# ESTIMATION OF THE CHANGE IN DENSITY OF CRYSTALLINE ROCKS OF THE EARTH' S CRUST WITH DEPTH IN THE AREA OF THE KOVDOR ALKALINE-ULTRABASIC MASSIF

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## Abstract

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# ESTIMATION OF THE CHANGE IN DENSITY OF CRYSTALLINE ROCKS OF THE EARTH' S CRUST WITH DEPTH IN THE AREA OF THE KOVDOR ALKALINE-ULTRABASIC MASSIF

## (KOLA GEOPHYSICAL PROVING GROUND)

*(Presented by Academician A. V. Peive, July 6, 1966)*

Of great importance in comprehensive investigations at the Kola geophysical proving ground (^1, ^2) is the establishment of regularities in the change of density in the Earth' s crust, based on analysis of the gravitational field of individual well-studied reference areas. An especially favorable object for these purposes, owing to its comparatively simple form, great extent at depth, and considerable excess density, is the Kovdor massif of ultrabasic-alkaline rocks, located in the western part of the proving ground within the Bothnian deep structure of the Earth' s crust. The study of the gravitational field and of the physical properties of the region was carried out by the Western Geophysical Trust and the Kola Branch of the Academy of Sciences of the USSR. According to geological concepts, the massif is a multiphase intrusion of central type, of Lower Paleozoic age; in plan it has an incomplete ring structure, with steeply dipping rocks toward its center and a vertical thickness on the order of several kilometers (^3). The enclosing rocks are strongly dislocated and migmatized gneisses of the Belomorian series of the Archean, represented mainly by biotite and amphibole varieties. A study of the density of 3,500 rock samples taken from outcrops and drill cores showed that the average density of the gneisses is 2.65 g/cm^3, with a tendency for this value to increase to 2.70 g/cm^3 (taking into account the weight of denser varieties developed within a radius of 50 km around the massif), while the weighted average density of the rocks of the massif is 3.07 g/cm^3, varying from 3.20 g/cm^3 for the ultrabasic rocks, which occupy 60% of the entire area, to 2.93 g/cm^3 for the alkaline rocks. The porosity of the gneiss samples ranges from fractions of a percent to 10% and, according to limited observations, exceeds the porosity of the rocks of the massif. In the gravitational field the massif was marked by an intense positive anomaly

Figure 1

Figure 1: Figure 1

of isometric form, characteristic of a vertical cylinder, against a background of negative gravity values.

The problem of studying the regularities in the change of density in the region was solved by selecting the form and depths of occurrence of the lower edge of the massif that best satisfy the observed values of gravity for known one-layer and two-layer density models of the Earth' s crust (ˆ4), and also for a gradient medium, whose existence may be assumed from the results of earlier investigations (ˆ5). In order to increase the reliability of the conclusions under conditions of instability in determining the depth of occurrence of lower edges, a thorough allowance was first made for effects distorting the gravity anomaly: allowance for the regional background, the anomalous vertical gravity gradient, and distortions associated with the influence of density inhomogeneities of the enclosing rocks and unconsolidated formations. In addition, the anomaly from a layer of kilometer-scale thickness of the massif with the real density distribution was reduced—

belongs to the anomaly from a vertical circular cylinder with the same thickness, but with the weighted-average density. As a result of these operations, for 4 branches of curves along radial detailed profiles 10-16 km long each, the confidence interval of the observed gravity values was estimated, taking into account, to some degree, the scatter of errors in isolating the local anomaly. The position of the lower edges of the massif models was chosen in accordance with hypotheses on the depths of magma

**Fig. 1.** Selection of theoretical gravity curves from a vertical cylinder for different laws of variation of excess density with depth.
**a** —single-layer model of the Earth' s crust: $\Delta\sigma = 0.50$ g/cm$^3$; $\Delta\sigma = 0.42$ g/cm$^3$; **b** —two-layer model of the Earth' s crust: $\Delta\sigma_1 = 0.50$ g/cm$^3$, $\Delta\sigma_2 = 0.30$ g/cm$^3$; $\Delta\sigma_1 = 0.42$ g/cm$^3$, $\Delta\sigma_2 = 0.27$ g/cm$^3$ (the thickness of the upper layer is taken as 15 km); **c** —gradient model of the Earth' s crust: $\Delta\sigma_1 = 0.54$ g/cm$^3$, $H_1 = 1$ km; $\Delta\sigma_2 = 0.49$ g/cm$^3$, $H_2 = 2.5$ km; $\Delta\sigma_3 = 0.44$ g/cm$^3$, $H_3 = 5$ km; $\Delta\sigma_4 = 0.40$ g/cm$^3$, $H_4 = 7.5$ km; $\Delta\sigma_5 = 0.36$ g/cm$^3$, $H_5 = 10$ km; $\Delta\sigma_6 = 0.33$ g/cm$^3$, $H_6 = 15$ km; $\Delta\sigma = 0.30$ g/cm$^3$ (the curves for different values of $\Delta\sigma$ and the same $H$ differ in their thickness).
1 —confidence interval of the observed gravity values; 2-5 —theoretical gravity curves from a vertical cylinder for different depths of occurrence of the lower edge: 2 —$H = 20$ km; 3 —$H = 50$ km; 4 —$H = 125$ km; 5 —$H = \infty$; 6 —massif model satisfying the middle part of the confidence interval of the observed gravity values.

formation (100-200 km) (4) and with ideas about the existence of intermediate

Fig. 2. Character of the change in porosity and density of rocks near the day surface as a function of the dimensions of the area studied. 1 –porosity, 2 –density

Figure 2: Fig. 2. Character of the change in porosity and density of rocks near the day surface as a function of the dimensions of the area studied. 1 –porosity, 2 –density

magmatic chambers explaining the mechanism of formation of multiphase intrusions (3). Calculations of the theoretical values of the gravity anomaly from different massif models were performed graphically.

1. Single-layer, homogeneous model of the Earth’ s crust: the excess density of the massif is a constant quantity (Fig. 1a). From examination of the figure it is evident that a comparatively good agreement of the theoretical curves from vertical circular cylinders with the confidence interval of the observed gravity values can be achieved by assuming $\Delta\sigma \simeq 0.46$ g/cm$^3$, but even then similarity between the observed and calculated curves will not be attained. This indicates the need to change either the shape of the massif or the model of the Earth’ s crust. For $\Delta\sigma = 0.54$ g/cm$^3$, for the shape of the massif as a truncated conical body, complete agreement of the theoretical values is observed; however, the large constant value of excess density, exceeding the established value of 0.42 g/cm$^3$, leads to the necessity of changing the model of the Earth’ s crust.
2. Two-layer model of the Earth’ s crust: the excess density of the massif is a constant quantity within individual “layers,” and at their boundary it

changes abruptly (Fig. 1b). (The case of no jump is analogous to the single-layer model of the Earth’ s crust considered above.) Calculations carried out for vertical circular cylinders show that the best agreement of the theoretical curves with the confidence interval can be achieved at $\Delta\sigma = 0.48$ g/cm$^3$ and 0.26 g/cm$^3$, and with a thickness of the upper “layer” of 8-15 km (6). However, in this case as well there is some discrepancy in the configuration of the curves, which is due either to a different shape of the massif or to a different model of the Earth’ s crust.

Calculations performed under the assumption of an insignificant decrease in the horizontal dimensions of the massif with depth made it possible to obtain good agreement between the theoretical and observed values. Nevertheless, this model of the Earth’ s crust also does not fully correspond to the true one, since for the upper “layer” it is characterized by a somewhat overestimated value of the excess density of the massif in comparison with that established.

**Fig. 2.** Character of the change in porosity and density of rocks near the day surface as a function of the dimensions of the area studied. 1 –porosity, 2 –density

3. **Gradient model of the Earth' s crust:** the density of rocks, gradually increasing with depth, tends toward a constant value; the excess density of the massif may remain constant, increase, or decrease. Constancy of the excess density means the same law of density change for the massif and the enclosing rocks. This case is analogous to the conical model of a massif in a homogeneous crust (Fig. 1a). An increase in excess density with depth presupposes the existence of a large vertical gradient of rock density in the massif or a decrease in the density of the enclosing rocks, which is unlikely and is not confirmed by the calculations performed. A decrease in excess density with depth means constancy of the massif density or a smaller gradient in the massif compared with the enclosing rocks. This variant is presented in Fig. 1b. The theoretical curves from vertical cylinders agreed well with the confidence interval of the observed values for the given law of change in excess density.

The results of the calculations show that in all cases the values of the selected excess density of the massif rocks near the day surface for a gradient medium exceed the value established empirically. This fact may possibly be explained by the unrepresentativeness of the results of studying physical properties on samples: when studying the density and porosity of rocks, samples of the order of 1 $dm^3$ in size are usually used, whereas in the interpretation of gravitational anomalies it is necessary to know these quantities for considerably larger volumes.

Figure 2 gives a graph of the change in the surface porosity of the gneiss complex of the area, constructed from the results of estimating structural porosity (examination of thin sections), structural and, in part, textural porosity (determinations on rock samples), pore spaces caused by tectonic fracturing, the blockiness of rocks (field observations), and zones of tectonic disturbances of various orders, including deep faults (from the results of deciphering aerial photographs and geophysical work). From these data the curve of change in the surface density of the gneisses was also calculated, indicating a considerably smaller value of the average macrodensity of the gneisses,

This is established from measurements on samples. To estimate the change in density with depth, one may, with only slight violation, apparently use the similarity criterion, using data on a 20–30% decrease in the porosity of samples with an increase in all-round pressure to 4000 $kg/cm^2$ (7). According to these estimates, the density of the granite-gneiss complex at depths of 3–10 km is about 2.70 $g/cm^3$. All this gives good confirmation of the gradient character of the medium. Evidently, because the influence of macroporosity is not taken into account, the density of the ancient Archean granite-gneisses is overestimated to a greater extent than that of the rocks of the Paleozoic intrusion. Therefore, the decrease in the excess density of the massif with depth should be considered probable, given a larger density gradient of the gneisses. Calculations performed for a model of the massif in the form of a conical body showed that satisfactory agreement with the confidence interval of the observed values of gravity can in many cases be achieved by varying the density of the massif and of the enclosing rocks and the depths of occurrence of the lower edges; however, the model was not confirmed by geological concepts. Apparently, if the massif does have a conical shape, then it differs little from a vertical cylinder. The depth of occurrence of the lower edge of the massif in the gradient model of the earth' s crust is estimated on average at about 50 km, with its variation from 20 to 200 km.

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