COMPLEX INTERPRETATION OF SEISMIC AND DENSITY ANOMALIES OF UPPER CRUST OF THE KHIBINY AREA (NW RUSSIA)

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ABSTRACT

The study area is located in the central part of the Kola Peninsula and represents a part of tectonically compound terrane, consisting of the AR, PR and PZ geological structures of the East of Fennoscandian shield (NW Russia). The Khibiny massif (PZ) intrudes the Archean complexes (the Northern contact) and the Paleoproterozoic volcano-sedimentary Imandra-Varzuga complex (Southern and SW-contacts).The results of the 3D seismic and density modelling showed two correlated local high-velocity and high-density anomalies with dimensions of 5 x 10 km approximately in central part of the Khibiny massif and close to contact with Imandra-Varzuga sedimentary-volcanic complex. The first anomaly cannot be explained by "substance" factor only (titanomagnetite-apatite ore bodies), as it has a structural disconformity to general structure of the pluton. The zone of abnormally high tectonic stress is the best explanation for this anomaly. Based on the properties of typical rocks and geological structure of the region the second anomaly is well interpreted by large layered intrusion of Fedorova-Pana type, subsurface of which is cut by Khibiny massif. Thus we forecast big “blind” (not outcropping) PGE-bearing layered intrusion, the upper part of which was cut during the magma intrusion of the Khibiny pluton.

Keywords: seismic and density modelling, upper crust, PGE-bearing layered intrusion, alkaline pluton, mafic-ultramafic, anomalies

INTRODUCTION

The study area is located in the central part of the Kola Peninsula (NE of the Fennoscandian Shield) and represents part of a large terrane in which the uneven-age (AR, PR and PZ) geological structures are spatially combined. This is one of most major mining regions of Russia. The complex apatite-nepheline ores are mined in the Khibiny, the ore of rare and rare-earth metals are extracted in the Lovozero massif. In Monchegorsk region the Cu-Ni, Cr and PGE-ore deposits and manifestations are well known. The largest in Europe PGE-deposit with accompanying Ni, Cu, Au, Co, Rh etc. is prepared for development in the Fedorovo tundra (Fedorovo-Pansky intrusion) [1]. Moreover the numerous occurrences of the Cr, Ti-V, Cu, Au, PGE and other ore types are known within an early Proterozoic riftogenic belt of Imandra-Varzuga. Due to the huge industrial potential the study area is traditionally object of the close attention and statement of the various geological and geophysical researches.

The Neoarchaean (?) - Paleoproterozoic rifting was the most geologically important stage in the history of development of this block of crust. The rifting was begun with a creation of depth faults, which together with the PR mantle plume controlled the formation and localization of the PGE-bearing layered mafic-ultramafic intrusions [2]. The Northern border of this rift on the modern geological maps is well marked by a chain of the quasiconformal with one massifs: from Fedorovo-Pansky intrusion on SE of the Imandra-Varzuga belt to the General Mountain massif in the Pechenga paleorifting structure on the NW of the region through massifs Main ridge, Monchetundrovsky, Monchepluton and others of Monchegorsk mineral area. The Paleozoic tectonic activation zone discordantly intersects the Paleoproterozoic and Archean structures. This zone controls the formation of central-type massifs (alkaline-ultramafic): from the Sokle massif in Finland to the Barents sea coast (close by the Ivanovsky armlet) through the Mavragubsky, Khibiny, Lovozero, Kurgansky, Kontozersky massifs. Discussed in the article the largest Khibiny massif of the nepheline syenites intrudes the Archean complexes (Northern contact) and the Paleoproterozoic volcanogenic-sedimentary Imandra-Varzuga complex (Southern and SW-contacts) [1]. According to the results of numerous researches [3-6 etc.] this massif is an ellipse-shaped in plan multiphase pluton, elongated in the latitudinal direction along the 82º azimuth, with shifted to the East the root. The shape of the Khibiny pluton is close to the asymmetrical lopolith, characterized by the steep Eastern and Northern contacts and the gentler South and West contacts. The Eastern contact in zone of carbonatite stock is sub vertical to the depths of 3 ÷ 4 km and tends to a sharp flattening at the depth of 4 ÷ 5 km. The Western and Southern contacts are falling towards the center at 65 ÷ 70° angle to the depth of 4 km. In the range of 4 ÷ 6 km the contact is gently sloping (30°), but the angle of incidence increases up to 50 ÷ 60° at the depth more than 7 km. The results of the 3D seismic and density modelling [6-7] have specified the structure of the pluton and its contact with Imandra-Varzuga sedimentary-volcanic complex and have revealed 2 unusual anomalies which interpretation is given below.

3D SEISMIC AND DENSITY MODEL

The design of the complex model of crust was carried out on the basis of the coordinated interpretation of the recorded (observed) geophysical fields with the greatest possible accounting of a priori geological information of surface formations of the region. 3D seismic and density model covers the all central part of the Kola region, including the world's largest alkaline plutons of Khibiny and Lovozero. The preparation and processing of initial data and 3D modelling have been realized during 2006-2014.

As the initial seismic data the first arrivals of the refractional waves based on retro materials of the seismic regional researches of the different types and detail were used. In total over 1800 seismic rays of the different types of seismic researches were prepared and processed. As initial gravimetric data were used the results of gravimetric surveys in large scales and also the data base of rock density on the Kola region.

The design of the 3D models is carried out with use of the approaches developed by V.N. Strakhov [8] and G.Ya. Golizdra [9] and advanced in proceedings of V.N. Glaznev [10]. Computing features of the gravimetry problem are considered in the proceedings [11-12], and the decision of the problem of the seismic tomography is realized in the Firstomo commercial package [13]. The network of 3D-calculations is chosen based on reasons of the enough reliable representation of anomaly objects: for density model it is

1x1 km in the plan, and for velocity model it is 4x4 km. At the first stage of interpretation the numerical density and velocity models of the geological environment corresponding to the general modern representations were created. Further the residuals of the gravitational and time fields were calculated. These residuals were used at the iterative deciding of the inverse problems within each of methods. Procedure of the complex inversion of the data of the gravimetry and seismometry represents iterative sequence of decisions of the inverse problem within the limits of one of the method and using the decision received as initial approximation for other method.

The Khibiny pluton in accordance with the obtained 3D models is allocated as the low-velocity anomaly at depth from 5 km to 11 km and characterized by average velocity below the background velocity at these depths (fig. 1). However in the upper part of the velocity model we can see two local high-velocity anomalies with dimensions of 5 x 10 km approximately. The intensity of the first anomaly which is detected at the depth of 1.5÷2.0 km and the spatial coincide with the central part of the massif is increased to the depth of 3 km (see fig.1). Within the anomaly the value of Vp-velocity reaches 6.8÷7.0 km/s relative to the value of the background velocity of approximately 5.5 km/s. The second high-velocity anomaly, discovered Southeast of the first anomaly at a depth of about 3 km, more clearly is revealed at a depth of about 4 km, where the intensity of the first anomaly begins to decrease.

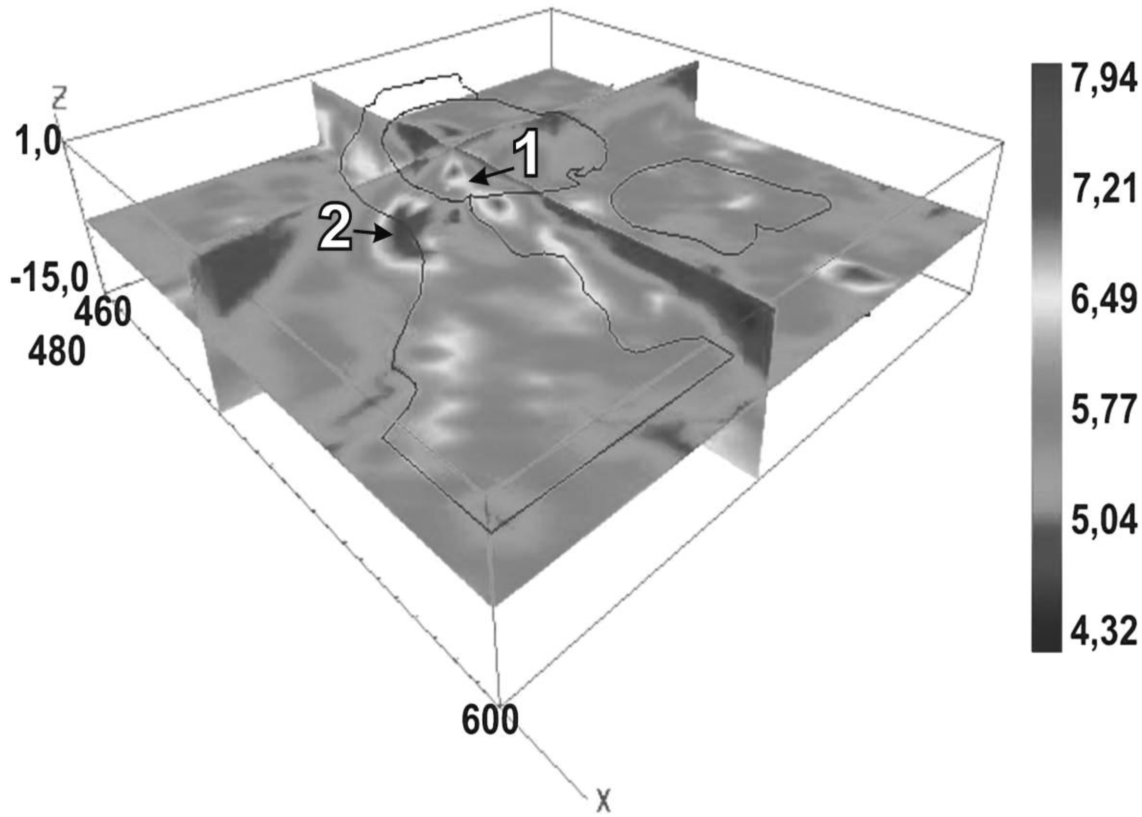

Figure 1 − Sections of 3D velocity model (values in km / sec) and two local high-velocity anomalies with dimensions of 5 x 10 km approximately, after [5]

COMPLEX INTERPRETATION OF SEISMIC AND DENSITY ANOMALIES

Variants of the interpretations of these anomalies were analyzed in terms of the correspondence to principal features: "substance", "state / rheology of the rock massif" and "structure". The first group conditionally unites interpretations of the anomalies by the properties of the mafic-ultramafic rocks, the second group explains the anomalies by status / rheology of rocks due to concentration of abnormally high tectonic stress, and the third group accounts for accordance of spatial position of anomalies to widespread structures of the study area and to their scales of manifestations.

The mafic-ultramafic complexes widespread in the area, such as: Imandrovsky lopolith, the Fyodorovo-Pansky stratified complex, mafic effusions of the complex Imandra-Varzuga, ultramafites and alkaline ultramafites of the first stage of formation of the Khibinsky massif (fig. 2) - meet requirements of "substance" factor. However the geological bodies of the Imandrovsky lopolith and effusions have the low thickness and sizes to be a source of such large anomalies. Respectively the layered intrusive of Fedorovo-Pansky type or the ultramafic derivatives of Khibiny magmas for second anomaly and the large accumulations of the titanomagnetite-apatite ores for first anomaly can be considered as their reason only (see fig. 1).

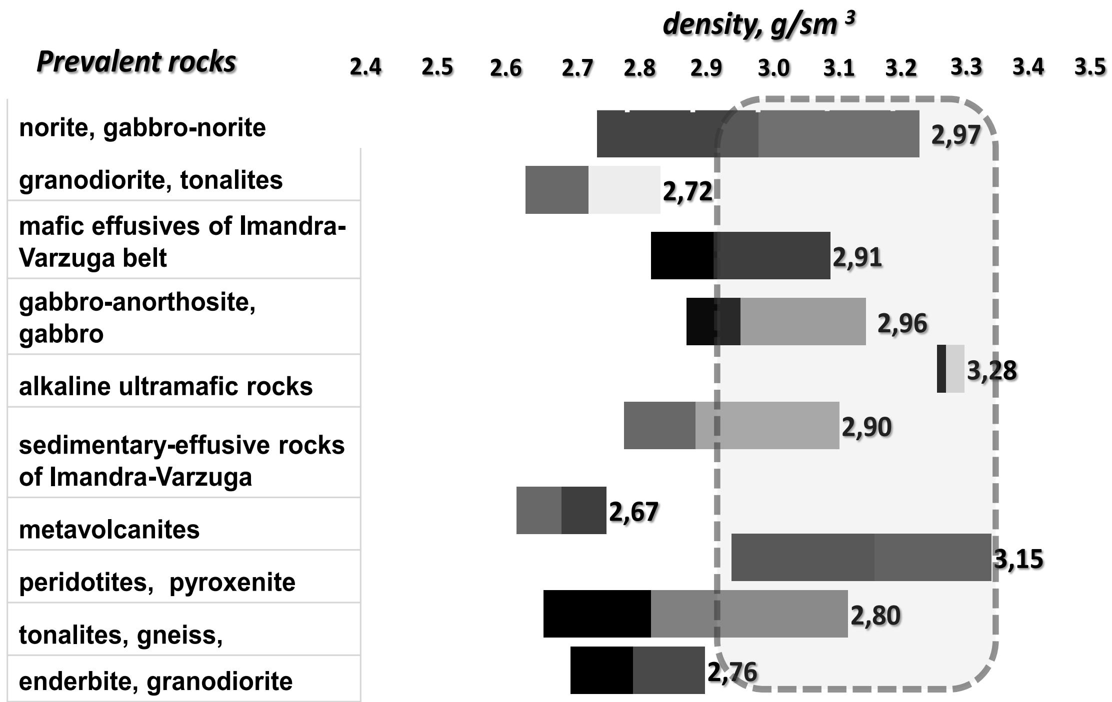

Figure 2 - Summary of density (range of deviation and weighted average) of Achaean & Paleoproterozoic complexes, after Turemnov & Grinchenko (data compilation), and value of density anomaly (dotted line).

The analysis of correspondence to the "structure" sign showed that the first anomaly (see fig. 1) cannot be caused by the titanomagnetite-apatite ore bodies as it has the structural discordance with the general structure of Khibiny pluton. Moreover the velocity values of this anomaly exceed velocity values of the main kinds of Khibiny rocks (fig. 3). Therefore we involved data of the Mining Institute (Kola Science Centre of Russian Academy of Sciences) based on results of studying of the stress and strain state of the Khibiny massif [14-15] for interpretation of this anomaly. According to the numerous instrumental measurements the actual (measured) values of stress are significantly greater than values calculated by weight of rocks. It is important the main normal axis of compressive stress has usually quasi-horizontal position. Thus, the zone of abnormally high tectonic stress is the best explanation for this anomaly (fig. 4). The quick isostatic uplift of the massif after the digression of the last glacier, during which the rocks did not have time to unload, can be a source of the increased horizontal stress.

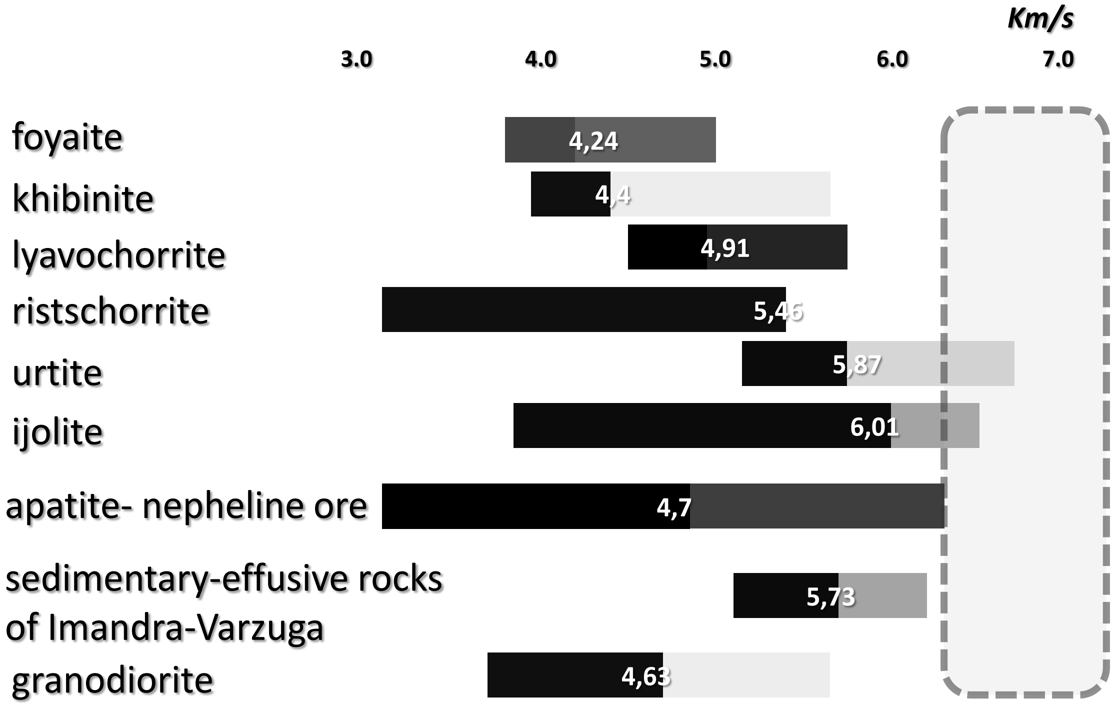

Figure 3 - Summary of Vp-velocity of Khibiny massif and host rocks after Turemnov & Grinchenko (data compilation), (range of deviation and weighted average) and value of velocity anomaly (dotted line).

Based on the properties of typical rocks and geological structure of the region the second anomaly is well interpreted by large layered intrusion of Fedorova-Pana type, subsurface of which is cut by Khibiny massif (see Fig. 4). Taking into account the current level of erosion the upper part of the layered intrusions is 2 ± 0.5 km of about surface. The maximum intensity of the velocity anomaly (7.0÷7.5 km/s) is observed at a depth of 4 to 7 km, and its lower boundary is defined on the basis of loss of contrast in the density and velocity models in the range of 9÷10 km from the surface. Anomaly marks the boundary of the Imandra-Varzuga paleorift zone, which corresponds well to the regional peculiarities of localization of the layered massifs of the Fedorovo-Pansky type. These massifs are always confined to the North - North-eastern tectonic boundary of the paleorift zone, which falls to the South at different angles from 15º to 70º in the study area. The thickness of the early Proterozoic layered mafic-ultramafic intrusions amount to several kilometres away and is well correlated with the size of the second anomaly.

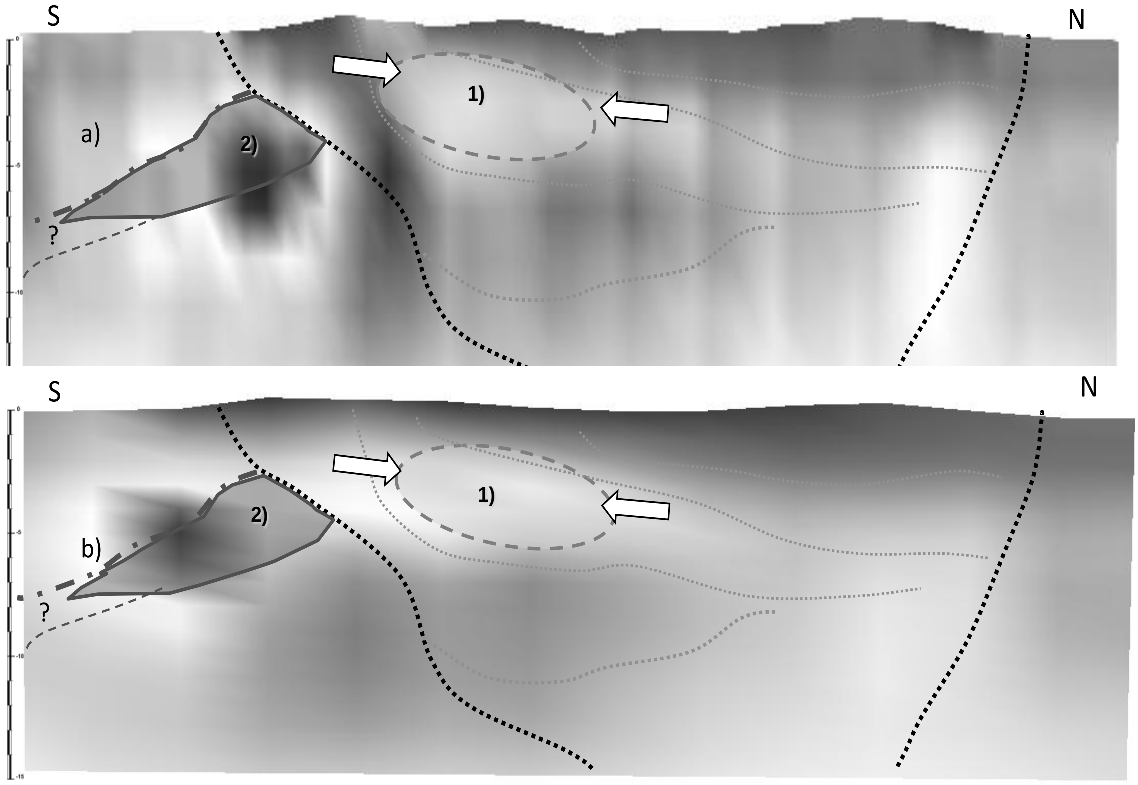

Figure 4 - Complex interpretation of seismic and density anomalies of upper crust of the Khibiny area. Sections of the density (a) and velocity (b) models with the marked and proposed: 1) zone of abnormally high tectonic stress; 2) probable layered mafic-ultramafic intrusion. Black dotted line - borders of Khibiny alkaline massif

CONCLUSION

The results of 3D seismic and density modelling showed a more complex structure of the Khibiny massif and its environment than existed up to this view, formulated in the predictive geological model. Both revealed anomalies (the high-velocity and density anomalies) cannot be interpreted by the "substance" factor only. We explain the first anomaly within the Khibiny massif due to the zone of anomalous tectonic stress, which was preserved during the isostatic uplift after the glacier (see Fig. 4). Concerning the second anomaly, we forecast a large "blind" (not outcropping) PT-bearing layered intrusion, the upper part of which was cut during the implementation of the Khibiny pluton. This zone is interesting from the point of view of the possible formation near the contact of the Paleoproterozoic layered massif and the Paleozoic alkaline intrusion of the unusual hybrid rocks and the secondary offset PGE and copper-nickel ores. In any case a borehole of 3 km depth can confirm or refute finally this hypothesis only. This is attainable for the current level of drilling technology and equipment.

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