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MOBILE-PERMEABLE ZONES IN THE BASEMENT OF THE NORTH-EASTERN BALTIC SHIELD AND CONDITIONS OF THEIR LOCATION

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ABSTRACT: *For the first time it is proposed to apply calculations of gradient stress fields when identifying weak zones that predetermine localization of magmatic processes in the basement. The elaborated methods can be used as methods for rapid diagnosis during the search of minerals. This work is based on numerical modeling to allow distinguishing the dependence of the formation of permeable zones in the crust on the regional natural stresses. The investigation revealed the heredity of the regional magma feeding channels from the Archaean to the Early Proterozoic.*

KEYWORDS: *numerical simulation, stress fields, Late Archaean, Early Proterozoic, magma feeding channels.*

1. Introduction

Interpreting the conditions that cause tectonic deformations is a most essential part of reconstructing the geodynamic regimes predetermining features of the regional development and affecting its metalogenic specialization. One of the most essential features of the tectonosphere is the stress and strain state that controls tectonic and geodynamic processes in the crust. By the example of the Kola region, tectonophysical simulation has been performed to reveal structures draining the uprise of mantle basic-ultrabasic magmas. The research has been carried out on the basis of numerical simulation to reconstruct zones of high permeability in the basement, which formed in the Late Archaean and determined the localization of the regional tectonic magmatic processes. For this purpose, quantitative models of the stress and strain state of the regional Earth's crust were constructed with due regard of its evolution. The paper pioneers quantitative estimates and interrelation of geodynamic factors interpreting mechanisms of the formation of deformed structures in the region. These factors also reflect peculiarities of the tectonic evolution of the NE Baltic Shield, which is mainly characterized by inherited properties of the regional geodynamic activity in the Early Precambrian.

2. Statement of the problem and principal equations

The northeastern part of the Baltic Shield is characterized by a long and complex history of development, and the observed structure reflects the cumulative effect of multiple transformations. It is recognized that the bulk of the crust of the Kola region formed in the late Archean (Radchenko et al, 1992; Mitrofanov et al., 1995). Mobile-permeable zones are treated as structures with the highest permeability for deep magmatic melts. The northeastern part of the Baltic Shield is traditionally known to contain the largest Archean structures (Murmansk, Kola, Belomorian, Karelian megablocks) limited by long-lived tectonic faults (Mitrofanov et al., 1995) (Fig. 1). Among the minor structures, the Archean Keivy structure occurs being embedded into the structure of the Kola megablock, Archean greenstone belts, e.g. Kolmozero-Voronja, Yona and Tersky-Allarechka, with the Proterozoic Lapland granulite belt, Pechenga-Imandra-Varzuga paleorift, and giant Paleozoic alkaline massifs (Khibiny, Lovozero).

According to the accepted assumptions, the northeastern part of the Baltic Shield is treated as a non-uniform elastic body affected by volume forces and stresses specified at the boundary. In the Late Archean, the Kola region was mainly stable under the conditions of fully uniform compression because of the remote forces. Therefore, we assume that the studied area is in an equilibrium state, and the components of the stress tensor σ_{ij} in case of the flat problem satisfy the conditions of equilibrium -

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yx}}{\partial y} + \beta_x = 0, \quad \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \beta_y = 0,$$ where β_x and β_y are volume forces.

The investigated area consists of several finite subdomains, each being considered homogeneously isotropic and linearly elastic zones with linear-elastic constants. The boundary element method was used in the numerical solution of the stress boundary value problem. The numerical solution is found using previously obtained analytical solutions for simple singular problems to satisfy the specified boundary conditions at each element of the contour. The formulas for calculating stresses σ_{xx}, σ_{yy}, σ_{xy} for any arbitrary point of the body are given in (Crouch and Starfield, 1983). The values of Poisson's ratio and Young's modulus for rocks of the Kola region were specified in accordance with the available experimental data (Melnikov, 1975).

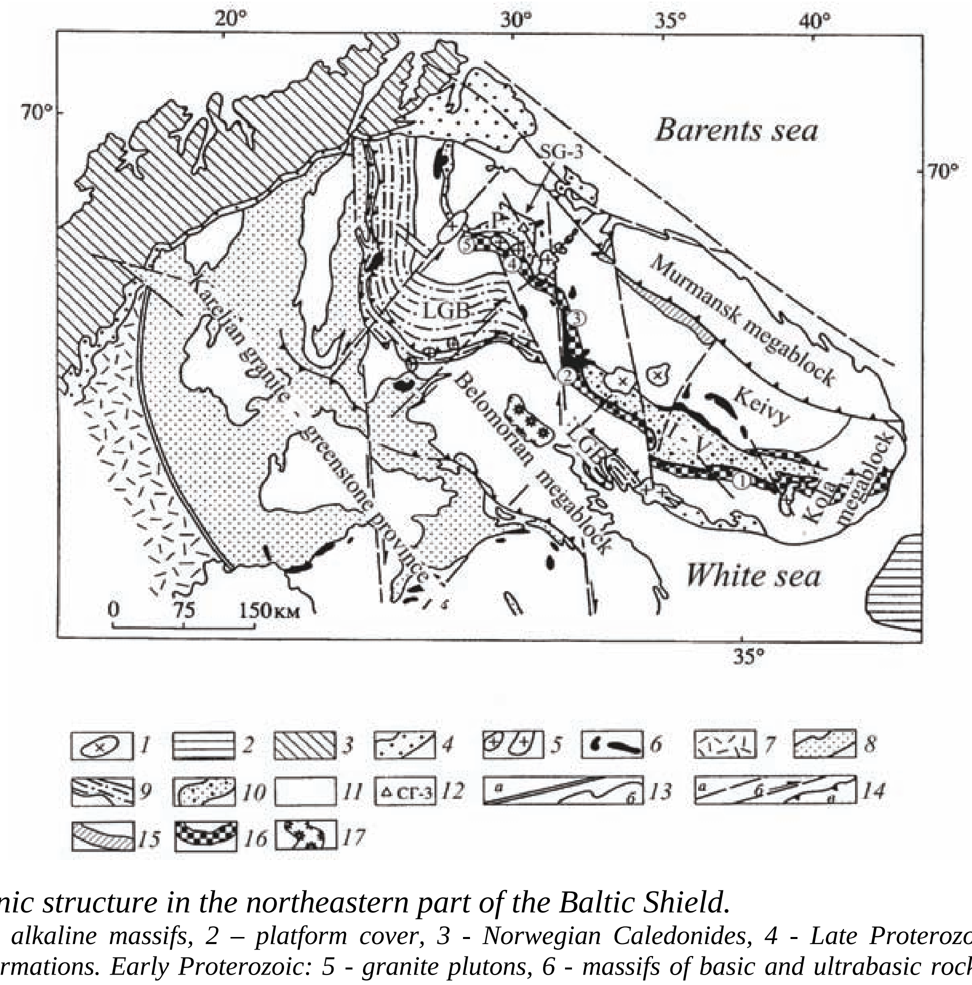

Fig.1. Tectonic structure in the northeastern part of the Baltic Shield.

Paleozoic: 1 - alkaline massifs, 2 – platform cover, 3 - Norwegian Caledonides, 4 - Late Proterozoic sedimentary formations. Early Proterozoic: 5 - granite plutons, 6 - massifs of basic and ultrabasic rocks. Sedimentary-volcanic complexes: 7 - Svecofennides, 8 - Karelides. 9 - Lapland granulite belt, 10 - Pechenga - Imandra – Varzuga paleorift, 11 - granite-gneissic basement of the Proterozoic structures. 12 - Kola superdeep borehole, 13 - geological boundaries, 14 - faults. Archean greenstone belts: 15 - Kolmozero-Voronja, 16 - Tersky-Allarechka, 17 - Yona.

The numbers in circles - areas: 1 – Tersky, 2 - Voche Lambina, 3 – Olenegorsk, 4 – Allarechka, 5 - Kaskama.

T load is set for the entire perimeter of the study area. Since we do not have reliable data on the absolute values of actual regional forces, we assume that their *T* intensity is equal to unity. Correspondingly, in the calculations, we obtain normalized values of stresses - σ_{xx}/T, σ_{yy}/T, σ_{xy}/T. The obtained quantitative estimates of stress σ_{xx}, σ_{yy} and σ_{xy} allow us to calculate the gradient of the stress field in the form $Gr = \left|(\sigma_{xx} - \sigma_{yy})/T\right|$, and determine the orientation of the principal stress axes by the formula (Muskheshvili, 1966): $tg2\theta = 2\sigma_{xy}/(\sigma_{xx} - \sigma_{yy})$, where θ is the angle between the principal stress axis σ_1 with the OX axis. A stress boundary problem is solved using numerical methods and computer algorithms developed for these purposes (Filatova, 2009). Two stages of the Archaean development of the Kola region have been studied: (a) 3.0-2.8 Ga; (b) 2.8 - 2.5 (2.55) Ga. At each stage a base model describing the Kola region in terms of geological structures formed by this time has been set. The purpose of these studies is to identify major Archaean magma feeding channels and to explane the mechanisms of their initiation.

3. Results and conclusions

Performed numerical simulations allowed for each base model to estimate stress values (σ_{xx}, σ_{yy}, σ_{xy}), stress gradients and the orientation of principal stress axes, which could occur in the continental plate of the northeastern Baltic Shield in the late Archean by external tectonic forces. Figure 2 shows the main channels for magma uplifting in the region, which are marked by anomalous values of stress field gradients. The formation of these structures as weakened zones occurred between 3.0 - 2.8 Ga. Zones 1-4 (1 - Kolmozero-Voronja, 2-Tersky-Allarechka belt, 3 - Tsaga, 4 - Schucheozero) are known as Archaean according to the geological data. Zones 5-6 (5 - Tuloma, 6 - Kolvitsa) known as Early Proterozoic. Zone 7 (Liina Hamari) can be traced along the fault extending NE. Local geologists believe that north-east-trending faults on the Kola Peninsula are Archaean.

In addition, local anomalous zones were identified in the field of stress gradients, the values of which are below the average for the region (fig. 2). These zones are also correlated with known geological structures of Archaean and Proterozoic age. Also the areas with anomalous values of tangential (shearing) stresses normalized with respect to the maximum value for the region are identified. All these sites concentrate within areas of high stress gradients and are confined to main channels for regional magma uplifting.

Figure 3 shows the tracing zones allocated according to the areas of maximum stress gradients for the second base model (2.8 - 2.5 Ga). Almost all the selected zones coincide with the areas where the activation of tectonic and magmatic processesis observed. Zones 1-5 (1 - Generalskaya Mt., 2 Poritash, 3 Salnaya Tundra-1, 4-Salnaya Tundra-2, 5-Monchetundra) are Early Proterozoic in age. Zones 1 and 2 (Generalskaya Mt. and Poritash) are subparallel. With regard to the location they are confined to the Pechenga structure and together form a structure that can be represented as a typical rift trough. Zone 6 (Khibiny) is known as Paleozoic. Zone 7 (East Kola) extends nearly north-southwards and intersects the eastern extremity of the Kola Peninsula and the White Sea.

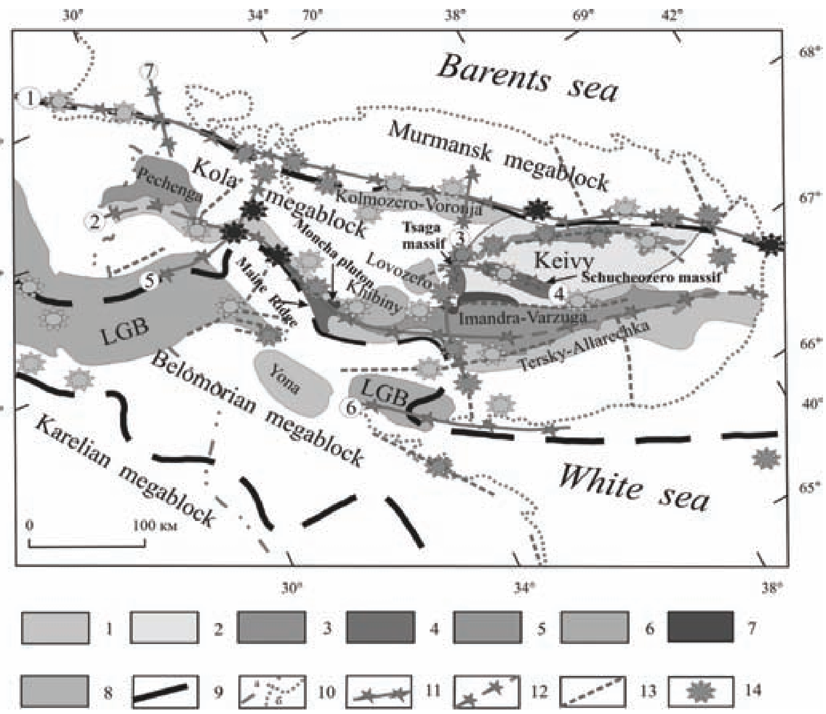

Fig 2. Weakened zones in the basement of the Kola region formed in the Archean (3.0-2.8 Ga).

1 - Archean greenstone belts, 2 - Keivy structure, 3 - high-alumina gneisses, 4 – massifs of anorthosite and gabbro-anarthosite (archaea / early Proterozoic), 5 - Pechenga-Imandra-Varzuga paleorift, 6 - Lapland granulite belt, 7 - layered massifs (Early Proterozoic), 8 - alkaline massifs (Paleozoic), 9 - faults (fault zones) at the contact of megablocks, 10 - a) Russian state border, b) the modern coastline, 11 - magma feeding channels established by anomalous values of the stress gradients, 12 - magma feeding channels highlighted in the field of stress gradients with values below the average (used local anomalies in the area of the Tersky-Allarechka belt), 13 - weakened zones in the basement marked in the field of stress gradients with values below the average, 14- tangential stresses normalized with respect to the maximum regional value (from darker to lighter color: 1-0,8; 0,8-0,6; 0.6-0.4).

This zone is not marked by geologists as a magma feeding channel; its age and genesis is unknown. It should be noted that Zone 7 intersects the fault system shown on the tectonic schemes of the Kola region at an angle of 30 ° (Radchenko et al, 1992). It is assumed that the faults formed in the Late Archaean.

Figure 3 also shows the distribution of tangential stresses with the largest magnitudes in the region calculated for the second base model. Anomalous values of tangential stresses are observed in the western sector of the Kola megablock (Lapland granulite belt, Monchegorsk ore district, the structure of the Tersky-Allarechka greenstone belt - Olenegorsk and Voche-Lambina) and in the northern part of the Belomorian megablock (Yona greenstone belt). In addition to these structures, the Pechenga structure, central part of the Murmansk megablock, eastern extremity of the Kola Peninsula, and some part of the White Sea are clearly distinguished in the field of tangential stresses.

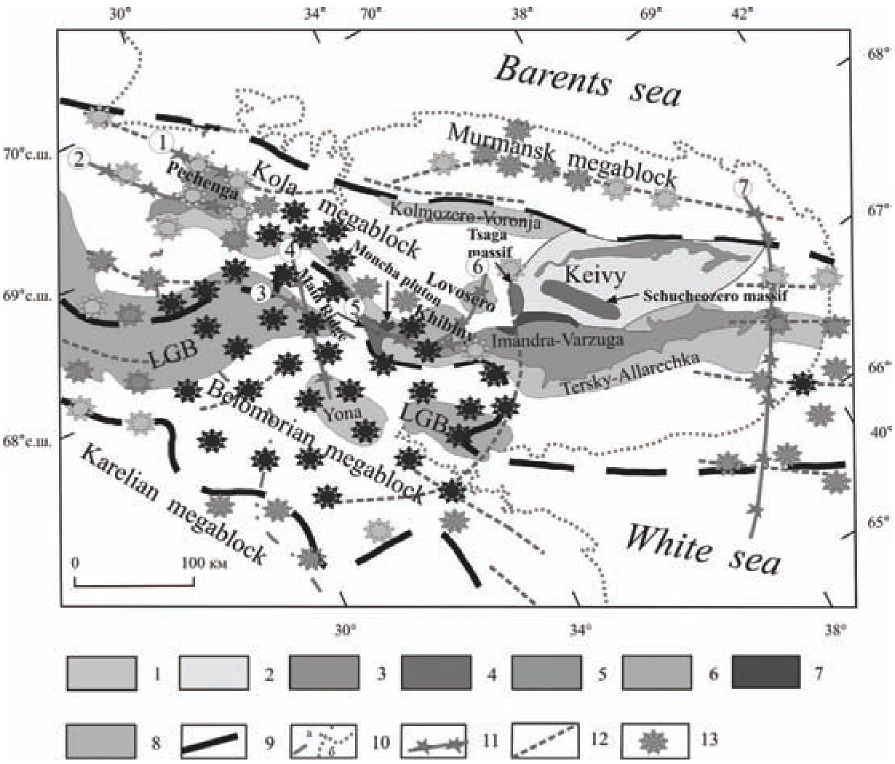

Fig.3. Weakened zones in the basement of the Kola region formed in the Archaean in the range of 2.8-2.5 Ga. *Symbols are shown in fig. 2.*

One feature should be specially noted that is traced when comparing the results for each base model. As to the first basic model (3.0-2.8 Ga), there is zone in the northern part of the Belomorian megablock including the Yona greenstone belt where the values of tangential stresses are negligible. For the second basic model (2.8-2.5 Ga), the fields of stress gradients including values from anomalous to average are fixed in the same territory while this area is covered by a zone of maximum tangential stresses. The available geological data indicate that in the interval 2.8-2.5 Ga, the rocks of the Belomorian megablock were repeatedly exposed to intense deformation. Also, they underwent high-to-moderate pressure metamorphism [Volodichev, 1990]. Consequently, in the interval 3.0-2.8 Ga, the most favorable conditions to form weakened zones in the basement and to control placement of the greenstone belts were created within the Kola megablock (Kolmozero-Voronja and Tersky-Allarechka greenstone belts). In contrast, in the range of 2.8-2.5 Ga, the most favorable conditions for the development of brittle fractures with subsequent localization of weakened zones originated in the northern part of the Belomorian megablock where the Yona greenstone belt extends.

Thus, the carried-out research has allowed reconstructing the area of increased permeability in the basement formed in the Late Archean and predetermined location of regional tectonic and magmatic processes. The obtained results revealed a local heredity of magma feeding channels in the region from the Archaean to the Early Proterozoic, which is confirmed by the geological data. Consequently, the stress and strain state could affect the way the geodynamic processes proceeded, contributing to the development of mobile-permeable zones within the rigid blocks of the northeastern part of the Baltic Shield. Analyzing results of the carried numerical experiment shows that the inception of the weakened zones in the Kola megablock basement, which predetermined location of the Kolmozero-Voronja and Tersky-Allarechka greenstone belts, occurred earlier than in the northern part of the Belomorian megablock, containing the area the Yona greenstone belt is common. The elaborated methods can be applied as the methods of a rapid diagnosis to allocate weakened zones in the basement and evaluate their permeability degree with the minimum time and resources required.

4. References

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