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Deep Structure of the Earth's Crust Along the SVEKA Profile and its Extention to the North-East

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Abstract

A new integrated seismic and density model along the SVEKA profile in Finland is presented. The model has been obtained as a result of application of non-traditional approach to gravity data inversion that uses non-linear relationship between rock density, compressional and shear seismic wave velocity. The distribution of P-wave velocity and S-wave velocity along the SVEKA profile was obtained due to re-interpretation of the original SVEKA'81 experiment data and new DSS data from the continuation of the SVEKA profile to the north-east. This seismic model and the new map of gravity field in Fennoscandia (1996) were used as a base for gravity modeling. The non-linear relationship between P-wave velocity, S-wave velocity and density was obtained as an inverse gravity problem solution and then used to calculate the density model along the SVEKA profile. Satisfactory fitting of observed and calculated model gravity field has been reached. It proves that using non-linear relationship between density, V_p *and* V_s *for the purpose of gravity modeling can increase the quality of gravity inversion results. The new density model of the SVEKA profile explains the origin of some gravity field anomalies along the profile and reveals new details of the deep lithospheric structure of Fennoscandia.*

Key words: lithosphere, Earth's crust, gravity modeling, density

1. Introduction

The SVEKA DSS experiment (Fig. 1) was carried out in 1981. It was the first seismic refraction experiment of such scale in Finland aiming to obtain information about the deep lithospheric structure of the two main Precambrian units of Finland, especially in their contact zone. The first seismic model of the SVEKA based on interpretation of P-wave arrivals was published by *Luosto et al*. (1984). The more detailed model based on interpretation of both P- and S-wave arrivals was published later by *Grad and Luosto* (1987). The first results revealed big differences between the deep lithospheric structure of Proterozoic and Archaean domains in Finland and showed that new seismic investigations in this area were necessary. Such investigations aiming to

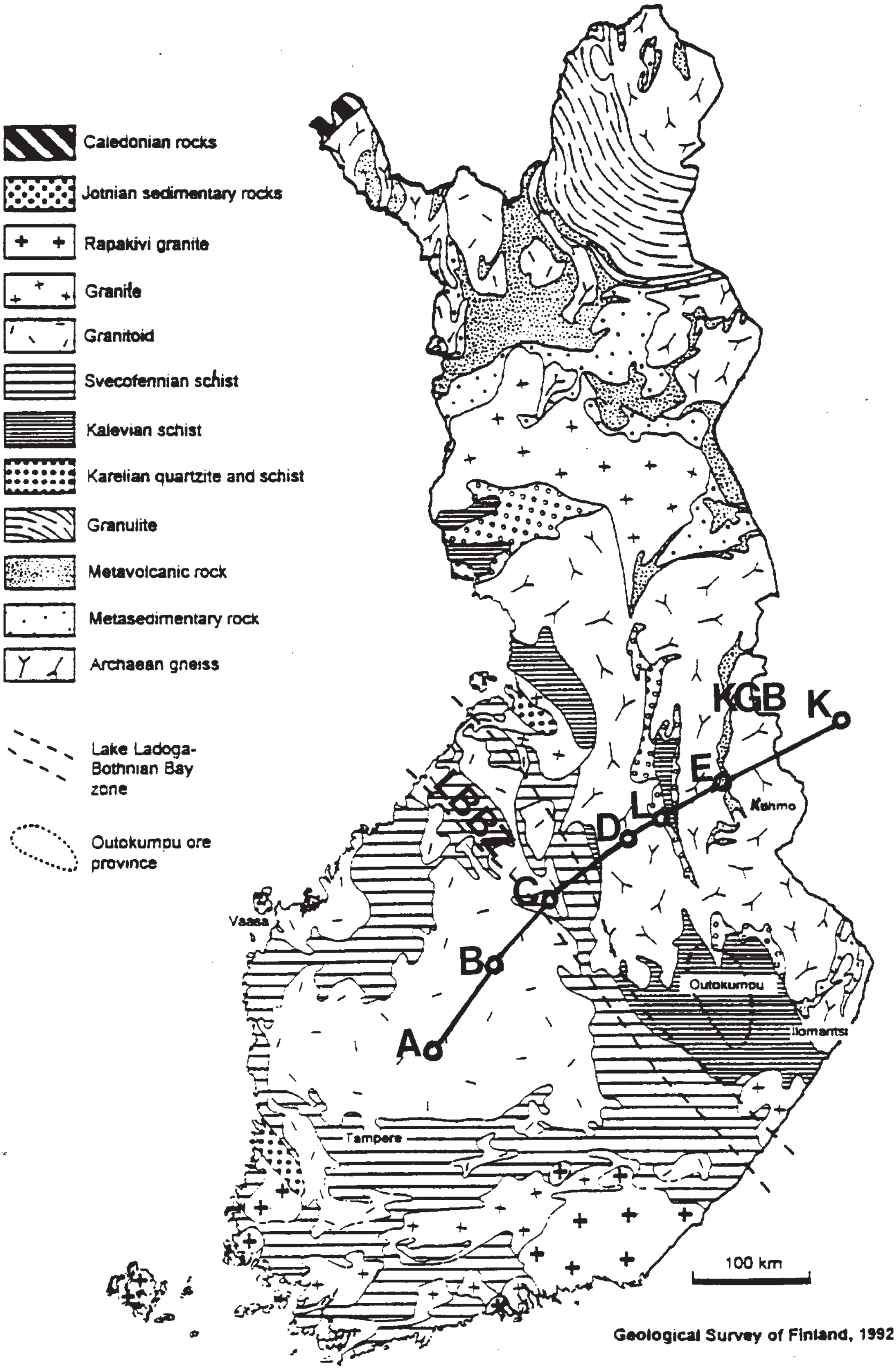

Fig. 1. Location of the extended SVEKA DSS refraction profile on the map of prequaternary rocks of Finland (after *Koljonen*, 1992). The capital letters A, B, C, D and E mark the shotpoints of the original SVEKA'81 profile. The letters K and L mark Kostamus (Russia) and Lahnaslampi (Finland) mining sites, respectively. LBBZ and KGB denote the Lake Ladoga-Bothnian Bay Zone and the Kuhmo Greenstone Belt, respectively.

study the structure of the late Archaean domain, including the Kuhmo Greenstone Belt in the eastern Finland were carried in 1984, 1985 and 1992 by the Department of Geophysics of Oulu University and the Geological Survey of Finland. During those years a new seismic refraction profile that extends the SVEKA'81 profile to about 100 km to the North-East was recorded. The mine tremors from Kostamus (Russia) and Lahnaslampi (Finland) were used as sources of seismic energy. The quality of experimental data was rather good and gave opportunity to recognize both P- and S-wave arrivals. Preliminary results of the new experiment showed that re-interpretation of the northeastern part of the SVEKA'81 profile was necessary. The new P- and S-wave interpretation of the SVEKA profile extention using also the original record sections of the SVEKA'81 profile was made by *Yliniemi et al*. (1996).

The physical properties of the lithosphere along the SVEKA line have been studied also by other geophysical methods including potential fields interpretation. But in spite of all these efforts not all the problems concerning geological and geophysical models of the SVEKA profile have been solved. One of such problems is apparent disagreement between existing seismic models and data of gravity observations. The main disagreement is that anomalously thick crust in the central part of the SVEKA profile does not have any correlation with the topographic relief. Such thickening of the crust should give significant decrease of the gravity field that is not observed. The second disagreement exists for those parts of the SVEKA profile where sharp positive anomalies of the gravity field take place (*Elo*, 1983). The first of them is located in the vicinity of the Lake Ladoga-Bothnian Bay Zone that is considered as marking a geological boundary of Proterozoic and Archaean domains, and the second one is associated with the late Archaean Kuhmo Greenstone Belt. That is why this profile still remains interesting for geophysical modeling that can provide additional information about the deep lithospheric structure.

In our investigation we made an effort to construct integrated seismic and density model that satisfy both experimental seismic and gravity data and to find the explanation of disagreement between gravity data and previous seismic models. For this purpose we used the relationship between rock elastic properties (P- and S-wave velocity) and rock density. Investigation of this relationship was the second purpose of our work. The seismic model of the SVEKA profile gives good possibility to solve these problems because it contains data on both P- and S-wave velocities.

2. *Relationship between density and seismic wave velocity*

The fact that there exists relationship between rock density and seismic wave velocity is a consequence of the elasticity theory. It shows that the velocity of seismic body waves propagation in elastic media depends on elasticity tensor as well as material density. The elasticity tensor in the most common form has 81 components, and the elasticity parameters show strong dependence on rock mineral composition.

That is why the direct application of elasticity theory to investigation of velocity-density relationship is difficult. But there exists rather strong correlation between rock density and compressional wave velocity. This fact has been empirically revealed by *Birch* (1961) under assumption that the compressional wave velocity in isotropic media depends primarily upon the mean atomic mass and material density. In the most common form the Birch equation connecting compressional wave velocity V_p and rock density σ can be written as

$$V_p = a + b\sigma \tag{1}$$

where a and b are empirical constants. Such linear relationships between density and V_p as well as more complicated non-linear equations have been obtained experimentally under laboratory conditions for various types of rocks, different geological areas and under different pressure and temperature as illustrated by the work by (*Krasovsky*, 1981) and (*Schön*, 1998). The usual way to use this great amount of a-priory information about the physical properties of rocks for gravity modeling is that the section under study is divided into blocks with constant density. The former is calculated using the linear relationship between density and P-wave velocity (Eq. 1). Coefficients *a* and *b* in eq. (1) can be different for various rock types. The geometry of blocks is defined from seismic data and then the more precise values of block densities and their boundaries are obtained from the observed gravity data inversion. In our opinion, there are several reasons why geophysicists are not very enthusiastic at present time to construct density models using this traditional approach. The main reason is that the structure of the lithosphere is rather inhomogeneous and more complicated than those represented by the traditional block model. Recent results of seismic investigations show that seismic interfaces often have very complicated forms. Velocities within the layers are as a rule non-homogeneously distributed. To describe adequately such complicated media by the traditional block model with uniform density, the former needs to have a great amount of parameters which makes gravity inversion a very complicated and ill-posed problem. If that traditional block parametrization is applied to 3-D problems, the number of parameters increases so dramatically, that inversion of gravity data becomes a problem with great amount of work and very poor result. But in spite of all these difficulties, it is not correct to make conclusions about rock composition of the deep lithospheric structures only from seismic models and ignore the information that interpretation of the gravity field can provide.

In the present paper we made an effort to solve the problem of adequate use of initial seismic data in the gravity modeling and construct an integrated seismic and density model along the SVEKA profile using interpretation of both P- and S-wave velocities.

For this purpose we applied a method of graviseismic modelling developed by *Karatayev and Kozlovskaya* (1996). This method differs from the above described traditional approach to gravity modeling, because a more complicated non-linear relationship connecting density, compressional and shear wave velocity is used. A very important difference of this technique from the traditional approach is that the velocity-density relationship is obtained as a solution to inverse gravity problem. The data from other geophysical and geological measurements can be used as a-priori information necessary to find a reliable solution. Then the density distribution within the geological section can be calculated using the equation obtained.

3. Method of integrated seismic and gravity modeling

The method developed by *Karatayev and Kozlovskaya* (1996) gives opportunity to construct various algorithms of several geophysical fields integrated interpretation, because it is based upon the assumption that there exists a class of geological objects with physical properties connected in accordance with some relationship.

Let us suppose that for some geological body T there exists and can be found by some way a non-linear relationship between its physical parameters (P- and S-wave velocity, density, electrical conductivity etc.) denoted as $b_1(\rho), b_2(\rho), ..., b_k(\rho),\ \rho \in T$:

$$W\left[b_1(\rho), b_2(\rho), ..., b_k(\rho)\right] = 0 \tag{2}$$

A geological body T with physical properties satisfying eq. (2) may be referred to as a *complex geophysical body*.

We can consider the real geological section under study as some complex geophysical body formed by various tectonic and physical processes and, as a result, having non-linear relationship connecting different physical properties of the rocks. This relationship depends upon pressure and temperature as well as rock composition. As a rule, these factors are known only for the upper and very thin part of the crust. But, in our opinion, some information about these unknown factors can be obtained from other geophysical and geological data, for example, from the magnetic field observed along the profile or its regional component. To find this relationship analytically is a rather complicated problem, but we can try to approximate it by some more simple relationships. The approximating equation must be constructed taking into consideration existing a-priory information about interrelation between rocks properties.

Recently many researchers have investigated the relationship connecting various rocks properties under laboratory conditions and tried to calculate more sophisticated regressions between seismic wave velocities and rocks densities. One of such empirical non-linear relationships connecting density and both compressional and shear wave velocities was obtained by *Khalevin et al*. (1986):

$$\sigma = 2.66 - 0.107V_p - 0.0535V_s + 0.026V_pV_s + 0.0463(V_p{}^2 - 1.3333V_s{}^2) \tag{3}$$

Eq. (3) is an additional experimental evidence of the fact, that the relationship between rock elastic properties and density is non-linear. It also gives some idea about how the relationship between density, V_p and V_s can be constructed. Unfortunately, it is hardly possible to use this equation directly for the purpose of the gravity modeling, because in reality the non-linear relationship between rock density $\sigma(x,y,z)$, P-wave velocity $V_p(x,y,z)$ and S-wave velocity $V_s(x,y,z)$ within some volume T depends also upon PT-conditions, tectonic differences in the region under study and rock composition. Taking into consideration these influencing factors, we can try to approximate the relationship between $\sigma(x,y,z)$, $V_p(x,y,z)$ and $V_s(x,y,z)$. by the following formula:

$$\sigma(x,y,z) = \sum_{k=0}^{16} A_k U_k(x,y,z) \tag{4}$$

where $U_0(x,y,z)=1$, $U_1(x,y,z)=V_p(x,y,z)$, $U_2(x,y,z)=V_{pmean}(x,y)$ is P-wave velocities averaged along z-axis, $U_3(x,y,z)=Z_s(x,y)$ is the observed magnetic field filtered by low-frequency filter (unfortunately, it was not available in the present study), $U_4(x,y,z)=H1_s(x,y)$, $U_5(x,y,z)=H2_s(x,y)$, $U_6(x,y,z)=H3_s(x,y)$ are three seismic interfaces from the initial seismic model. They can be the basement surface, interface between upper and lower crust and Moho boundary. $U_7(x,y,z)=F1_s(x,y)$ and $U_8(x,y,z)=F2_s(x,y)$ are filtered by low frequency filter values of some additional geophysical fields measured along the profile (heat flow, for example). In our study these functions are two additional seismic interfaces from the initial seismic model. The other functions can be calculated as follows: $U_9(x,y,z)=V_{pmean}(x,y)V_p(x,y,z)$, $U_{10}(x,y,z)=dV_{pmean}(x,y)/dx$, $U_{11}(x,y,z)=V_s(x,y,z)$, $U_{12}(x,y,z)=V_s(x,y,z)V_p(x,y,z)$, $U_{13}(x,y,z)=V_p^2(x,y,z)$, $U_{14}(x,y,z)=V_s^2(x,y,z)$, $U_{15}(x,y,z)=1./V_s(x,y,z)$, $U_{16}(x,y,z)=V_p(x,y,z)/V_s(x,y,z)$.

The functions $U_j(x,y,z)$, $j=2...9$ are included in eq. (4) as giving some information about unknown PT-conditions and reflecting structural and tectonic differences in the area under investigation. The coefficients A_k in eq. (4) are unknown.

Substituting eq. (4) into forward problem operator for gravity field and making all the necessary transformations and numerical integration we obtain the gravity effect caused by the density distribution $\sigma(x,y,z)$ on the observation surface $S=(x,y)$:

$$Q(x,y) = \sum_k \left\{ A_k W_k(x,y,z) \right\} + A_{17}, \quad k = 0,...,16 \tag{5}$$

where $Q(x,y)$ is the calculated gravity field and functions $W_k(x,y,z) = \sum_i \sum_j \sum_m \left\{ L_{ijm}(x,y) U_k(i\Delta x, j\Delta y, m\Delta z) \right\}$ are calculated from the initial functions $U_k(x,y,z)$, $k=0,...,16$. In the former expression $L_{ijm}(x,y)$ is the gravity effect of a rectangle 3-d prism with the density $\sigma(x,y,z)=1$. The center of this prism is located in a node of the regularly spaced grid defined in the initial velocity distribution. If Δx ,Δy and Δz are the steps of the grid along x- ,y- and z- axis, respectively, then the coordinates of the prism center are $(i\Delta x, j\Delta y, m\Delta z)$ and Δx, Δy and Δz are horizontal and vertical sizes of the prism.

It is very convenient for the purpose of calculation, that the functions $W_k(x,y,z)$ in eq. (5) only has to be calculated once before the inverse problem is solved. Minimizing the difference between observed on the surface $S=(x,y)$ and the calculated model gravity field we can find the unknown coefficient A_k in eq. (4):

$$\| \Delta g(x,y) - Q(x,y) \| \Rightarrow \min_{A_k}, \qquad k = 0,1,2,...,17, \tag{6}$$

Consequently, calculating the density model can be done in three main steps.

First, the functions $U_k(x,y,z)$ are calculated from a-priory obtained seismic velocity model and results of other geophysical mesaurements (magnetic field observation, heat flow etc.) if they are available. Then they are used to calculate functions $W_k(x,y,z)$.

Second, the coefficients A_k, $k=1...17$ are calculated as a solution to inverse gravity problem formulated as eq.(6).

Third, the coefficients A_k and $U_k(x,y,z)$ functions are substituted in eq. (4) and (5) to calculate the density distribution $\sigma(x,y,z)$ and the gravity effect caused by it.

The residual field

$$\Delta Q(x,y)=\Delta g(x,y)-Q(x,y) \tag{7}$$

indicates the areas where bodies with anomalous density that are not reflected in the initial seismic velocity model may be located.

In our opinion, the above described approach is rather flexible and has the following advantages comparing with the traditional one:

1. It allows to model non-homogeneous density distributions.
2. Inverse gravity problem in such formulation has a fixed and relatively small number of parameters.
3. It allows to construct algorithms for solution of 2-D and 3-D gravity modeling problems. The number of model parameters remains the same.
4. The calculation of forward gravity problem is necessary to perform only once when calculating functions $W_k(x,y,z)$.
5. It allows to use various kinds of seismic data for gravity data interpretation, i.e. P- and S- waves velocities, seismic interfaces as well as additional a-priori geological and geophysical information.

This method has been applied for integrated interpretation of seismic and gravity data along the SVEKA profile.

4. *Results of modeling*

Density model along the SVEKA profile

The 2-D density model along the SVEKA profile has been obtained using an initial seismic model by *Yliniemi et al*. (1996) and the Bouguer gravity field data along the profile from *Gravity Anomaly map of Central Fennoscandia* of 1:1000000 scale (1996). The seismic model (*Yliniemi et al*., 1996) is presented by velocity sections for P- and S-waves (Fig. 2). The above described technique of graviseismic modeling was applied to the initial seismic model and the equation connecting density and seismic wave velocities has been obtained (Table 1). The big values of coefficients A_k corresponding to non-linear terms of eq. (4) prove that the density depends non-linearly upon both P- and S- wave velocity. The equation was then used to calculate the density distribution and model gravity field. The observed gravity field along the profile, the model field and their residual field are shown on Fig. 3.

Table 1. Equation connecting density, Vp and Vs.

Equation connecting density and seismic wave velocity	Non-corrected gravity field	Corrected gravity field (1-st variant)	Corrected gravity field (2-nd variant)
Functions	A_k	A_k	A_k
$U_0(x,y,z)=1$	-0.899	-1.095	-1.087
$U_1(x,y,z)=V_p(x,y,z)$	0.161	0.149	0.127
$U_2(x,y,z)=V_{pmean}(x,y)$	0.000	0.000	0.000
$U_3(x,y,z)=Z_s(x,y)$	0.000	0.000	0.000
$U_4(x,y,z)=H1_s(x,y)$	0.007	0.009	0.007
$U_5(x,y,z)=H2_s(x,y)$	0.000	-0.001	-0.001
$U_6(x,y,z)=H3_s(x,y)$	-0.001	0.000	0.000
$U_7(x,y,z)=F1_s(x,y)$	0.000	-0.001	-0.001
$U_8(x,y,z)=F2_s(x,y)$	0.004	0.003	0.002
$U_9(x,y,z)=V_{pmean}(x,y)V_p(x,y,z)$	-0.051	-0.051	-0.045
$U_{10}(x,y,z)=dV_{pmean}(x,y)/dx$	0.000	0.000	0.000
$U_{11}(x,y,z)=V_s(x,y,z)$	0.252	0.208	0.134
$U_{12}(x,y,z)=V_s(x,y,z)V_p(x,y,z)$	-0.018	-0.014	-0.011
$U_{13}(x,y,z)=V_p^2(x,y,z)$	0.041	0.040	0.034
$U_{14}(x,y,z)=V_s^2(x,y,z)$	-0.003	0.002	0.012
$U_{15}(x,y,z)=1./V_s(x,y,z)$	0.000	0.000	0.000
$U_{16}(x,y,z)=V_p(x,y,z)/ V_s(x,y,z)$	-0.251	-0.162	-0.039
$U_{17}(x,y,z)=const$	491.989	745.452	966.739
RMS error (mGal)	5.033	2.749	2.107

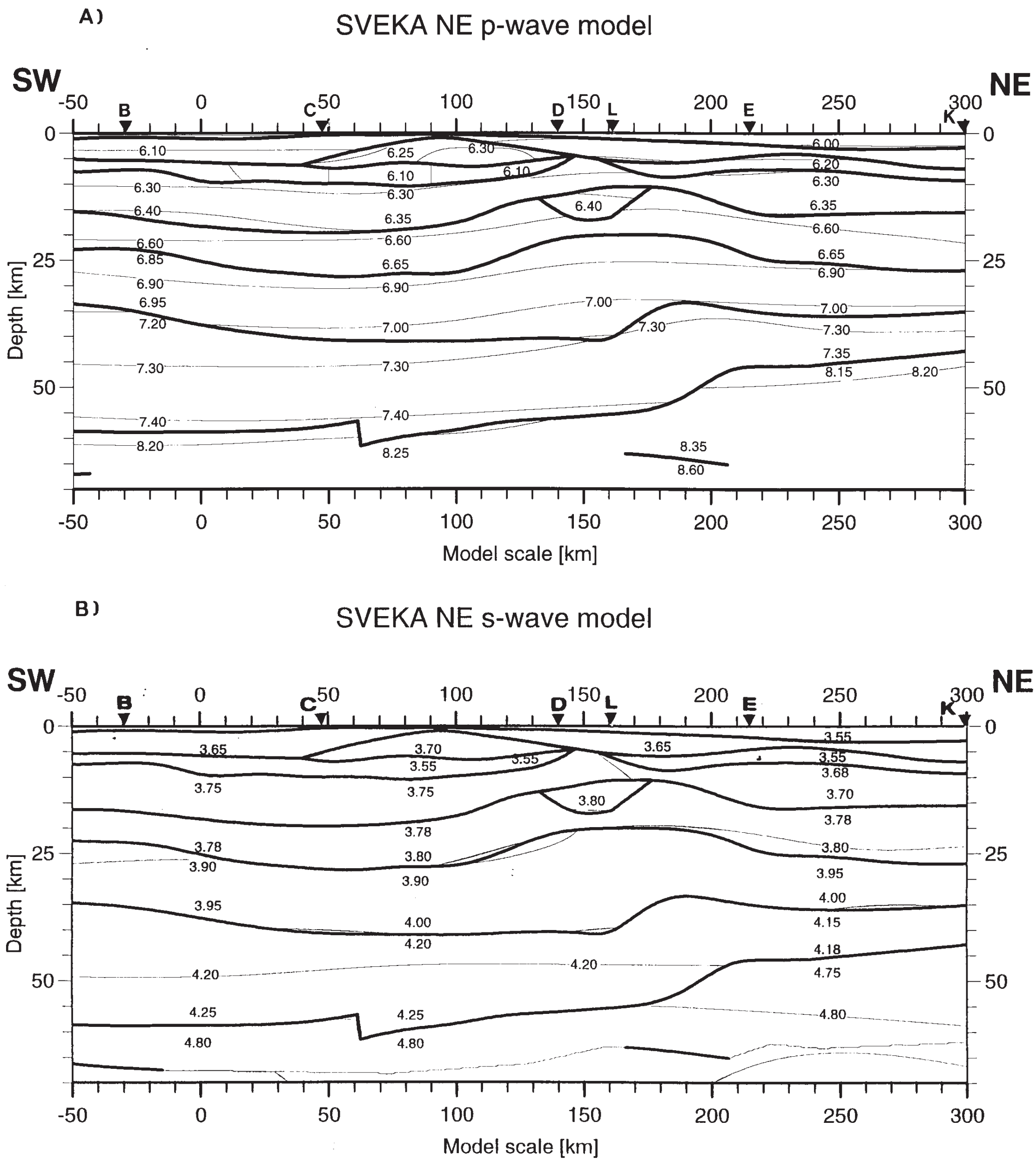

Fig. 2. P-wave (a) and S-wave (b) seismic section of the extended SVEKA profile. Shotpoints are shown by black triangles.

The analysis of the residual between observed and calculated model gravity field showed that the initial seismic model is in relatively good agreement with the observed gravity field except of two intensive positive anomalies corresponding to the Kuhmo Greenstone Belt and Svecofennian schists in the vicinity of the Lake Ladoga-Bothnian Bay Zone. As it is known from geological investigations of rock properties in this areas, this can be an effect of relatively dense bodies located near the surface. In this case it is possible that the DSS method cannot reveal such small and shallow details. To check this hypothesis and also prove that the calculated non-linear approximation of relationship between density and seismic waves velocity is stable, an additional modeling was performed. The hypothetical effect of small dense bodies was removed from the observed gravity field and the modeling was repeated several times with different values of additional bodies density. In all cases very similar solutions approximating the eq. (4) have been obtained. Some of them are shown in Tab. 1 and the final density model is shown on Fig. 4.

Observed, calculated and residual gravity field alond the SVEKA DSS profile

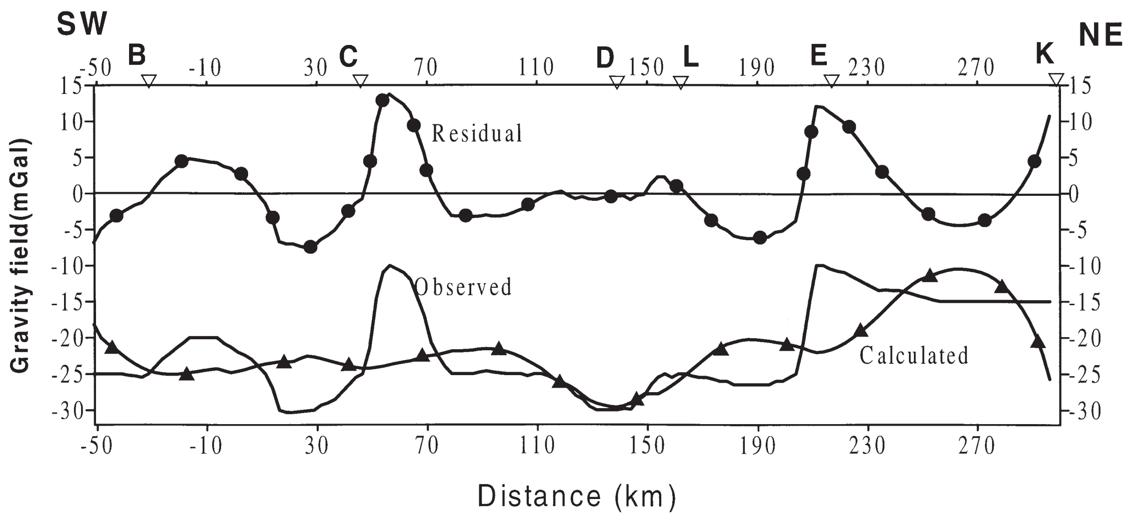

Fig. 3. The observed Bouguer anomaly of gravity field along the SVEKA profile (solid line), calculated model field (black triangles) and their residual (black circles). The observed Bouguer anomaly was adopted from the *Gravity Anomaly Map of Central Fennoscandia* (1996).

Fig. 4. The density model along the extended SVEKA profile. The additional dense bodies corresponding to the LBBZ and KGB are not shown because of their small scale.

To explain the factors that are not reflected in the initial velocity model, the residual gravity field has been interpreted separately. Interpretation showed, that positive anomalies corresponding to the Kuhmo Greenstone Belt and the Lake Ladoga-Bothnian Bay Zone can be explained as caused by small scale bodies located near the surface and having higher density comparing with the adjoined areas. The result of separated modeling of the residual gravity field is presented on Fig. 5. The densities of these additional bodies are 2812 kg/m^3 and 2840 kg/m^3, respectively. These values are in agreement with data about rocks density obtained from laboratory measurement *(Elo et al.*, 1978, *Elo*, 1997).

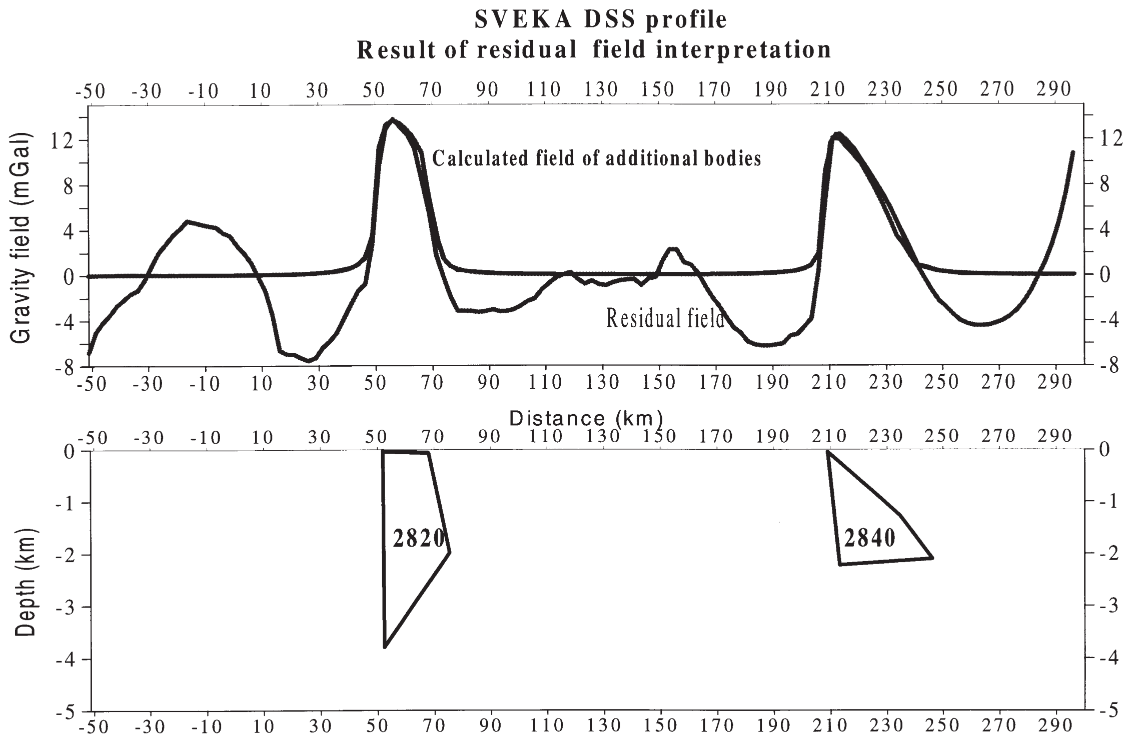

Fig. 5. Result of the residual gravity field interpretation: additional dense bodies in the upper crust and their gravity effect. The density of the additional bodies is in kg/m^3.

The integrated seismic and density model shows very clearly two different types of deep structure of Proterozoic and Archaean lithosphere. The mostly interesting is a contact zone between the Archaean and Proterozoic crust. On the density section it is clearly seen that this contact is some inclined and rather broad zone in which density change. The model also reveals a number of deep inhomogeneties in the crust.

The density model shows that the crust along the SVEKA profile can be considered as being in a state of isostatic equilibrium: the thinner Archaean crust has smaller average density than the thicker Proterozoic. It is important to stress, that the values of density in the Proterosoic and Archaean lower crust are sufficiently different. The density is about 3050-3150 kg/m^3 in the Proterozoic lower crust, and it does not exceed 3000 kg/m^3 to the north-east of the Archaean Kuhmo Greenstone Belt. The presence of material with such high density in the lower crust explains, why the gravity field increment in the vicinity of the Kuhmo Greenstone Belt is smaller than can be caused by the uplift of the Moho boundary from about 57 km up to 46-43 km. *Elo* (1997) came to the same conclusion about presence of dense material in the lower Proterozoic crust under the SVEKA profile. As we can conclude from the initial seismic model, the density under the Moho boundary beneath the Proterozoic crust is also larger than beneath the Archaean. Unfortunaley, the more precise structure of the upper mantle cannot be obtained from the initial seismic model. The future results of SVEKALAPKO geophysical experiment can help to obtain new models of density and velocity under the Moho as well as the more detailed structure of the contact zone between two main tectonic units in Finland.

5. *Conclusions*

Application of the new method of graviseismic modeling for combined interpretation of seismic and gravity data along the SVEKA profile allowed us to obtain new information about the deep lithospheric structure in Fennoscandia. The method allows us to use various kinds of experimental seismic data for interpretation, i.e. P- and S-waves velocities and seismic interfaces location. Using the non-linear relationshoip between density, V_p and V_s gives possibility to construct density models of complicated non-homogeneous geological media and reveal such details of deep lithosphere structure that cannot be obtained from seismic data alone.

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