4.2

Integrated geophysical studies of Precambrian mobile belts to constrain evolutionary and mineragenic crustal models (experience from Fennoscandian Shield)

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4.2.1 Introduction

Mobile belts surrounding Archean nuclei of ancient cratons have imprinted and preserved distinct marks of earlier structural evolution of the Earth, caused by tectonic, and accompanied by mineragenic processes. Transition from extensional mantle plume environment to the collision and subduction events of juvenile plate tectonics on the frontier of Archean and Palaeoproterozoic time corresponded to active upper mantle–crust interaction with upwelling heat and mass transfer. This period was characterized by under- and inter-plating of the mantle-derived magmas resulted in variety of mafite-ultramafite stratified intrusives, thickening of the continental crust, and consequent regional metamorphism as well as progress in global oxygenation with geobiological changes (Mints et al., 2015; Korja et al., 2006; Gaal, 1990; Larionova et al., 2013; Konhauser et al., 2017). These and other features of the evolving Earth were favorable for productive minerageny, especially extensive in earlier Proterozoic time when unique reserves of ore and nonmetallic deposits have been accumulated (Vaittinen et al., 2012; Larionova et al., 2013; Chashchin, Mitrofanov, 2014; Konhauser et al., 2017). Palaeoproterozoic tectonic cycle (2.5–1.7 Ga) on the Fennoscandian Shield has lead to the formation of the Svecofennian accretionary orogen, bordering from the southwest the Arhaean Karelain Craton, and Lapland-Kola and Onega fold belts in the framework of latter one (Fig. 4.2.1). These areas include several rich and well-known mineragenic provinces. Nevertheless during two last decades increased interest to this region has been revealed by international geological community due to actual demands of both geological and mineragenic studies in new constraints for further development

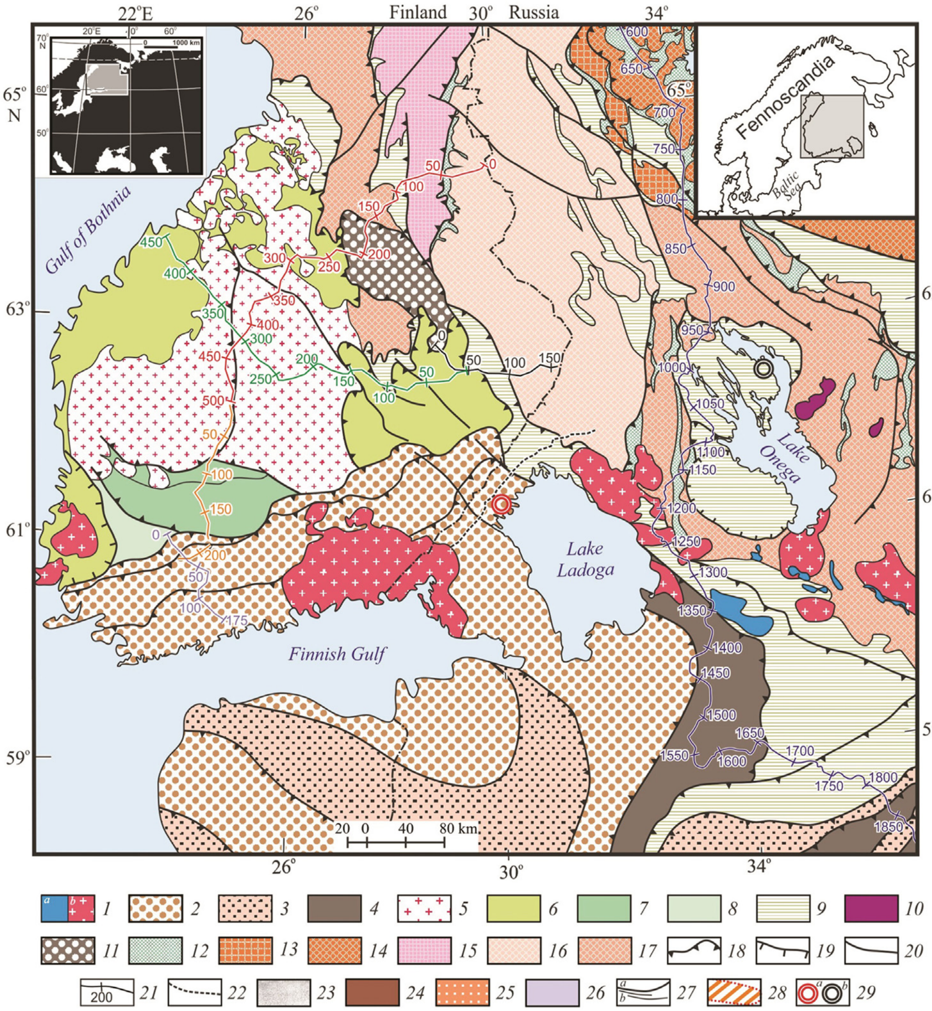

FIGURE 4.2.1 Geological map of the Southeastern Fennoscandian Shield (the sedimentary cover removed). Legend to Fig. 4.2.1–4.2.3. 1–10—Palaeoproterozoic: 1—intrusive rapakivi granite (A) and gabbro-anartozites (B), 2–4—Lapland-Middle Russian–South Baltic orogen: 2—South Finnland granulite-gneiss belt (gneiss of granulite and amphibolite facies, granite); 3—gneiss, amphibolites, metasediments; 4—mafite granulites; 5–8—Svecofennian accretionary orogen: 5—Central Finland Granitoid Complex, 6–8—volcanic-sedimentary belts: 6—Hameenlinna, 7—Pirkanmaa–Tampere, 8—Pohjanmaa, Savo, Saimaa; 9—epicontinental belts: Raahe–Ladoga (passive margin of the Karelian craton) and Onega; 10—mafite-ultramafite stratified intrusive; 11–17—Archaean: 11–granulite-gneiss belt Varpaisjarvi; 12—greenstone belts; 13–17—microcontinents (granite-greenstone domains): 13—Kovdozero, 14—Hetolanbinskiy, 15—Kianta, 16—Kuhmo-Segozero, 17—Ranua, Iisalmi and Vodlozero; 18–20—tectonic boundaries: 18—thrusts and upthrusts, 19—normal faults, 20—strike-slip faults. 21—seismic profiles (highlighted in colour lines with picket numbers): FIRE-1—purple, FIRE-2a—orange, FIRE-2—red, FIRE-3a—green, FIRE3—black, 1-EU—grey; 22—magnetotelluric sounding (*MTS*) profile "Vyborg-Suojarvi." 23–28—additional symbols on geological sections: 23—seismic image, suggested accretionary crust; 24—reflectivity zone in the lower crust, presumably by the under- and inter-plating of mantle mafic magmas; 25—acoustically homogeneous region, presumably a region of intense metamorphic reworking; 26—mantle, 27—tectonic boundaries (a) and boundaries of structural domains (b), 28—areas of increased electrical conductivity; 29—graphite deposits: (a)—Ikhala coarse- and medium-flaky graphite field;(b)—schungites fields (Shunga, Zazhogino, Palezhaevskoe).

of Fennoscandian Shield evolutionary models as well as in a solid and modern scientific basis for mineragenic zoning and intensification of prospecting activity.

Integrated geophysical investigations, being the main tools to study the structure and material properties of ancient craton interiors, have played the premier role. The results of the Baltic Electromagnetic Array Research deep magnetotelluric soundings and the Seismic Tomography Experiment, which began at the border of two centuries a new round of Fennoscandian studies from the upper mantle properties' exploration, have been summarized in Hjelt et al. (2006). These two key geophysical experiments of EUROPROBE's SVEKALAPKO project have demonstrated high upper mantle heterogeneity under the Shield and urged an intensification of the crustal researches. The following two first decades of XXI century has been crowned by the implementation of new world-class crustal experiments on the territory of Central and Eastern Fennoscandian Shield: Finnish-Russian FIRE and MT-FIRE Projects (Kukkonen and Lahtinen, 2006; Vaittinen et al., 2012) and Russian 1-EU (Mints et al., 2010) and LADOGA (Sokolova et al., 2016; Sokolova and Ladoga WG, 2017) Projects.

The paper is focused on the results of the aforementioned recent geophysical studies held in the rich mineragenic provinces of the Shield: large scale seismic reflection profiling (FIRE) and broad-band/long-period magnetotelluric (MT) soundings (FIRE-MT and LADOGA) across Raahe-Ladoga pericratonic zone at the border of the Arhean and South-Eastern Paleoproterozoic domains (Fig. 4.2.1).

Results of both methods cross-verified and complimented each other in the course of joint interpretation of the data. The interpretation of seismic migrated cross-sections has been completed on the common methodical background with the earlier studies of composite East European Craton (EEC) (Mints et al., 2015). In the Lake Ladoga area, in the absence of modern seismic data, the magnetotelluric soundings have become the main instrument of crustal structure resolution. The results for both provinces have been compiled and a new geotectonic model of Svecofennian accretionary orogen and adjacent Karelian craton has been suggested.

We demonstrate the mineragenic inferences from new model, in particular, regarding deep roots and the origin of prominent Ikhal'sky deposit of the coarse and medium-flaky graphite. On this background and on the experience of near-surface prospecting works at the Onega Lake Palaeoproterozoic structure, the effective set of appropriate geophysical methods is suggested for detailed exploration of the Ikhala field which is now preparing for further extension of explorations.

4.2.2 Seismic-based geotectonic model of central Svecofennian accretionary orogen

Both FIRE (Korja et al., 2006, Kukkonen and Lahtinen, 2006) and 1-EU (Mints et al., 2015) seismic reflection projects have introduced the century and have given new insights into regularities of the Fennoscandian Shield crustal structure. They have provided grounds for a higher level of geological generalizations both in the frames of composite East European Craton and in correlations with North American Craton, where LITHO-PROBE Program has realized similar modern seismic method coverage (Cook et al., 2010). To reach this level and to overcome the problems of results' correlation within different interpretational approaches, a special course of FIRE data interpretation has been carried out on the same methodical background that was used for 1-EU data analyses in (Cook et al., 2010). The modeling utilized data of geological mapping and reflection seismic studies along profiles FIRE-1-2a-2 and FIRE-3-3a (Fig. 4.2.1).

The accretionary complex in seismogeological model (Fig. 4.2.2A) is modeled by inclined layering: the tectonic sheets ~15 km thick composed of volcanic–sedimentary rocks, and granitoids, monotonously, and consecutively plunge eastward under the Karelian craton. Having reached a level of the lower crust, the tectonic sheets of accretionary complex lose their distinct outlines and in the bottom of the section are replaced by uniform acoustically translucent medium, where separate sheets are traced only fragmentary. The crust–mantle boundary demonstrates a diffused character and is recorded in disappearance of vaguely drawn boundaries of tectonic sheets and in gradual transition of acoustically homogeneous lower crust into transparent mantle. Geoelectrical data of magnetotelluric profiling SVECA (Korja et al., 2002) and MT-FIRE (Vaittinen et al., 2012), juxta-posed on the prepared seismogeological pattern, have perfectly confirmed the structural features (Fig. 4.2.2A and B), supported the continuation of the layers to the low crustal levels and helped to resolve ambiguity in understanding of their filling with material properties (i.e., to distinguish electroconductive graphite-bearing volcanic-sedimentary sequences and granitic composition) for unexposed ("blind") model elements in Savo, Kainuu belts.

4.2.3 Geoelecric-based model of southeastern part of Svecofennian orogen

The extension of the tectonic model of Svecofennian accretionary Orogen to the south-east was hampered by the absence of appropriate seismic data. Nevertheless, already from 70th of last century there a bright crustal structure marker in the southeastern segment of Ladoga-Bothnian tectonic zone was known—Lake Ladoga conductivity anomaly (LLA)—one of the strongest conductors in EEC, correspondent in the anomalous object general parameters to elongated conductive structures found along AR-PR borders in other Precambrian cratons (Kovtun, 1989; Zhamaletdinov and Kulik, 2012; Yin et al., 2014). The models of LLA, constructed on the magnetotelluric and magnetovariational (MT/MV) sounding data of XX century (Kovtun, 1989; Zhamaletdinov and Kulik, 2012), had not enough resolution to make a choice from several hypotheses of LLA origin. New synchronous MT\MV experiment LADOGA (Sokolova et al., 2016; Sokolova and Ladoga WG, 2017) significantly improved level of crustal structure resolution in comparison with earlier sounding results.

The observations at 200 km long "Vyborg–Suojarvi" profile (VS) carried out in 2013–14 by Nord-West Ltd, MSU and IPE RAS with "Phoenix" and "LEMI" MT stations have resulted in 50 broad-band and 9 long period MT/MV soundings with synchronous recording in remote bases (Figs 4.2.1 and 4.2.3). Modern processing techniques (software provided by equipment manufacturers and remote reference and multi-RR schemes (Varentsov et al., 2003, 2005) were

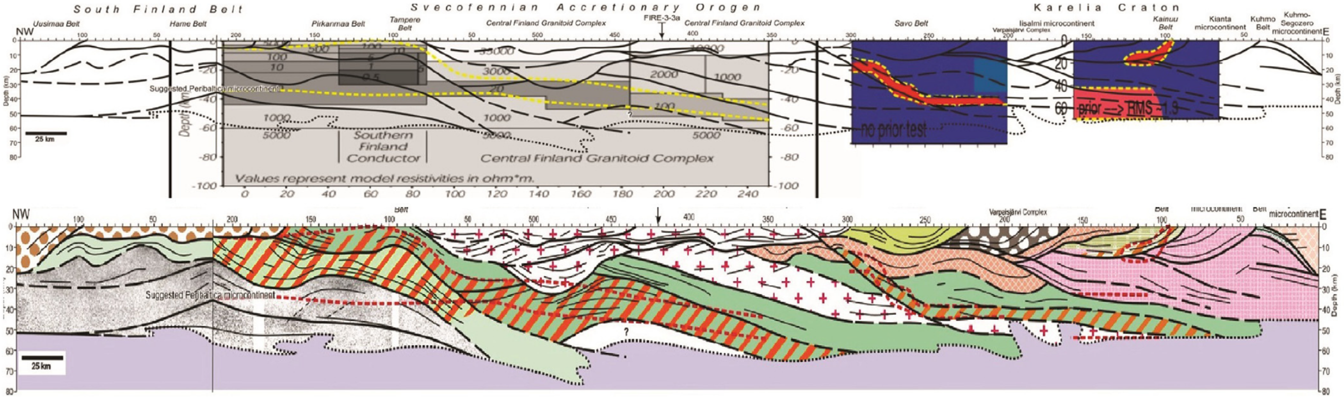

FIGURE 4.2.2 The Earth's crust and crust-mantle boundary models along FIRE-2a-2-1 reflection seismic profile: (A) (top) structural pattern of seismogeological model with juxtaposed distribution of the electrical resistivity: on the left the results of MT soundings in the southern part of the SVEKA MTS profile from Korja et al. (2002) are shown (profile practically coincides with the seismic profile, the electrical resistivity values of blocks are given in Ohm m), in the center and in the eastern part of the profile, electrical resistivity models are projected from nearby MT-FIRE profiles [10] (red color shows conductors); (B) (bottom)—geological section with zones of increased electrical conductivity (see legend in Fig. 4.2.1). *MT*, magnetotelluric; *MTS*, magnetotelluric sounding.

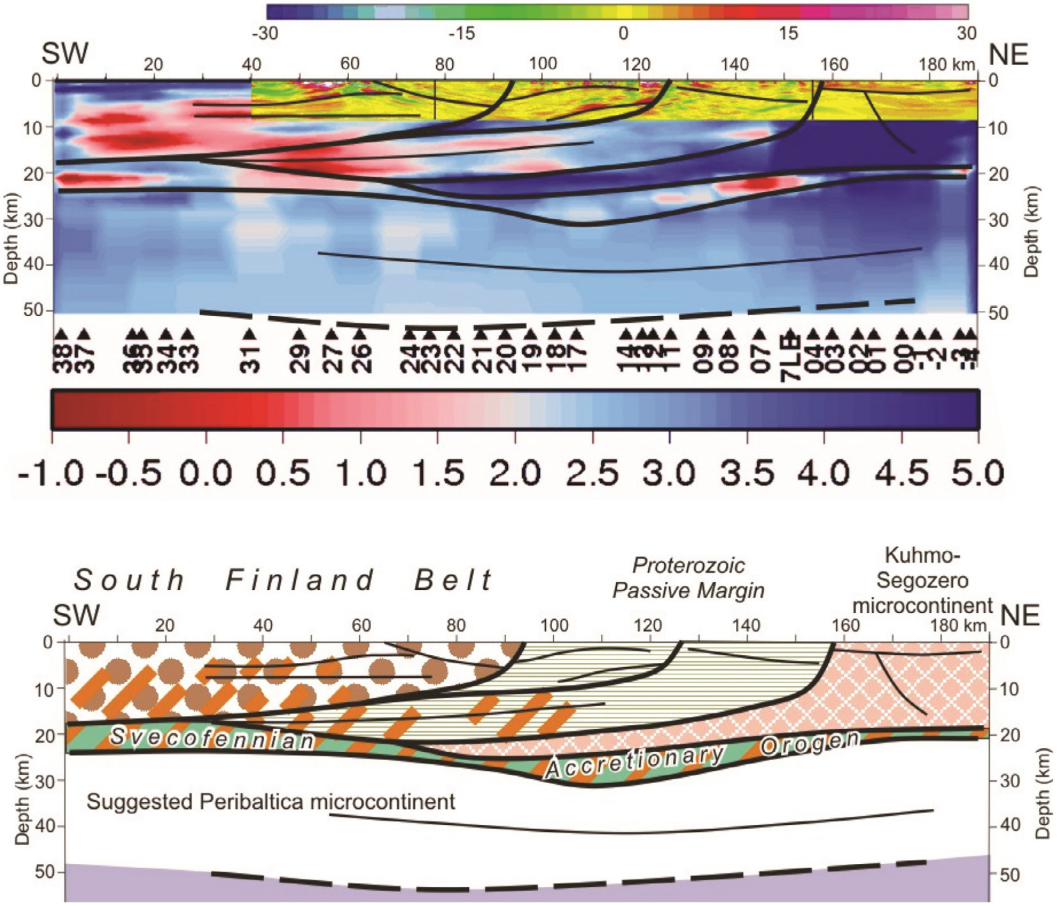

FIGURE 4.2.3 Result of bimodal 2D MT/MV data inversion at "Vyborg-Suojarvi" profile with elements of tectonic interpretation accounting for corresponding density and magnetic accessibility models: upper panel – multi-component bi-modal inversion result (impedance Z and tipper Wz data in 0.1–1024s range, estimated in sounding sites indicated below, WRMS = 2.4) presented according to resistivity scale bar below (in lg Ohm·m) with upper-crustal part overlapped by corresponding cross-section of 3D effective magnetic susceptibility model (scale bar above, in relative units); lower panel – the model of the deep tectonic structure of Svecofennian accretionary Orogen along the VS profile resulted from resistivity cross-section interpretation with inferred structural tectonic lines, superimposed on both panels (legend in Fig. 4.2.1). X~63 km in upper panel indicates approximate location of prominent Ikhal'sky graphite field.

used to suppress electromagnetic (EM) noises. The local (impedance Z, tipper Wz) and interstations (horizontal magnetic tensor M) transfer functions have been estimated in broad band or combined broad band long period ranges (up to 10,000 s). Their invariant analyses have defined general strike (45–50°NE) and dimensionality (quasi-2D with local 3D distortions) of the data and thus have approved application of 2D interpretational approach (Sokolova et al., 2016; Sokolova and Ladoga WG, 2017).

The course of profile inversions with robust reguularized code (Varentsov, 2007) has produced the resistivity model which demonstrates that LLA is caused not by a single anomalous object but by a complicated ensemble of conductive features of different structural identity (Fig. 4.2.3).

The resolution of the cross-section permitted to carry out meaningful geotectonic and evolutionary interpretation. At mid-crustal levels the conductive structures are generally characterized by distinct SW dip and, hypothetically, correspond to thrust zones, developed along graphite-bearing slippery surfaces of supracrustal Palaeoproterozoic formations during their accretion/thrusting upon the SW border of Karelian Craton in the late Palaeoproterozoic. At the upper levels, they are steepening and connecting to the major faults recognized at the surface, including ones activated at neotectonic stage in Ladoga–Bothnian zone borders. In the upper crust (5–7 km) of NE part of the profile bowl-formed association of conductive features is imaged in resistivity cross-section and correspond to structure of effective magnetic susceptibility profile distribution. They describe the structure of Raahe–Ladoga suture zone across its ~50 km width.

Relevant correspondences of geoelectric, density (Glaznev et al., 2015), and magnetization (Fig. 4.2.3A) images of deep structures in cross-section of the profile support obtained tectonic inferences and ideas of regional predominance of the collisional tectonic over extensional one in the Paleo- and Meso-proterozoic times. It is suggested that long period MT Lake Ladoga anomaly is caused by deeply metamorphosed complexes of South-Finland Granulite-Gneiss Belt, which include crystal graphite and could be similar to exhumed formations of Lapland Granulite Belt. While in pericratonic zone enhanced upper-crustal conductivity is connected with frequently exposed graphite- and/or sulphide-bearing sedimentary-volcanic schists of lower metamorphic stages.

4.2.4 Mineragenic inferences from the geoelectric and tectonic models constructed

Conductive graphite and sulphide-bearing formations (correspond to Kalevian and Ladoga series) are revealed by MT/MV soundings at NE segment of the profile. They can be indicative for gold and polymetallic mineralization formed by the upwelling fluids in the deep fault zones.

In Finland, they are well-known in famous Outokumpu ore area. Similar deposits and occurrences are abundant in Russian segment of the Raahe-Ladoga suture (northern Ladoga area) but they are far from being properly explored. In the SW part of the resistivity cross-section, significant inflation of the deepest conductive layer (about 15–25 km depth) was found which seems to produce the very Lake Ladoga anomaly originally discovered by pioneering long-period MV surveys. One can assume that this extremum of the conductivity is caused by deeply metamorphosed complexes of South-Finland Granulite-Gneiss Belt (Fig. 4.2.1) which could be similar to exhumed formations of Lapland Granulite Belt and include graphite in crystalline form.

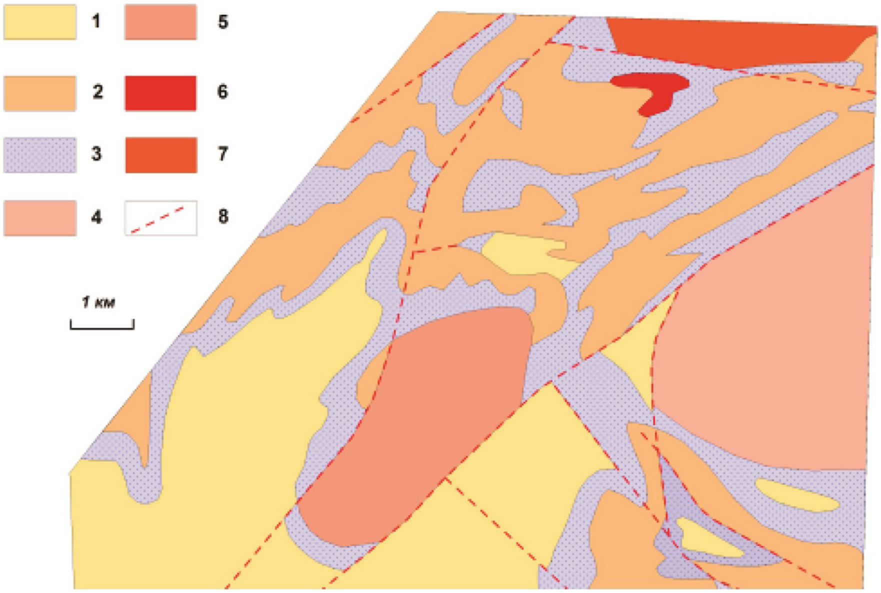

FIGURE 4.2.4 Ikhal'skoe grapfite field geological map (adopted from Biske, 1987). Legend: 1—granite-biotite and a amphibolite-piroxen gneiss and migmatites; 2—biotite-amphibol-piroxen crystal schists and granite-biotite gneiss and migmatites;3—productive graphite schists; 4—biotite with gneiss-granites; 5—potassium-alcoline rocks; 6—plagiogranites; 7—diorites and granodiotites; 8—hypothetical tectonic lines.

The formations of the coarse- and medium-flaky graphite are exposed at the prominent Ikhal'sky field located in the nappe of the South-Finland Granulite Belt (Figs 4.2.1 and 4.2.4). The main productive sequence is represented by quartz-biotite graphite-bearing schists, which form steeply dipping 1700 m long body with stable strike and thickness of 450 m, which is poorly discovered at a depth. Economical estimates of explored resources exceed 40 billion $. Ikhala graphite can be consumed in wide range of applications (from pencils and electrodes to microelectronics, neutron inhibitors at atomic power stations and graphene production for nanotechnologies). The graphite field is at the stagnant exploration stage since 2004 and needs intensification of the development.

The conductive formations probably have roots in the deep-seated conductive fabrics revealed in the resistivity cross-section (Fig. 4.2.3). To resolve these deep structures in more details additional MT/MV would be the best approach. While for prospecting and exploration targets direct applications of MT (high-frequency audiomagnetotellurics soundings) could meet obstacles-distortions caused by strong near-surface conductors. Future exploration activity at Ikhala field should also be based on EM geophysics. A rational integrated complex of geophysical methods can be suggested according to recent experience at Zazhoginskoe field of shungites (Fig. 4.2.1).

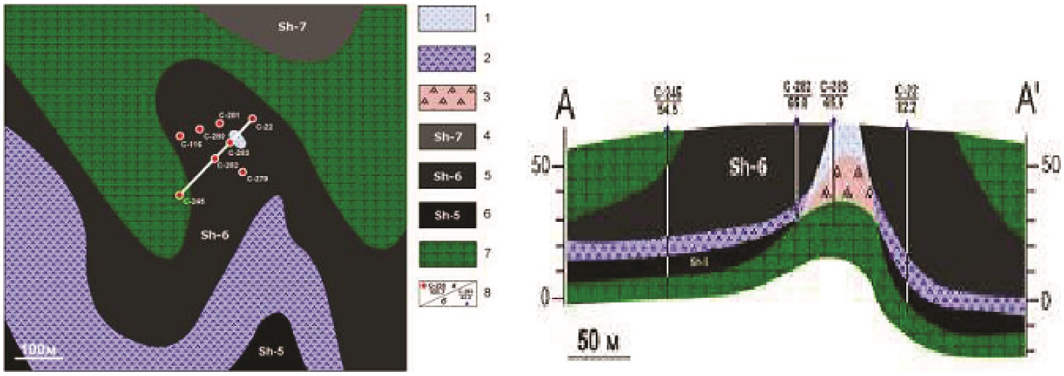

FIGURE 4.2.5 Results of integrated geophysical studies of Zazhoginskoe schungite field (Eastern Fennoscandian Shield, Karelia, Onega Lake): structural geological map and cross-section of the field. Legend: 1—silicate tuff, schungite with low content of carbon; 2—interbedding of tuffs with different composition; 3—carbonate metasomatites; 4–6—schungites horizons(5–7—correspondingly); 7—dolerites; 8—boreholes.

4.2.5 Case study of integrated geophysical prospecting in the area of highly conductive near surface structures

Zazhoginskoe schungite field belongs to Onega Lake Palaeoproterozoic epicontinental volcanic-metasedimentary fold belt developed in the frames of AR Karelian craton (Figs 4.2.1 and 4.2.5).

Schunga village in Karelia near Onega Lake is the place, where schungite deposit was described first time. Schungite contains up to 98 weight percent of carbon, is a product of lower grade metamorphism of ancient organic material, represents a transient form from anthracite to graphite, also very conductive, abundant in Karelia, and has wide spectrum of industrial applications. Zazhoginskoe schungite field (30 km long, about 20 km width) locates in the axial zone of large syncline structure of the belt with the folds' strike 330°. Schungites (layers from 5 to 52 m) are imbedded in dolomites, alevroilites, and tuffs layers over metadoletites and gabbro-diabase sills and are superimposed by 5–20 m thick quaternary limnological and glacial facies (Fig. 4.2.5). The structure of the magnetic anomalies at the area of Polezhaevskoe schungite deposit (Fig. 4.2.6, left), where the prospecting carried out by MSU and Nord-West Ltd, highlights NW strike of axial zone of the schungite-bearing folds. The productive sequences are overlaid by metadiabase sills with increasing thickness in NW directions. Correspondent area is marked by increased anomalous magnetic field while negative anomalies reflect uplift of schungite-bearing layers to the surface at SE. The apparent resistivity map, constructed on electrical profiling and induced polarization data, corresponds well to the magnetic data, and presents increased apparent resistivity values at the NW of the survey indicating dominant distribution of the effusive rocks and decreased level at SE, corresponding to schungites (Fig. 4.2.6, right). The most comprehensive information on the conductive properties of the subsurface has been obtained by EM soundings with control source (CSS). In Fig. 4.2.7, geoelectrical cross-sections constructed

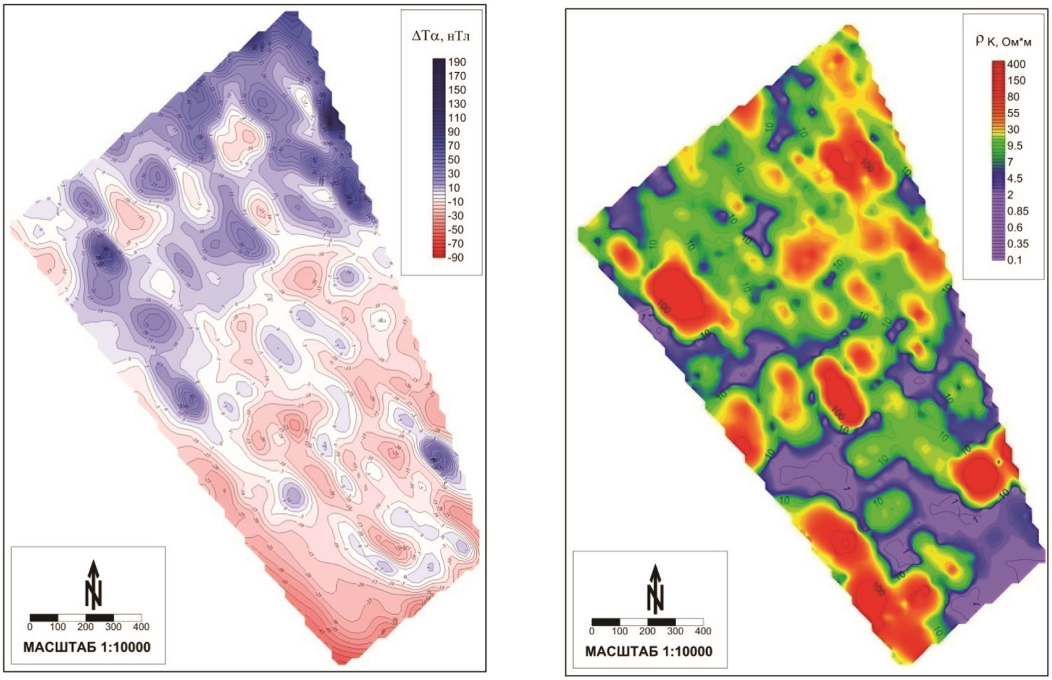

FIGURE 4.2.6 Results of integrated geophysical studies of Zazhoginskoe schungite field (EasternFennoscandian Shield, Karelia, Onega Lake): results of magnetic survey (left) and apparent resistivity mapping byelectrical profiling and induced polarisation methods (right) at Polezhaevskoedeposit of Zazhoginskoe schungite field.

by 2D inversions of CSS data demonstrate the configuration of the schungite horizons, estimate their thicknesses, and resistivity values in the range 10—2–10 —1 Ohm m.

4.2.6 Concluding remarks

Geotectonic model of Svecofennian accretionary Orogen and adjacent Karelian craton has been elaborated on the geological and newest reflection seismic and magnetotelluric data over Central and SE Fennoscandian Shield and supported by potential field data. The common methodical approaches and evolutionary conception with similar regional reconstruction for the neighboring NW Russian areas of East European Craton were applied. The model emphasizes the ancient boundaries of the crustal units and traces deep thrust/fault zones, which were favorable for increased heat and mass transfer and participated in the geodynamic activity and mineral deposits' formation. This facilitates more deep understanding of regional minerageny and shows directions for intensification of geological prospecting.

Inferred structural background of prominent Ikhal'sky graphite field and the experience of integrated geophysical prospecting of near-surface schungites at the Onega Lake as well as other

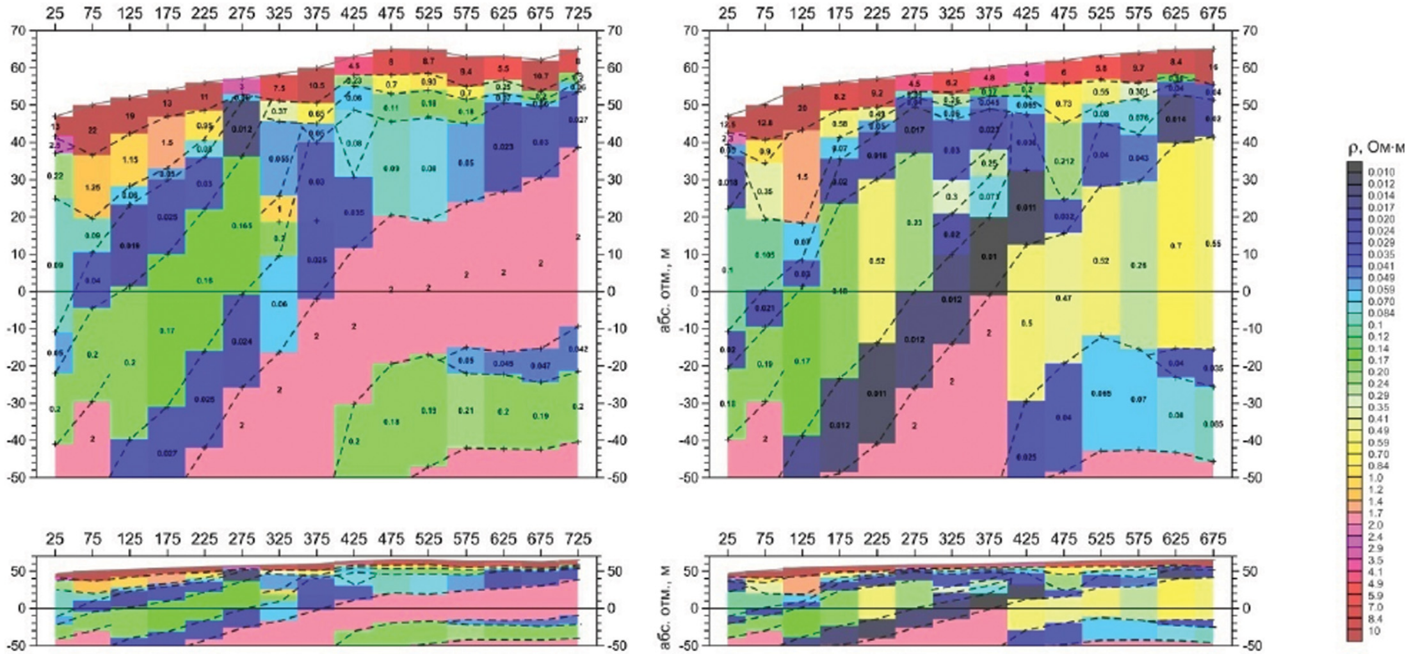

FIGURE 4.2.7 Results of integrated geophysical studies of Zazhoginskoe schungite field (Eastern Fennoscandian Shield, Karelia, Onega Lake): geoelectrical models of Polezhaevskoe schungite depositalong two profiles of control source sounding (*CSS*): horizontal axis distance along the profiles from SW to NE (m),vertical axis—absolute elevations (m); vertical scale bar of apparent resistivity in Ohm m.

highly conductive ore deposits have suggested an effective set of appropriate geophysical methods for further detailed exploration of the Ikhala. This complex of geophysical methods should be based on combination of different modifications of prospecting electromagnetic soundings (electrical tomography, DC, and induced polarization electrical profiling, control source electromagnetic soundings, audio magnetotellurics), should include magnetic survey and be adjusted in optimal way with account for specific signal/noise ratio estimates of preliminary works.

The authors are grateful to the Russian Foundation for Basic Research (RFBR) for supporting projects No. 15-05-01214, 16-05-00543, 16-05-00975. The work was supported also by the FASO of Russia (project 0135-2016-0014) and State Assignment of Schmidt Institute of Physics of the Earth, Russian Academy of Sciences.

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