkonen, 1992).

3. Data

In the present paper we used the digital map of the Bouguer anomaly compiled by the Geological Survey of Finland from the results of gravity measurements owned by the Finnish Geodetic Institute (Korhonen et al., 2002). The average linear spacing of the observations stations is 5 km and the Bouguer anomaly map used in this study is defined on 10 km × 10 km regular grid (Korhonen et al., 2002; Elo, 1997; Kääriäinen and Mäkinen, 1997). The Bouguer anomaly map is presented in Fig. 1b. The coordinate system is the National Finnish Coordinate System (KKJ) (Hirvonen, 1949; Ollikainen et al., 2001).

The digital map of the surface bulk density (Fig. 1c) was compiled from results of laboratory measurement of density of rock samples collected all over Finland (Korhonen et al., 1997). As the sampling points were not evenly distributed, particularly in the relatively small area considered in this study, the density map was obtained by interpolation of the raw data to a regularly spaced grid of 2 km × 2 km. The density values in the nodes of the grid were obtained as weighted sum of density at points closest to the node and also by taking into account the boundaries of the geological structures from 1:1 000 000 geological map of Finland (Pirttijärvi, 2005). The borehole data used were obtained as a part of the search for the site for radioactive waste disposal. The borehole RO-KR1 (Fig. 1a) is 980 m deep and it was drilled in 1987. The studies of the rock samples of the drill core included petrographic and mineralogical determinations of rock types and fracture fillings and their geochemical and petrophysical properties (Anttila et al., 1990).

4. P-wave velocities in the Kuhmo Greenstone Belt based on the SVEKA'81 wide-angle reflection and refraction seismic profile

SVEKA'81 wide-angle reflection and refraction profile (Fig. 1a) was made 1981 and it was the first long seismic profile in Finland aiming at studying regional-scale geological structures. The eastern part of the profile crossed the Kuhmo Greenstone Belt area (Fig. 1a). The distance between recording stations along the profile was about 2 km. The geometry of shotpoints and recording stations makes it possible to recover the velocity inhomogeneities within the crust with the size of several dozens of kilometres. Due to the absence of thick sediments in the area crossed by the profile, high-quality data for both P- and S-waves reflected and refracted from the crust were obtained (Fig. 2). The first velocity model of the SVEKA'81 profile was made by Luosto et al. (1984). After that Yliniemi enhanced the profile to the north-east (Yliniemi et al., 1996) and obtained revised P- and S-wave velocity models (Kozlovskaya and Yliniemi, 1999), demonstrating that the Moho depth changes from almost 60 to 40 km beneath the belt (Fig. 3c).

The P-wave velocity model (Kozlovskaya and Yliniemi, 1999) was obtained by trial-and-error modelling using ZPLOT program (Zelt, 1994), e.g. synthetic travel times and synthetic seismograms were calculated with SEIS83 raytracing program (Cerveny and Psencik, 1983; Komminaho, 1998) and compared to recordings of the SVEKA profile. The velocity model of the SVEKA profile has one major boundary in the uppermost crust in the vicinity of the Kuhmo Greenstone Belt (Fig. 3a and b) with P-wave velocities of 5.85–6.15 km/s above the layer and 6.2–6.35 km/s below. The boundary is most probably an unconformity with more fractured rocks above it. As can be seen from the seismic recordings of the shotpoints E and D and also from the velocity model, the Kuhmo Greenstone Belt is not marked by any lateral change of velocity in the place where the maximum of the Bouguer anomaly is observed.

5. Petrophysical constraints: seismic velocities and density of rocks of the Kuhmo Greenstone Belt calculated from the modal mineralogy

To constrain the seismic velocities and density of the Kuhmo Greenstone Belt and to find the explanation of the apparent disagreement between low seismic velocities and the gravity high, we used petrophysical data from the borehole RO-KR1 in Romuvaara area (Anttila et al., 1990, Fig. 1a). The surrounding area is mainly comprised of late

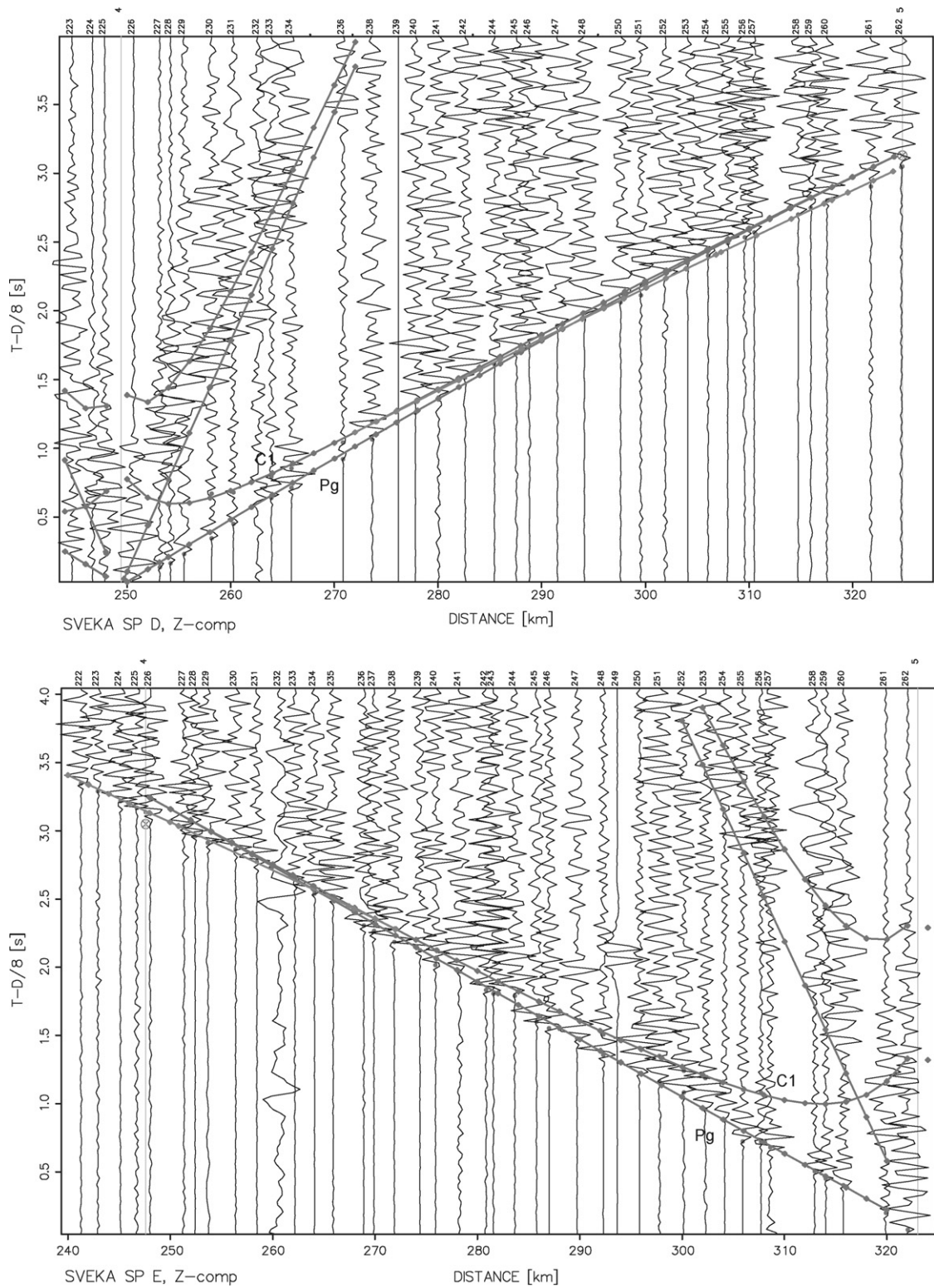


Fig. 2. The raytracing results for the 2D P-wave velocity model of Fig. 3a. First arrival times and reflections have been marked with dots. Calculated refracted and reflected waves are marked with lines for both P- and S-waves. First arrivals of P-waves are denoted as Pg and the P-wave reflection from a boundary in upper crust is denoted as C1.

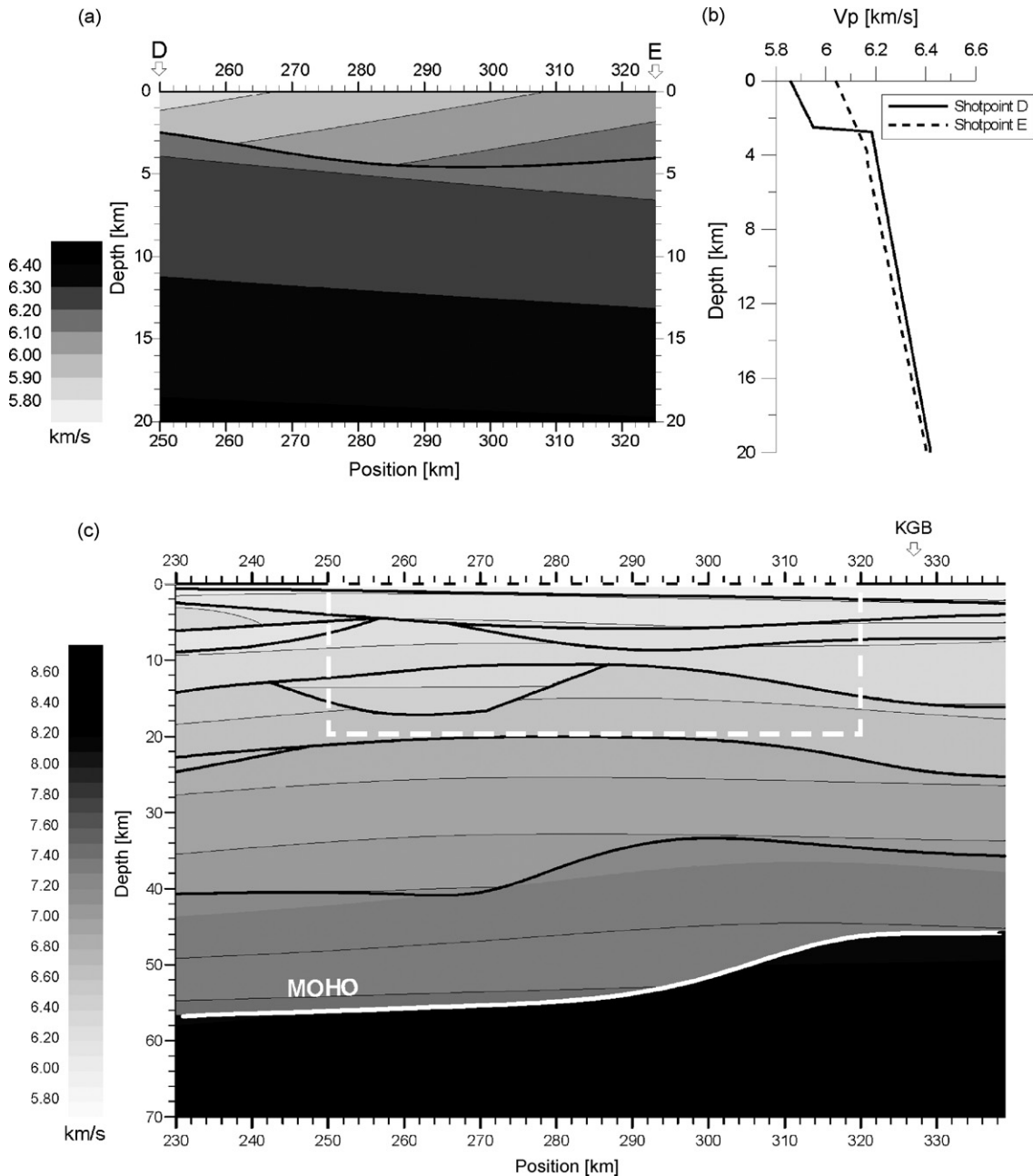


Fig. 3. P-wave velocity model of the SVEKA'81 profile between shotpoints D and E. Subplot (a) is the 2D velocity model developed by forward raytracing. Subplot (b) shows 1D velocity model under the shotpoints. Subplot (c) is adopted from the earlier work by Yliniemi et al. (1996). The area of subplot (a) is marked with white rectangle in subplot (c). The Moho boundary has been marked with white line and the Kuhmo Greenstone Belt (KGB) with an arrow in subplot (c).

Archean banded amphibolites, migmatites, granitoids and the metavolcanic rocks and metasediments of the Kuhmo Greenstone Belt. The borehole is almost 1 km deep and samples were taken from the drill core with quite even distances between them. To eliminate the influence of random non-lithological factors like porosity and seismic anisotropy, we estimated the physical properties of main types of rocks of the belt from their modal mineralogy using Monte-Carlo simulation. As it was demonstrated by Kozlovskaya et al. (2004b), such a modelling makes it possible to estimate the influence of certain minerals on density and seismic velocities.

Table 1
The mineral content (by weight) limits for the rock types used in this research

	Granite	Granodiorite	Tonalite	Amphibolite
Plagioclase	24.9–40.8	39.6–51.3	30.3–65.4	17.7–46.7
Quartz	19.8–42.5	23.6–37.2	15.7–33.7	0–15.1
Potassium feldspar	16.5–45.4	9.3–20.2	0–5.2	0
Biotite	0–12.7	4.8–8.1	7.6–36.4	0–13
Muscovite/sericite	0.1–8.1	0.2–2.2	0–9.9	0–2.1
Epidote	0–5.7	0.4–2.3	0.2–16.4	0–9
Amphibole	0–0.4	0	0	25.1–67.2
Number of samples	8	4	7	6

Also the number of the samples per rock type is included. The rock samples are from borehole RO-KR1 and are sampled by Lindberg and Kukkonen (in Anttila et al., 1990).

In homogenous material the seismic velocities are related to the density and elastic properties of the material, which, in turn, can be characterized by elastic moduli. The early work on the properties of the composite materials like rocks was done by Voigt (1990) and Reuss (1929). The Voigt relationship leads to the upper boundary below which the values of the elastic parameters of the compound material must lie, while the Reuss relationship defines the lower boundary. One method to obtain values between these two boundaries was proposed by Alexandrov and Eisenberg (1966) and it uses the logarithms of the moduli. For example, the Young's modulus of the rock would be defined as

$$\ln E_A = \sum_{i=1}^n V_i (\ln E_i), \quad (1)$$

where E_A is the Young's modulus of the composite material, E_i the Young's modulus and V_i the volume fraction related to the component material i . This method has been used in the present work.

If material is assumed to be isotropic, its compressional and shear seismic velocities can be calculated from the Young's modulus E , shear modulus μ , and Poisson ratio σ (Schön, 1998):

$$V_p = \sqrt{\frac{E(1-\sigma)}{\rho(1-2\sigma)(1+2\sigma)}}, \quad V_s = \sqrt{\frac{\mu}{\rho}}, \quad (2)$$

where ρ is the material density. For a composite material density can be defined as

$$\rho = \sum_{i=1}^n V_i \rho_i, \quad (3)$$

where ρ_i is the density of the component material i .

Lindberg and Kukkonen (in Anttila et al., 1990) analysed the mineralogical composition of the rock samples from the borehole RO-KR1. From these samples we estimated the minimum and maximum volume fractions of major rock forming minerals in most abundant rock types of the belt. Samples with anomalously high content of certain minerals were excluded.

Rock types selected were granite, granodiorite, tonalite and amphibolite (the samples were classified by Lindberg and Kukkonen (in Anttila et al., 1990)). The mineral content limits of these minerals for the four rock types are listed in Table 1. Seven most abundant minerals in the samples were plagioclase, quartz, potassium feldspar, biotite, muscovite, epidote and amphibole. Elastic parameters E , μ and σ and density ρ for these minerals were taken from Dortman (1992) and are summarized in Table 2.

The Monte-Carlo method was used to calculate the seismic velocities and densities for the rocks selected using the data of Tables 1 and 2. First 10 000 samples of each rock type were calculated with a random number generator. Then the elastic parameters, the seismic P- and S-wave velocities, and the density were calculated for each rock using Eqs. (1)–(3) and plotted to the density–P-wave velocity plot (Fig. 4a), density–S-wave velocity plot (Fig. 4b), and density– V_p/V_s plot (Fig. 4c).

As it was demonstrated by Kozlovskaya et al. (2004b), the comparison of the density–velocity relationships to certain reference curves makes it possible to understand the influence of the main rock forming minerals on rock

Table 2

The elastic properties (Young's modulus E , shear modulus μ , and Poisson's ratio σ) and densities (ρ) for minerals used in this research

	ρ (kg/m ³)	E (GPa)	μ (GPa)	σ
Plagioclase	2690	83.20	32.00	0.29
Quartz	2620	96.40	44.67	0.08
Potassium feldspar	2560	64.80	25.00	0.29
Biotite	3070	69.60	27.40	0.25
Muscovite	2880	78.90	31.60	0.25
Epidote	3400	154.20	61.00	0.26
Amphibole	3260	128.80	50.40	0.28

The parameters are taken from [Dortman \(1992\)](#).

elastic properties. The density–velocity relations by [Sobolev and Babeyko \(1994\)](#) for anhydrous magmatic rocks that did not undergo metamorphic reactions can be used as such reference curves. The relationships were calculated for major crustal lithologies having different average chemical composition (e.g. granites, granodiorites and gabbro). The reference relationships are shown by solid lines in corresponding density–velocity plots in [Fig. 4a–c](#).

[Kozlovskaya et al. \(2004b\)](#) demonstrated that rocks with high content of Ca-rich plagioclase have higher values of V_p and lower density than the reference density–velocity relationship, while high content of amphibole results in lower values of V_p and higher density compared to the reference relationship. As can be seen from [Fig. 4](#), all the rocks analysed have lower seismic velocities (in particular, P-wave velocities) and higher densities than the reference curve. This can be

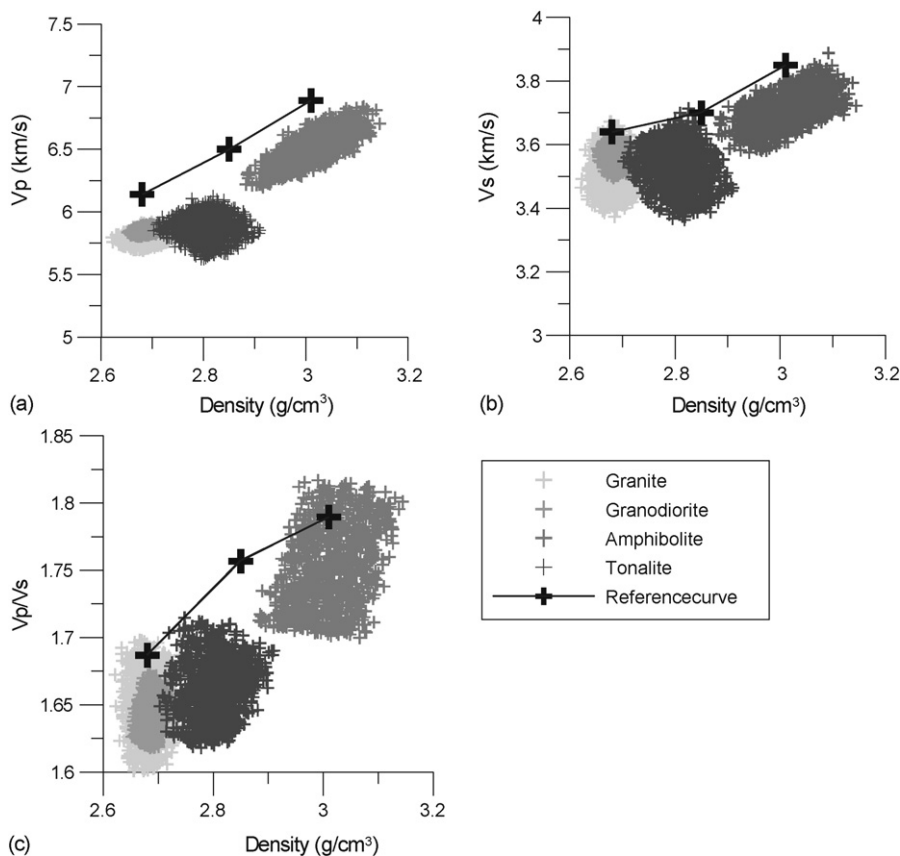


Fig. 4. Density–seismic velocity diagrams calculated with Monte Carlo method from modal mineralogy. Subplot (a) is the density–P-wave velocity diagram, subplot (b) is the density–S-wave velocity diagram and subplot (c) is the density– V_p/V_s diagram. The density–velocity relations by [Sobolev and Babeyko \(1994\)](#) for anhydrous magmatic rocks that did not undergo metamorphic reactions are shown by thick lines.

explained by not only high content of amphibole, but also by relatively high content of biotite and muscovite (Table 1). The latter minerals have rather high densities and low values of isotropic elastic parameters (Table 2). This specific modal mineralogy of the rocks of the Kuhmo Greenstone Belt explains the gravity high and relatively low seismic velocities in the uppermost crust within the belt. In particular, tonalities have low seismic velocities (5.6–6.1 km/s) similar to those detected by the SVEKA profile and high densities (e.g. $(2.75\text{--}2.90) \times 10^3 \text{ kg/m}^3$). This suggests that tonalitic rocks are widely spread within the belt, while other rocks are subordinate.

In addition, the rocks of the belt have generally lower P- and S-wave seismic velocities, but higher densities than the velocities and density in the middle crust beneath the belt (6.30–6.65 km/s, 3.68–3.8 km/s and $2.7\text{--}2.85 \times 10^3 \text{ kg/m}^3$, respectively) (Kozlovskaya and Yliniemi, 1999). This indicates their different composition and implies that the belt does not continue to the middle crust. We tested this suggestion by 3D gravity modelling of the uppermost crust around the belt.

6. 3D structure of the belt obtained by gravity forward modelling

For 3D gravity modelling and inversion we used an interactive computer program for visualization and editing of large-scale 3D models (Bloxxer) and a gravity modelling and inversion software (Grabox) based on a 3D block model (Pirttijärvi et al., 2004).

The starting model was made by selecting about $150 \text{ km} \times 130 \text{ km} \times 16 \text{ km}$ rectangular block from the existing regional 3D density model for central and southern Finland (Kozlovskaya et al., 2004a). The regional model does not include such shallow features as the Kuhmo Greenstone Belt. The regional model was also used to calculate the effect of the densities beside and below the research area. In this way features that affected the research area from outside could be eliminated from the data.

The selected part of the regional 3D model was approximated by $8 \text{ km} \times 8 \text{ km} \times 2 \text{ km}$ blocks. In the model the average density of 2 km thick layers increases downwards and densities of each block are calculated as the residual of the average density of the layer and the density value of the block. Such approximation of the density model makes it possible to use absolute density values in the gravity modelling instead of relative ones (Kozlovskaya et al., 2004a).

The major density contrast in the starting model is a density contrast at the boundary between upper and middle crust. However, this contrast is not enough to explain the positive gravity above the belt. As it was demonstrated in Kozlovskaya et al. (2004a), the pronounced regional trend in the vicinity of the belt that is partly explained by the Moho uplift by more than 20 km. In our modelling we approximated this trend by a function

$$g_b = g_0 + (x - x_0) dg_x + (y - y_0) dg_y, \quad (4)$$

where g_b is referred hereafter as base anomaly, g_0 is the base anomaly at the south-west corner of the model with coordinates x_0 and y_0 and dg_x and dg_y are the gradients of the base anomaly field. These were found using the Grabox program, namely the base value of -46.708 mgal at south-west point of study area (3500, 7070) and gradients of $0.21497 \text{ mgal/100 km}$ toward north and $0.08485 \text{ mgal/100 km}$ toward east.

To fit the observed Bouguer anomaly, a 4 km deep body with constant density representing the belt was added to the model (Figs. 5a and 6a–c). The density value of $2.84 \times 10^3 \text{ kg/m}^3$ was selected basing on result of 2D gravity modelling in (Kozlovskaya and Yliniemi, 1999). In their work they tested multiple density values and found this value to give best results in their 2D model along the SVEKA'81 profile. As it was shown in Section 5, this value corresponds to the average density of tonalities. It is also in agreement with the data about the density of rocks of the belt obtained from laboratory measurements (Elo et al., 1978; Elo, 1997). The shape and position of the body were defined from the geological map (Fig. 1a). This is anyway quite rough approximation, because the size of blocks in the model was $8 \text{ km} \times 8 \text{ km} \times 2 \text{ km}$ and, in accordance to geological data, the belt is just over 10 km at its widest and mostly about 5 km wide.

The final model was made by trial and error method using Grablox program to compute the Bouguer anomaly of the model and to compare it to the observed Bouguer anomaly. With the regional field described above, the maximum and minimum differences between measured and calculated field are about 5 and -5 mgal , respectively, if the boundary effects at the edges of the model are ignored (Fig. 7a).

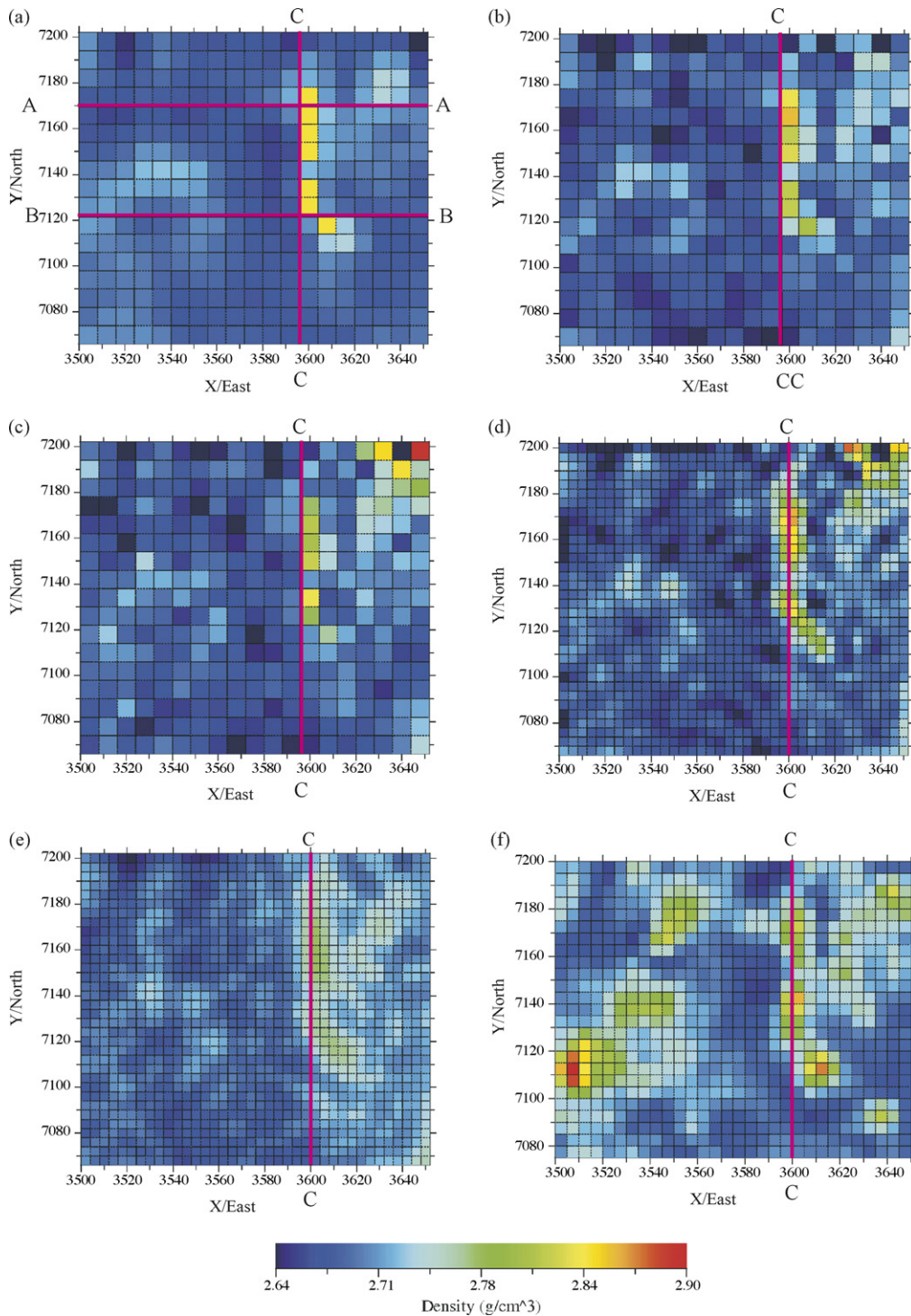


Fig. 5. The density at the surface for different 3D density models. Subplot (a) is the initial model with $4\text{ km} \times 4\text{ km} \times 2\text{ km}$ blocks made with trial-and-error method. Subplot (b) is the density optimised version of the initial model. Subplot (c) shows the model after height and subsequent density optimisation. Subplot (d) is the density optimised version of the initial model after the blocks have been divided into two in both north-south and east-west directions. Subplot (e) shows the model after the density optimisation, but with 3D smoothing. Subplot (f) is the model obtained by the Occam inversion from the initial model with the density in the uppermost layer equal to the bulk density in Fig. 1c. The red lines mark location of the sections shown in Fig. 6. Both axes are in kilometers.

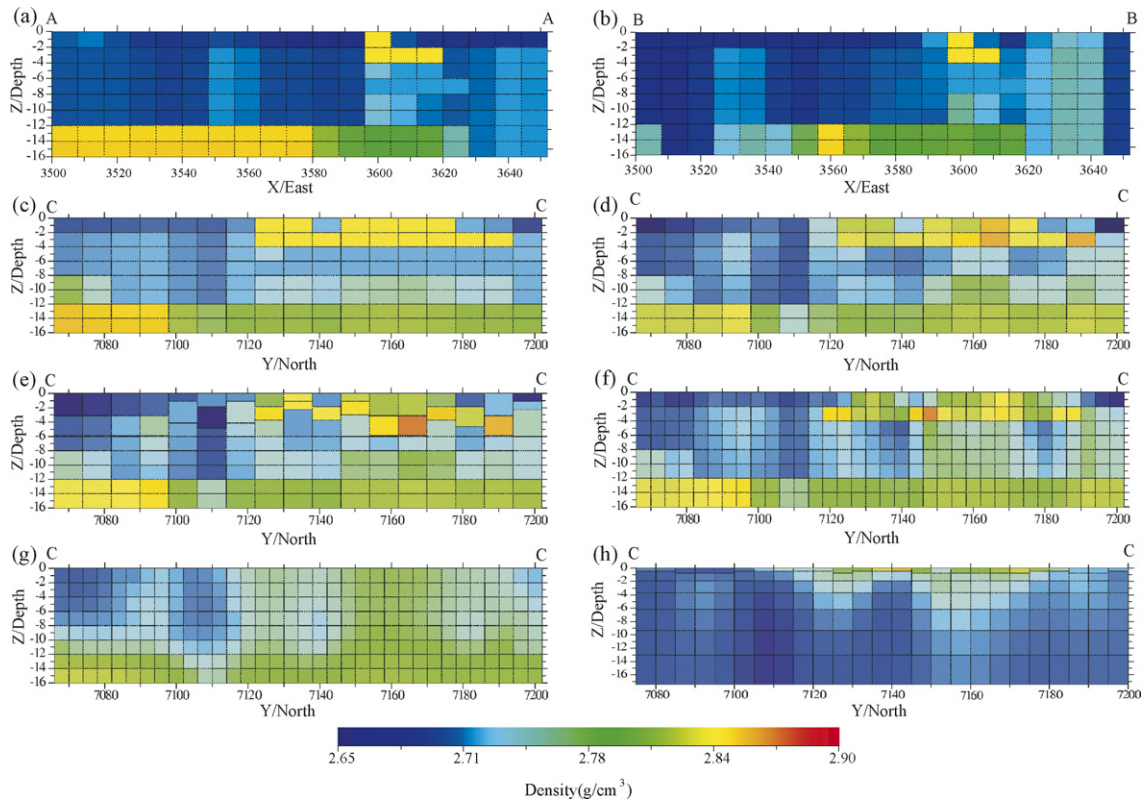


Fig. 6. Selected vertical sections across the 3D density models. The location of the sections is marked with red lines in Fig. 5. Subplots (a)–(c) correspond to the sections A, B and C in Fig. 5a, respectively. All the other sections are north-south directed sections marked with C in Fig. 5. Subplots (d)–(h) correspond to subplots (b)–(f) in Fig. 5, respectively.

7. Density model of the belt obtained from the gravity data inversion

After the model was made by trial-and-error as good as possible, inversion was tried in order to improve the fit to the observed Bouguer anomaly. However, inversion of the gravity data is generally non-unique; therefore, we applied different methods of gravity data inversion in order to evaluate the stability and uniqueness of the solutions obtained.

The program Grablox uses two major inversion methods, namely, singular value decomposition (SVD) and Occam inversion (Hjelt, 1992). In each method three possible ways to parameterise the model (height, density and height + density inversions) are available. In the density inversion the sizes of blocks are kept constant and density of blocks is optimised. In the height inversion densities and their horizontal sizes are fixed and block heights are optimised. It is possible to use vertical, horizontal and 3D smoothing, which is regulated by several parameters. The parameters regulate the maximal change of density of the blocks and define whether the inversion should give more importance to minimizing the data error or to the model roughness. The strength of the smoothing is controlled by so-called F-option (factor), that may take values between 0 and 1. The same parameterisation methods are used in the Occam inversion.

As the gravity data inversion is generally non-unique, different inversion algorithms and the selected smoothing and grid size may result in different density models. Thus in the following sections we investigated the effect of these factors on the solution obtained. For the background density we used the mean-layer background density method in which background density (the density surrounding the research area) was defined separately as the mean density of that layer.

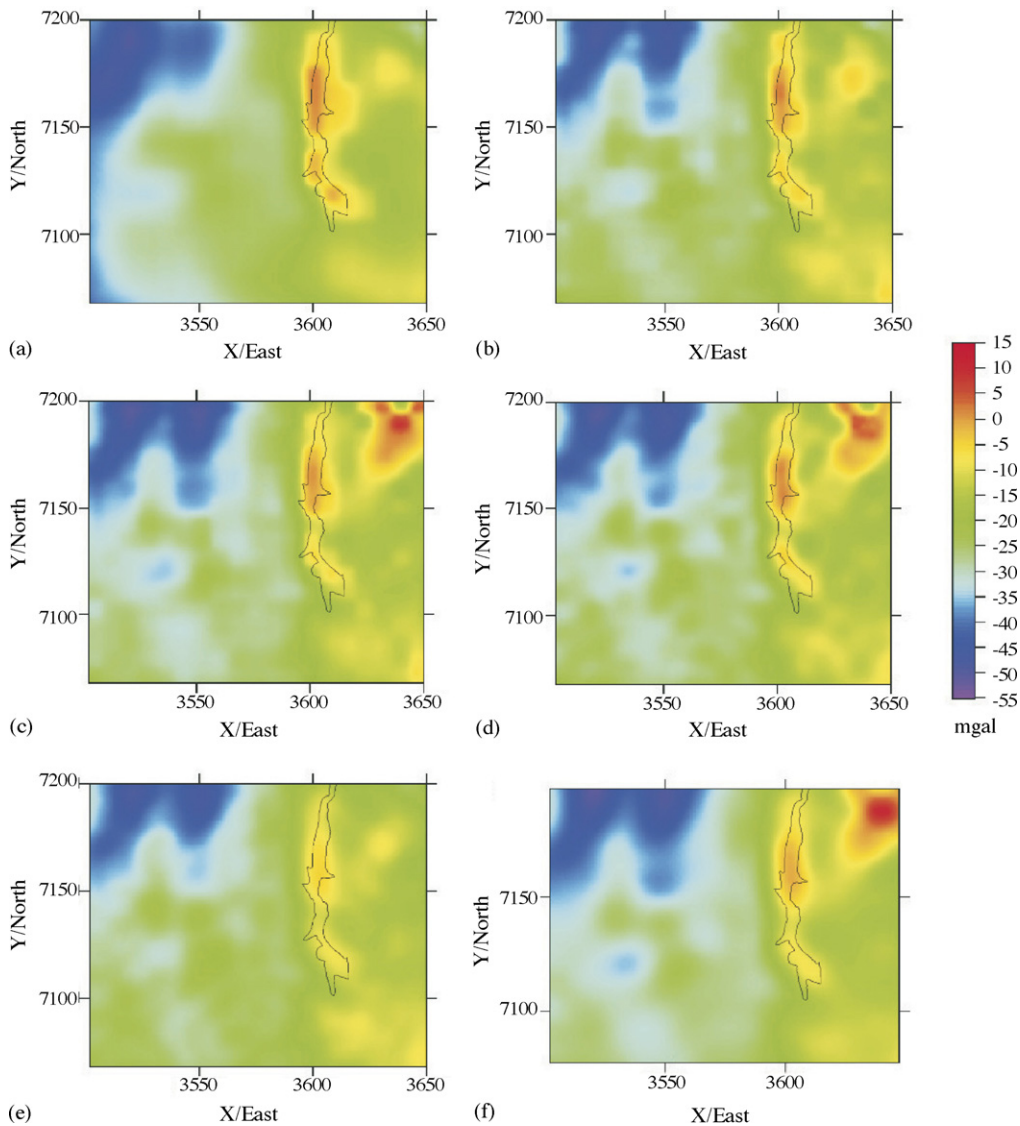


Fig. 7. Calculated Bouguer anomalies of the selected gravity modelling results with the boundary of Kuhmo Greenstone Belt. Subplots (a)–(f) correspond to the models shown in Fig. 5a–f, respectively.

7.1. Inversion using SVD technique

7.1.1. $8\text{ km} \times 8\text{ km} \times 2\text{ km}$ model

The trial-and-error model with $8\text{ km} \times 8\text{ km} \times 2\text{ km}$ blocks was used as the starting model for the inversion. Both density and height inversion were applied.

The height inversion seemed to give better results when used together with the density inversion. If only the height inversion was used, the algorithm tried to fit all gravity anomalies by varying block heights, and the greenstone belt was “broken” into many pieces. In the case of density inversion without smoothing, the density differences between blocks near the surface of the model became quite large, and the densities did not agree with the petrophysical data. However, if the 3D smoothing was too large, then the density contrasts between the greenstone belt and the surrounding bedrock could not be modelled. In the worst case the whole greenstone belt almost disappeared before small enough difference between measured and calculated data was obtained.

Figs. 5b and 6d show a model obtained by the density inversion after 15 iterations. The RMS value for the model is 0.062 and difference between calculated and measured Bouguer anomaly varies mainly between +4 and –4 mgal (Fig. 7b). Larger differences near boundaries of the study area are explained by side effects. This model compensates the thin areas of the belt by adding smaller densities to the blocks where the belt is less than 8 km wide on the geological map as in the southern part of the belt.

When the height inversion (2 iterations) was followed by the density inversion (10 iterations) applied to layers at the top of the model, the result shown in Figs. 5c and 6e was obtained. The RMS value for the model is 0.021 and the difference between calculated and measured Bouguer anomaly varies between +4 and –2 mgal (Fig. 7c). The model has lower densities in the surface layer and higher densities in the second layer. This is similar to the model obtained with the density inversion only. The height inversion lowered the lower boundary of the belt from the depth of 4 km in the starting model to the depth of 6 km.

The result demonstrates that approximation of the model by $8\text{ km} \times 8\text{ km} \times 2\text{ km}$ blocks is nearly too rough to this work. Therefore, also finer grid was tried.

7.1.2. $4\text{ km} \times 4\text{ km} \times 2\text{ km}$ model

Starting model with $4\text{ km} \times 4\text{ km} \times 2\text{ km}$ blocks was made from the model with $8\text{ km} \times 8\text{ km} \times 2\text{ km}$ blocks obtained by forward trial-and-error modelling by subdividing all blocks in north-south- and east-west-directions. This resulted in significant increase of the calculation time. Because of this, only different types of density inversion were tried.

The model in Figs. 5d and 6f was obtained after eight iterations using density inversion without smoothing. The RMS value for the model was 0.022 and the difference between measured and calculated Bouguer anomaly was between –3 and +1 mgal (Fig. 7d).

When 3D smoothing was applied, the densities of the blocks inside greenstone belt were again smoothed towards the host density, but not as much as with model composed of $8\text{ km} \times 8\text{ km} \times 2\text{ km}$ blocks. To obtain the model presented in Fig. 5e, we used F-option equal to 0.25. The RMS value for the model is 0.069. The vertical section across the model is shown in Fig. 6g and the calculated Bouguer anomaly in Fig. 7e.

However, with the smoothing we obtained other regional features of the density distribution, which were not seen with normal density optimisation. For example, the Kainuu schist belt can be seen as a relatively high density between $X=3530$ and 3560 (Fig. 5e), while the greenstone belt is stretching along coordinate $X=3600$.

7.2. The test with Occam inversion

The Occam inversion was tried with model composed of $5\text{ km} \times 5\text{ km}$ horizontal blocks with depth increasing from 0.6 to 4.2 km, so that the first layer was 0.6 km deep and the second one two times thicker, the third one three times thicker, etc., the seventh layer being 4.2 km thick. The density values in the first layer of the initial model were obtained from the bulk density map (Fig. 1c). In other layers the density was assumed to be constant ($2.65 \times 10^3\text{ kg/m}^3$); that is equal to the average density in the area. The same value was used also as a background density. Regional field was calculated as described in Section 6.

At first iteration, the Occam height optimisation was applied to evaluate the thickness of the surface layer. After that the parameters of the layer were fixed. Then the Occam density inversion was tried with different values of F-option. The RMS value for the final model is 0.012. However, such inversion resulted in artificial density models, with unrealistically lower density values beneath the surface layer (Figs. 5f, 6h and 7h). In addition, all cells with maximum density (densities that were $2.75 \times 10^3\text{ kg/m}^3$ or higher) at the surface have cells with minimum density ($2.60 \times 10^3\text{ kg/m}^3$ and lower) just below them except the Kuhmo Greenstone belt area. This may indicate that the surface density values, taken from petrophysical measurements, were overestimated.

8. Discussion and conclusion

The main conclusions that follow from our study are

1. Petrophysical modelling demonstrates that the main rocks types of the Kuhmo Greenstone Belt have lower seismic velocities (in particular, P-wave velocities) and higher densities than the density–velocity relationship by Sobolev

- and Babeyko (1994) selected as a reference curve. This can be explained by high content of amphibole, biotite and muscovite. This specific modal mineralogy explains the gravity high and relatively low seismic velocities in the area of the Kuhmo Greenstone Belt.
2. The rocks of the belt have generally lower P- and S-wave seismic velocities, but higher densities than the velocities and density in the middle crust beneath the belt. This indicates their different composition and implies that the belt does not continue to the middle crust.
 3. The average density of the surrounding rock west of the belt differs only slightly from the density east of the belt (2.69×10^3 and 2.72×10^3 kg/m³, respectively). Therefore, the difference in regional Bouguer anomaly west and east of the belt is explained by the trend produced by the Moho uplift (Fig. 3c). This verifies the previous results by Kozlovskaya and Yliniemi (1999).
 4. Based on both forward modelling and inversion, the Kuhmo Greenstone Belt is a surface structure that is 10–12 km wide with depth less than 7 km and average density of 2.84×10^3 kg/m³. The belt has no deep “root” in the middle crust and lower crust. Values of the depth to the lower boundary of the belt obtained in various inversion trials did not vary significantly.

The shape of the belt revealed in our study allows us to examine different geodynamic theories explaining its formation. Generally, the Archean greenstone belts can be formed by various processes and because of that by tectonic slices of Archean ophiolites, island arc basalts, oceanic plateaus, continental basalts and rift sequences (Luukkonen, 1992; de Wit, 1998; Puchtel et al., 1998; Samsonov et al., 2005; Benn et al., 2006). Most of the Archean greenstone belts are composed of geodynamically contrasting rock assemblages; that is why it is not easy to distinguish between different models explaining their origin.

Like others Archean greenstone belts, the Kuhmo Greenstone Belt had complex evolution. Archean rocks in the Kuhmo area are roughly 2650–3100 Ma old. These rocks were deformed in six late Archean deformation phases and at least two early Proterozoic stages of reactivation (Luukkonen, 1992). The migmatitic tonalite-trondhjemites containing the amphibolitic enclaves on the area around Kuhmo Greenstone Belt represent the remnants of the formerly more extensive, about 3000 Ma old, protocrust. This crust was first deformed ca. 2843 ± 18 Ma ago with amphibolite-granulite facies metamorphism and the accompanying plutonic event. The next major plutonic period spanned between ca. 2740 and 2690 Ma. Between these plutonic two events (2800–2790 Ma ago), there was a short-period extension phase during which the greenstones of the Kuhmo Greenstone Belt were deposited. The belt was deformed multiple times during the successive late Archean folding-faulting phases. The major lithostratigraphic units of the Kuhmo Greenstone Belt exposed at present erosion level are submarine lava plains, submarine to subaerial central volcanic complexes, and submarine to subaerial fault-bounded basin fill (Luukkonen, 1992).

The geodynamic models for the Kuhmo Greenstone Belt included subduction-related magmatic arc or marginal basin settings (Pirainen, 1988; Taipale, 1983, 1988) or crustal downsagging (Martin et al., 1984). Luukkonen (1992) proposed intracontinental rift model, in which he explained the origin and evolution of the belt by the mantle plume arising from a thermal boundary layer deep within mantle, or from the core–mantle boundary. This resulted in stretching and thinning of the crust, and incipient rifting, but not to the extent of forming new oceanic crust (Luukkonen, 1992). Ruotoistenmäki (1996) suggested thermal currents as the driving force behind the tectonic model of Luukkonen (1992).

All these models have been developed using mainly geochemical, geochronological and structural data. However, Peschler et al. (2004) demonstrated that 3D regional-scale density models of greenstone belts can be used to distinguish between various models of their origin. They used gravity modelling to analyse 3D structures of greenstone belts from various Precambrian regions ranging in age from ca. 3400 to 2700 Ma and revealed that the belts in the terranes older than 2800 Ma are relatively thick and commonly have deep-seated root zones, when compared to the batholiths of the Late Archean terranes. They suggested that the presence (Middle Archean) or quasi-absence (Late Archean) of deep batholith roots may indicate changes in continental geodynamics and in the processes of cratonic formation and batholith assembly from a crustal-scale diapirism-type model prior to 2800 Ma to a more plate tectonic-like model after 2800 Ga. These findings, together with the results obtained in our study and isotopic ages of the Kuhmo Greenstone Belt may suggest that it was formed as a result of subduction like processes rather than intracontinental rifting. This agrees with recent geochemical and geochronological studies of other Archean greenstone belts in the Fennoscandian Shield (Puchtel et al., 1998; Samsonov et al., 2005) which suggested an accretionary origin of the belts, the volcanosedimentary and plutonic complexes of which were formed in a convergent plate margin setting.

Because of these findings and our results, a new geodynamic model that includes subduction-related processes should be built not only for the Kuhmo Greenstone Belt, but also for the whole Karelian craton.

Acknowledgements

This study was funded by the Academy of Finland (Project 3D crustal model of the Finnish part of the SVEKALAPKO study area), Suomalainen Konkordia-liitto, Tauno Tönnöngin säätiö and Tekniikan edistämissäätiö. The gravity map used was made by J. Korhonen of the data by Finnish Geodetic Institute and Geological Survey of Finland. The authors thank Dr. Markku Pirttijärvi for the softwares Bloxer and Grablox, with which the density models were compiled and gravity fields calculated and inversion tested, and also for the surface density map. Special thanks go to Professors G. Ranalli and K. Benn as well as to an unknown reviewer for their valuable suggestions and comments.

References

- Alexandrov, K.S., Eisenberg, L.A., 1966. Sposob vycisleniya fizicheskikh konstant polikristallicheskich materialov. Dokl. A. N. SSSR, 1967 No. 5.
- Anttila, P. (Ed.), Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M., Wikström, L., Öhberg, A., 1990. Final disposal of spent nuclear fuel in Finnish bedrock—Romuvaara site report. Posiva 99-11. Posiva Oy, Finland.
- Benn, K., Mareschal, J.-C., Condie, K. (Eds.), 2006. Archean geodynamics and environments. Geophysical monograph 164. American Geophysical Union, United States of America, 320 pp.
- Bleeker, W., 2002. Archean tectonics: a review, with illustrations from the Slave craton. Geological Society of London, Special Paper 199, pp. 151–181.
- Cerveny, V., Psencik, I., 1983. SEIS83—numerical modelling of seismic wave fields in 2-D laterally varying structure by the ray method. In: Engdahl, E.R. (Ed.), Documentation of Earthquake algorithms, World Data Cent., A Solid Earth Geophys., Rep. SE-35, pp. 36–40.
- de Wit, M.J., 1998. On Archean granites, greenstones, cratons and tectonics—does the evidence demand a verdict? Precambrian Res. 91, 181–226.
- Dortman, N.B. (Ed.), 1992. Petrophysics. A Handbook. Book 1, Rocks and Minerals. Nedra, Moscow (in Russian).
- Eilu, P., Sorjonen-Ward, P., Nurmi, P., Niiranen, T., 2003. A review of gold mineralization styles in Finland. Econ. Geol. 95, 1329–1353.
- Elo, S., Puranen, R., Airo, M., 1978. Geological and areal variation of rock densities, and their relation to some gravity anomalies in Finland. Geoscripter 10, 123–164.
- Elo, S., 1997. Interpretation of the gravity map of Finland. Geophysica 33 (1), 51–80.
- Gaál, G., Gorbatshev, R., 1987. An outline of the Precambrian evolution of the Baltic shield. Precambrian Res. 35, 15–52.
- Hamilton, W.B., 2003. An alternative Earth. GSA Today 13, 4–12.
- Hjelt, S.-E., 1992. Pragmatic Inversion of Geophysical Data. Springer-Verlag, Germany, 262 pp.
- Hirvonen, R.A., 1949. Die Gauss-Krügerische Projektion für breite Meridianstreifen auf dem Internationalen Ellipsoide. Suomen Geodeettisen laitoksen julkaisuja, vol. 36, Helsinki, Finland.
- Komminaho, K., 1998. Software manual for programs MODEL and XRAYs—a graphical interface for SEIS83 program package. Report No. 20. University of Oulu, Department of Geophysics, 31 pp.
- Korhonen, J., Säävuori, H., Kivekäs, L., 1997. Petrophysics in the crustal model program of Finland. In: Autio, S. (Ed.), Geological Survey of Finland, Current Research 1995–1996, GSF, Special Paper 23, pp. 157–173.
- Korhonen, J.V., Aaro, S., All, T., Elo, S., Haller, L.Ä., Kääriäinen, J., Kulinich, A., Skilbrei, J.R., Solheim, D., Säävuori, H., Vaher, R., Zhdanova, L., Koistinen, T., 2002. Bouguer Anomaly Map of the Fennoscandian Shield 1:2 000 000. Geological Surveys of Finland, Norway and Sweden and Ministry of Natural Resources of Russian Federation.
- Korsman, K., Koistinen, T., Kohonen, J., Wennerström, M., Ekdahl, E., Honkamo, M., Idman, H., Pekkala, Y. (Eds.), 1997. Bedrock Map of Finland 1:1 000 000. Geological Survey of Finland.
- Korsman, K., Korja, T., Pajunen, M., Virransalo, P., 1999. The GGT/SVEKA transect: structure and evolution of the continental crust in Paleoproterozoic Svecofennian orogen in Finland. Int. Geol. Rev. 41, 287–333.
- Kozlovskaya, E., Yliniemi, J., 1999. Deep structure of the Earth's crust along the SVEKA profile and its extension to the north-east. Geophysica 1–2, 111–123.
- Kozlovskaya, E., Elo, S., Hjelt, S.-E., Yliniemi, J., Pirttijärvi, M., SVEKALAPKO STWG, 2004a. 3D density model of the crust of southern and central Finland obtained from joint interpretation of SVEKALAPKO crustal P-wave velocity model and gravity data. Geophys. J. Int. 158, 827–848.
- Kozlovskaya, E., Janik, T., Yliniemi, J., Karatayev, G., Grad, M., 2004b. Density–velocity relationship in the upper lithosphere obtained from P- and S-wave velocity models along the EUROBRIDGE'97 wide-angle reflection and refraction profile and gravity data. Acta Geophys. Polonia 52 (4), 397–424.
- Kukkonen, I., Heikkinen, P., Ekdahl, E., Hjelt, S.-E., Yliniemi, J., Jalkanen, E., and FIRE Working Group, 2006. Acquisition and geophysical characteristics of reflection seismic data on FIRE transects, Fennoscandian Shield. In: Kukkonen, I.T., Lahtinen, R. (Eds.), Geological Survey of Finland, Special Paper 43, pp. 13–43.
- Kääriäinen, J., Mäkinen, J., 1997. The 1979–1996 Gravity Survey and Results of the Gravity Survey of Finland, vol. 125. Publications of the Finnish Geodetic Institute, p. 24.

- Luosto, U., Lanne, E., Korhonen, H., Guterch, A., Grad, M., Materzok, R., Perchuc, E., 1984. Deep structure of the Earth's crust on the SVEKA profile in central Finland. *Ann. Geophys.* 2, 559–570.
- Luukkonen, E., 1992. Late Archean and Early Proterozoic structural evolution in the Kuhmo-Suomussalmi Terrain, eastern Finland. *Ann. Univ. Turkuensis, Ser. A. II* 78, 1–37.
- Martin, H., Auvray, B., Blais, S., Capdevila, R., Hameurt, J., Jahn, B.M., Piquet, D., Querré, G., Vidal, P., 1984. Origin and geodynamic evolution of the Archean crust of eastern Finland. *Bull. Geol. Soc. Finland* 56 (Parts 1–2), 135–160.
- Ollikainen, M., Koivula, H., Poutanen, M., 2001. EUREF-FIN—koordinaatio ja EUREF-pistetihennykset Suomessa. *Geod. Laitos, Tiedote* 24 (in Finnish).
- Peschler, A.P., Benn, K., Roest, W.R., 2004. Insights on Archean continental geodynamics from gravity modelling of granite–greenstone terranes. *J. Geodyn.* 38, 185–207.
- Piirainen, T., 1988. The geology of the Archean greenstone-granitoid terrain in Kuhmo, eastern Finland. In: Marttila, E. (Ed.), *Archean Geology of the Fennoscandian Shield*. Geological Survey of Finland, Special Paper 4, pp. 39–51.
- Pirttijärvi, M., Kozlovskaya, E., Elo, S., Hjelt, S.-E., Yliniemi, J., 2004. 3-D geophysical crustal model of Finland. In: Ehlers, C., Eklund, O., Korja, A., Kruuna, A., Lahtinen, R., Pesonen, L. (Eds.), *Listosphere 2004. Programme and extended abstracts*, pp. 101–103.
- Pirttijärvi, M., 2005. Petrock—lithologically weighted interpolation of petrophysical data. User's Guide. Report: Q16.2/2005/1. Geological Survey of Finland.
- Puchtel, I.S., Hofmann, A.W., Mezger, K., Jochum, K.P., Shchipansky, A.A., Samsonov, A.V., 1998. Oceanic plateau model for continental crustal growth in the Archean: a case study from the Kostomuksha greenstone belt, NW Baltic shield. *Earth Planet. Sci. Lett.* 155, 57–74.
- Reuss, A., 1929. Berechnung der Fliegengrenze von Mischkristallen. *Angew. u. Mech.* 9, 49–58.
- Ruotoistenmäki, T., 1996. A schematic model of the evolution of Finnish bedrock. Geological Survey of Finland. Report of Investigation 133, 23 pp.
- Samsonov, A.V., Bogina, M.M., Bibikova, E.V., Petrova, A.Yu., Shchipansky, A.A., 2005. The relationship between adakitic, calc-alkaline volcanic rocks and TTGs: implications for the tectonic setting of the Karelian greenstone belts, Baltic Shield. *Lithos* 79, 83–106.
- Schön, J.H., 1998. *Physical Properties of Rocks: Fundamental and Principles of Petrophysics*. Pergamon, The Netherlands.
- Sobolev, S.V., Babeyko, A.Y., 1994. Modeling of mineralogical composition, density and elastic wave velocities in anhydrous magmatic rocks. *Surv. Geophys.* 15, 515–544.
- Stott, G.M., 1997. The Superior Province, Canada. In: DeWit, M., Ashwol, L.D. (Eds.), *Greenstone Belts*. Oxford Monographs on Geology and Geophysics, vol. 35, pp. 480–507.
- Taipale, K., 1983. The geology and geochemistry of the Archean Kuhmo greenstone-granite terrain in the Tipasjärvi area, eastern Finland. *Acta Univ. Ouluensis A* 151, 98, *Geol* 5.
- Taipale, K., 1988. Volcanism in the Archean Kuhmo Greenstone Belt, eastern Finland. In: Marttila, E. (Ed.), *Archean Geology of the Fennoscandian Shield*. Geological Survey of Finland, Special Paper 4, pp. 151–160.
- Vaasjoki, M., Sorjonen-Ward, P., Lavikainen, S., 1993. U–Pb age determinations and sulfide Pb–Pb characteristics from the late Archean Hattu schist belt, Ilomantsi, eastern Finland: Geological Survey of Finland, Special Paper 17, pp. 103–131.
- Vaasjoki, M., Taipale, K., Tuokko, I., 1999. Radiometric ages and other isotopic data bearing on the evolution of Archean crust and ore in the Kuhmo-Suomussalmi area, eastern Finland. *Bull. Geol. Soc. Finland* 71, 155–176.
- Voigt, W., 1990. *Lehrbuch in Kristallphysik*. Teubner-Verlag, Germany.
- Yliniemi, J., Jokinen, J., Luukkonen, E., 1996. Deep structure of the Earth's crust along the GGT/SVEKA transect extension to northeast. In: *Global Geoscience Transect/SVEKA, Proceedings of the Kuopio Seminar, Finland, November 25–26, 1993*, Espoo, p. 56.
- Zelt, C.A., 1994. ZPLOT—An Interactive Plotting and Picking Program for Seismic Data. Bullard Lab, University of Cambridge, UK.