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PETROLOGY

FORMATION CONDITIONS OF THE POSTCOLLISIONAL GRANITES OF THE KARA OROGEN (NORTHERN TAIMYR, CENTRAL ARCTIC): APPLICATION OF 3D NUMERIC MODELING

© 2025 Academician of RAS V. A. Vernikovsky[a, c], A. N. Semenov[b, c], O. P. Polyansky[b], A. V. Babichev[b, c], A. E. Vernikovskaya[a, c], and N. Yu. Matushkin[a, c, *]

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Abstract. Using 3D numerical modeling, we analyze the formation of postcollisional granitoids of the Kara orogen in Northern Taimyr under conditions of elevated heat flow due to the orogen's breakup prior to its mantle plume episode (280–250 Ma). The initial geometry of the model area, the boundary conditions and physical properties for the crust and the mantle have been selected to reflect the structure of the crust in the junction zone of the Kara, Central Taimyr, and Siberian blocks. Comparing 2D and 3D modeling results with identical parameters and medium physical properties defined by the Rayleigh number shows that 3D modeling yields a more realistic and correct description of relevant magmatic processes. At the base of the modeled Earth crust at the depth of ~50 km an area of melting of continental crust appears, possibly with slight input of mantle component, which generates magma uplift and the formation of closely spaced granitoid intrusions. Plutons with diameters 10–20 km were emplaced at depths 14–8 km during 15 million years, which is close to the actual geological position of postcollisional stocks of the Kara orogen.

Keywords: *Arctic, Kara orogen, North Taimyr, Siberian craton, collision, mantle plume, granite, thermal model*

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INTRODUCTION

The Kara orogen is one of the key structures in the Arctic, extending along the northern part of the Taimyr Peninsula for almost 1000 km. Its formation occurred as a result of oblique collision of the Kara microcontinent with Siberia during the Carboniferous-Triassic periods (literature review in [1, 2]). The orogenic belt contains a large volume of granitoids and metamorphic rocks of different facies (Fig. 1). Based on geological-structural, petro-geochemical and U-Th-Pb isotopic data for zircons from granites, stages of syn-collisional (315–282 Ma) and post-collisional (264–248 Ma) granitoid magmatism have been identified ([3, 4] and literature review therein). In the structure of the Kara orogen, granitoids are zonally distributed – in the western and central parts of the region, predominantly syn-collisional, and in the eastern part, post-collisional (Fig. 1). Syn-collisional granitoids are localized in migmatization zones among rocks of amphibolite facies metamorphism and are represented mainly by granodiorites and granites, less by diorites. They form irregularly shaped bodies of different sizes: lens-shaped from a few meters among migmatites to large (several hundred km^2) massifs, often elongated in shape, conforming to the strike of folded and thrust-strike-slip structures (literature review in [3]).

Post-collisional granitoids cut through rocks of both northern and central domains, including unmetamorphosed Paleozoic deposits of the Central Taimyr accretionary belt cover, forming distinct contact hornfels aureoles [1, 2]. They have oval and rounded pluton shapes, small sizes, usually up to several tens of km^2 (Fig. 1). Their material composition is more diverse than that of the above-described syn-collisional varieties. They are represented by porphyritic biotite

[a]*Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia*
[b]*Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia*
[c]*Novosibirsk State University, Novosibirsk, Russia*
**e-mail: MatushkinNY@ipgg.sbras.ru*

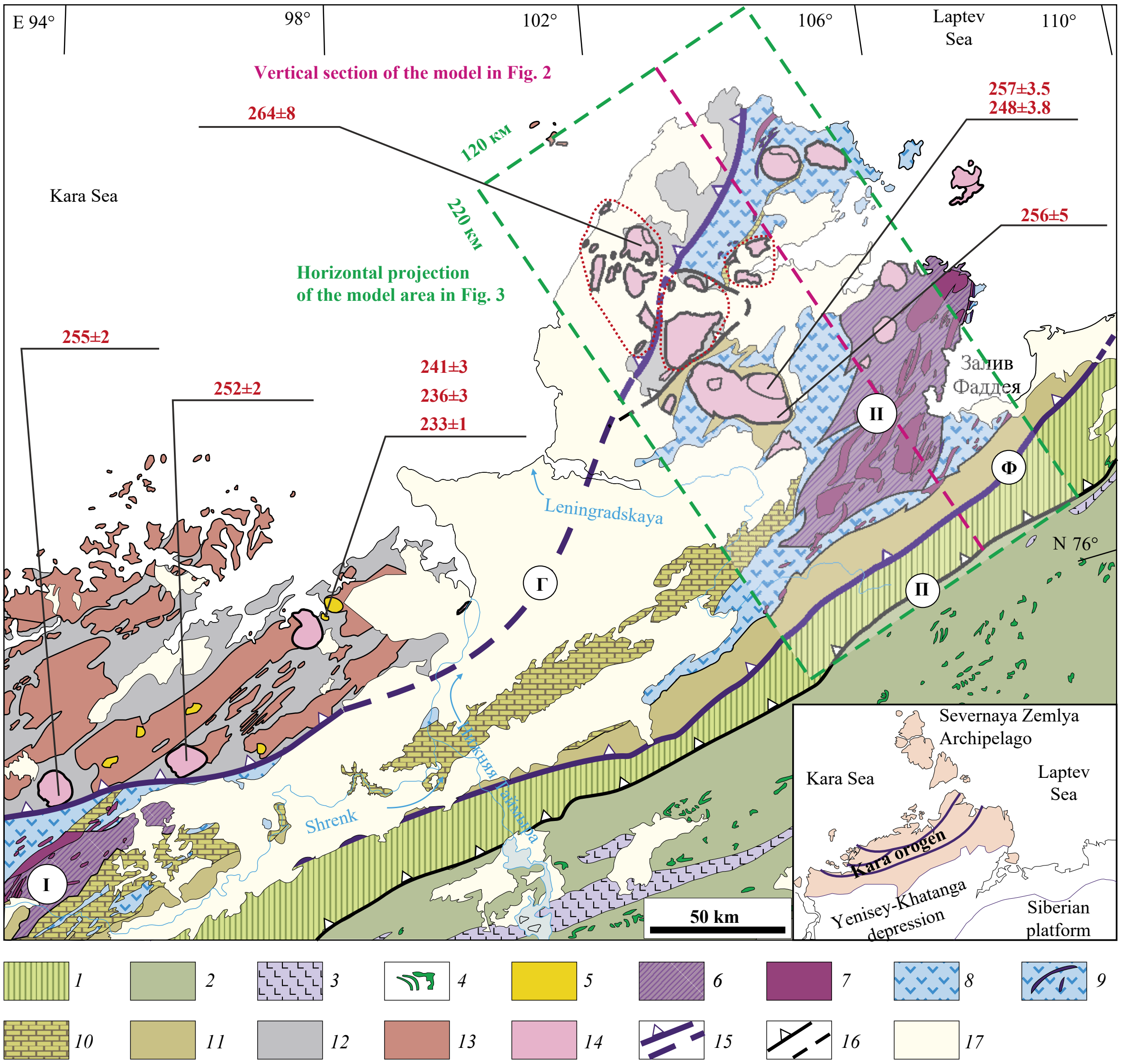

Fig. 1. Geological-tectonic scheme of the northeastern part of the Kara orogen according to [2] with modifications. *1–2* – Southern domain (South Taimyr fold belt) – deformed passive margin of the Siberian paleocontinent): *1* – predominantly dolomites and limestones of the North Byrranga zone ($O–C_2$); *2* – predominantly sandstones, mudstones and coal-bearing deposits of the South Byrranga zone ($C_3–P_2$); *3–5* – formations of the Siberian Traps ($P_3–T_1$): *3* – basalts and tuffs; *4* – dolerite sills; *5* – alkaline and subalkaline syenites, granites and monzonites (249–233 Ma); *6–10* – Central domain (Central Taimyr accretionary belt): *6* – Mamonto-Shrenkov (I) and Faddeev (II) granite-metamorphic terranes (PP–MP); *7* – Neoproterozoic granitoids (940–850 Ma); *8* – island-arc complexes ($NP_{1–3}$); *9* – ophiolites, including plagiogranites (750–730 Ma); *10* – carbonate terranes; *11* – deformed cover of the Siberian paleocontinent ($NP_3–C_1$); *12* – Northern domain (North Taimyr (Kara) block) – passive margin of the Kara microcontinent (NP_3–Є); *13* – syncollisional granites (315–305 and 287–282 Ma); *14* – postcollisional granites (264–248 Ma) (red dotted line – presumed contours of intrusions); *15* – tectonic sutures – thrusts (G – Main Taimyr, F – Pyasino-Faddeev); *16* – P – Boundary thrust; *17* – overlying deposits (J–Q). U–Pb zircon ages are taken from [1, 2, 5, 6]. [vertical model section in Fig. 3, Laptev Sea, Kara Sea, Horizontal projection of the model area in Fig. 3]

granites, subalkaline granites, biotite-amphibole granodiorites and quartz diorites, amphibole-biotite quartz syenites and monzonites ranging from weakly peraluminous to weakly metaluminous varieties predominantly of alkali-calcic magmatic series. These rocks are enriched in large-ion lithophile elements such as K, Ba, and Sr (literature review in [2]). The intrusion of allochthonous post-collisional granites occurred during the final stage of collision, after the cessation of the main movements of the Kara microcontinent in the formed fold-thrust structure. This is evidenced by the relatively isometric shape of the massifs and the absence of deformations in them.

In previous works considering the formation mechanisms of the Kara orogen at the syn-collisional and post-collisional stages [3, 4]. Two-dimensional modeling (2D) was used in the formulation of plane strain problems, examining a cross-section of the orogen perpendicular to the Main Taimyr Suture. The application of a two-dimensional model of the Kara orogen was justified by the great extent of the main faults and the quasi-linear structure of the orogen in the longitudinal direction (northeast-southwest).

Based on modeling, a mechanism for the formation of syncollisional granitoids of the Kara Orogen has been proposed due to heat generation from radioactive elements in the thickened crust of the orogen without significant contribution from mantle heat sources [3]. It is shown that between the beginning of crustal stacking (thickening) and the main pulse of granitoid magmatism in collisional orogens, there is a time interval of about 25 Ma, required for heating the earth's crust to temperatures suitable for granite melt formation. A realistic scenario of uneven plate convergence along the orogen front (oblique collision) is proposed, explaining the sequence of stages of syncollisional magmatism in the Kara Orogen in the intervals of 315–304 and 287–282 Ma ago.

For the post-collisional magmatism stage, a 2D model was developed taking into account the structure of the Kara orogenic belt, which experienced tectonic stacking and crustal thickening with the formation of a thick granite layer with increased content of radioactive heat sources [4]. This model assumes that the Siberian superplume at the initial stage affected the lithosphere as a thermal one, with an excess temperature of about 250°C relative to the surrounding mantle, and its apical part was located in the junction area of the Siberian and Kara plates according to [7]. Such a temperature gradient caused an increased heat flow above the plume, heating and softening the contact zone of the plates. Under the influence of heat flow in the "pre-plume" period of the Kara Orogen development, the temperature at the base of the earth's crust increases by approximately 100°C, which is sufficient for re-melting in the deep parts of the crust. However, the two-dimensional model did not allow solving the problem of the formation of post-collisional granitoid intrusions observed in the upper, non-metamorphosed sedimentary complexes.

The problem of magma intrusion into cold, poorly consolidated sediments remains poorly studied, therefore, for this purpose, we have constructed a three-dimensional thermomechanical numerical model based on solving a closed system of Navier-Stokes equations with an experimentally established rheological law of medium behavior. The problem statement and modeling results are presented below.

MODEL PARAMETERS

The formulation of the thermomechanical numerical modeling problem was determined by the following constraints, based on available geological data.

1. The absence of mantle basitic magmas is assumed, as the granitoids of the post-collisional stage of magmatism have an age preceding the Permian-Triassic boundary of the main phase of trap eruption (251–250 Ma ago).

2. Due to the long duration of the tectonic stage of orogen collapse (first tens of millions of years) compared to the short, pulse-like impact of a magmatic event (no more than hundreds of thousands to a million years), it was assumed that an increased mantle heat flow was acting for a long time as the cause of melting and formation of granitoids.

3. This paper examines local manifestations of post-collisional granitoid magmatism in separate areas of the orogen. Magmatic formations are represented by groups of small granitoid bodies with oval or rounded shape in plan view, not exceeding 10–30 km in diameter, and therefore an essential point for reconstructing the formation of intrusions is the choice of model dimensionality.

Two-dimensional modeling allows adequately describing the behavior of systems that change little in one of the directions in rectangular or cylindrical coordinates. Geological objects for the application of two-dimensional models are, for example, magmatic tabular bodies of dikes and sills. Post-collisional granitoid bodies of the Kara orogenic belt cannot be described within the framework of a plane- or axisymmetric structure due to the irregular shape of the bodies and random mutual arrangement of massifs (Fig. 1). Therefore, the only possible approach is the use of three-dimensional modeling.

Modeling was carried out for the post-collisional stage (Permian-Early Triassic) with a duration of ~30 Ma (280–250 Ma). It is assumed that during the preceding stage of collision, crustal thickening occurred due to folding and tectonic stacking of the sedimentary-metamorphic cover of the Kara microcontinent and the Siberian craton. In the interval of 264–248 Ma, the intrusion of allochthonous post-collisional granites occurred in the formed fold-thrust zone [2]. This magmatic episode is the subject of modeling in this work.

The initial geometry of the model area, boundary conditions, and physical properties for the crust and mantle are selected to correspond to the structure of the Earth's crust in the junction zone of the Kara, Central Taimyr, and Siberian blocks. We considered a section of the Earth's crust in the eastern part of the Central Taimyr block with dimensions of 270*120*65 km (length – width – depth) in the area of the Main Taimyr Suture (Fig. 1). According to geophysical data, the crust thickens from 40 km in the Kara block (Northern domain) to 46 km under the Central one. In the frontal zone of the Main Taimyr thrust, we assume the presence of a thickened crustal "keel" up to 50 km with a width of 100 km based on seismic data and by analogy with the structure of Alpine-type orogens [8].

The thermophysical, rheological properties, and the amount of radiogenic heat of the crustal tectonic blocks were set similar to those in works [3, 4]. The boundary temperature conditions are: mantle heat flow outside the orogenic belt 18 mW/m^2, thermally insulated lateral boundaries, and constant temperature at the surface. Under the Kara orogen, in a 90 km wide strip, an increased mantle heat flow was set, which varied in the models from 36 to 72 mW/m^2 [9].

The increased heat flow is assumed due to two factors: (1) due to the presence of a thickened heat-generating crustal layer under the orogen and (2) the effect of thermal impact on the lithosphere from the mantle superplume that approached the base of the lithosphere thinned to 160 km [10]. The temperature distribution in the Earth's crust and mantle at the initial moment is set linearly from 0 at the surface to 850°C at the lower boundary of the model at a depth of 65 km. The initial moment (model time $t = 0$) in the calculations is taken as the age of 280 million years, i.e., the moment of completion of the collision stage, marked by the age of the emplacement of the latest syn-collisional granites (282 million years ago).

The modeling was carried out using the ANSYS Fluent software package; the system of equations and description of the numerical method are presented in [11].

MODELING RESULTS

The modeling results are presented as evolutionary patterns showing the shape of the solidus surface and temperature distribution in the host rocks and in the partial melting region. Fig. 2 shows the isothermal surface with a solidus temperature of 730°C, which is the boundary of the melting region in the Earth's crust, as well as the temperature in the vertical cross-section and at the crust-mantle interface. In all models, melting occurs in the most submerged and heated area of the crust. Vertical magma ascent takes place in the thickened crust area under the influence of increased heat flow. Almost simultaneously with the onset of increased heat flow, melts formed in the lower crust during its thickening at the syn-collisional stage (315–282 Ma) become mobile due to re-melting (post-collisional) of the crust. The process of magmatic material ascent begins when the melt fraction reaches approximately 6–7%. These values of granite melting degree correspond to the rheological threshold at a melt volume fraction of 6–8%. Melt formation occurs at the transition from thickened crust with increased heat generation to normal crust. The maximum temperature near the base of the crust reaches 780°C. This location is the area of melt formation. The average ascent time for magma reaching depths of 8–10 km is approximately 15 million years, after which repeated ascents of magma portions occur, forming smaller bodies with a periodicity of 1–2 Ma.

Plutons (stocks) of granitoids form in practically unmetamorphosed upper crust. The process has a periodic character: the molten magma cools and partially crystallizes during ascent, while at the base of the crust, melting continues due to the continuous action of increased mantle heat flow, and new portions of melt form, which rise along the heated path of magma ascent.

The horizontal sections in Fig. 3 show the evolution of temperature at depths of 10 and 15 km at moments from 27 to 36 Ma from the beginning of the increased heat flow. It is important to note that in the model, intrusion occurs in the form of a "cluster" of several bodies about 30–35 km in diameter, which does not shift over time. The distance between the bodies can reach 10–15 km. Subsequently, the following portions of magma rise along the most heated path, and in such places, magma reaches the maximum level of uplift up to 8–10 km.

A comparison of modeling results in two- and three-dimensional settings was conducted with completely identical model parameters and physical properties of substances, characterized by the Rayleigh number $Ra = g\alpha\Delta T d^3\rho/\mu\varkappa$, where the symbols denote (sequentially): gravitational acceleration, thermal expansion, temperature difference, crust thickness, density, viscosity, and thermal diffusivity.

Currently, the development of numerical methods and computing technology allows researchers to model Rayleigh-Bénard convective flows not only in a plane (2D), where two spatial coordinates are present, but also in a three-dimensional (3D) setting. In this regard, a number of problems arise in interpreting the results obtained in 2D settings and results obtained with the introduction of the third coordinate (3D), which are discussed in [12-15].

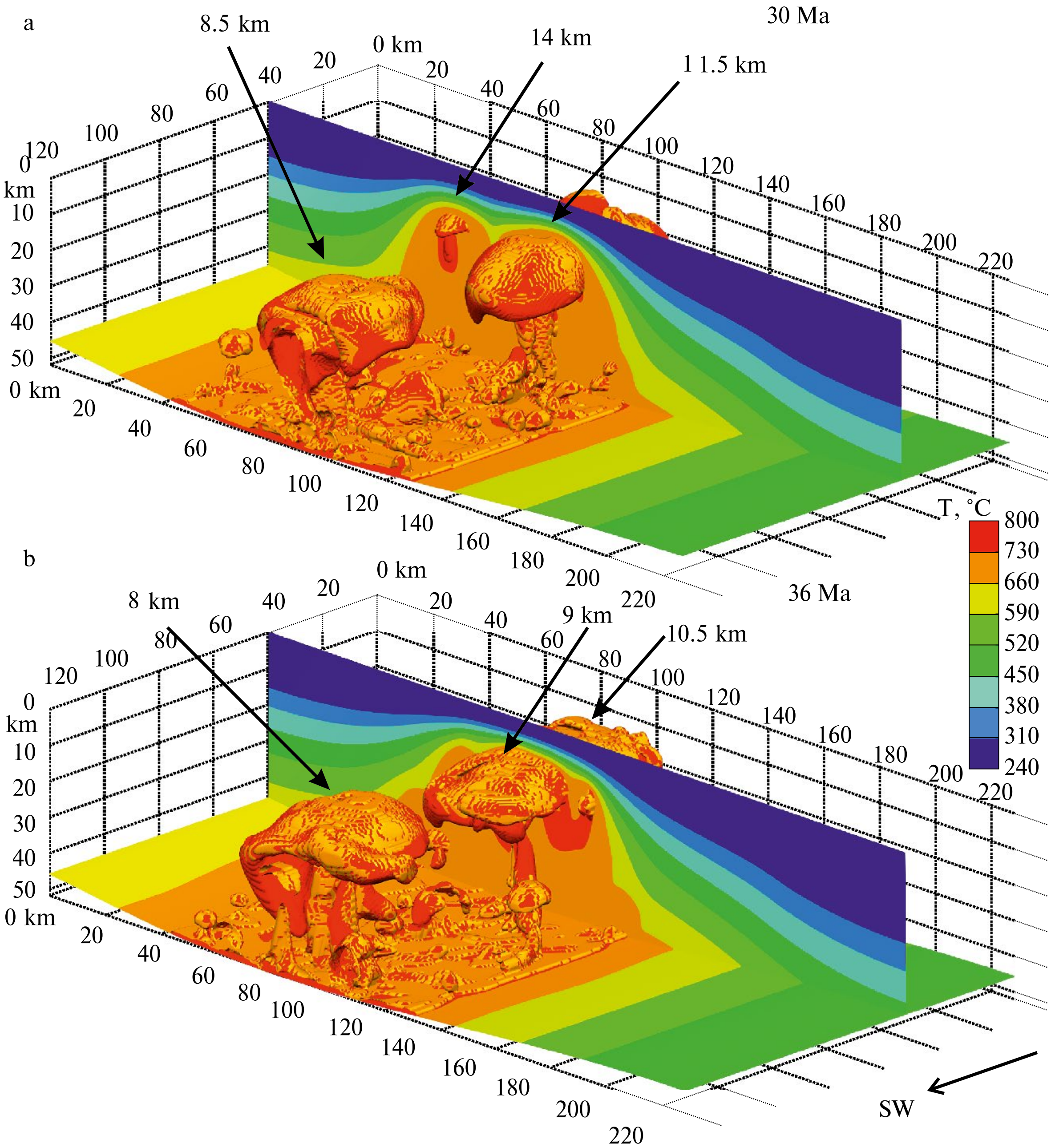

Fig. 2. Results of 3D modeling. The area corresponds to the rectangle in Fig. 1, where the left far edge of the model relates to the Kara block, the right near edge to the Central Taimyr, and the lower surface to the base of the Earth's crust. The isothermal solidus surface is shown at moments 30 (a) and 36 (b) Ma from the beginning of the increased heat flow, with maximum uplift marked. The color scale is given in the range of 240–730°C for detailing the structure of massifs.

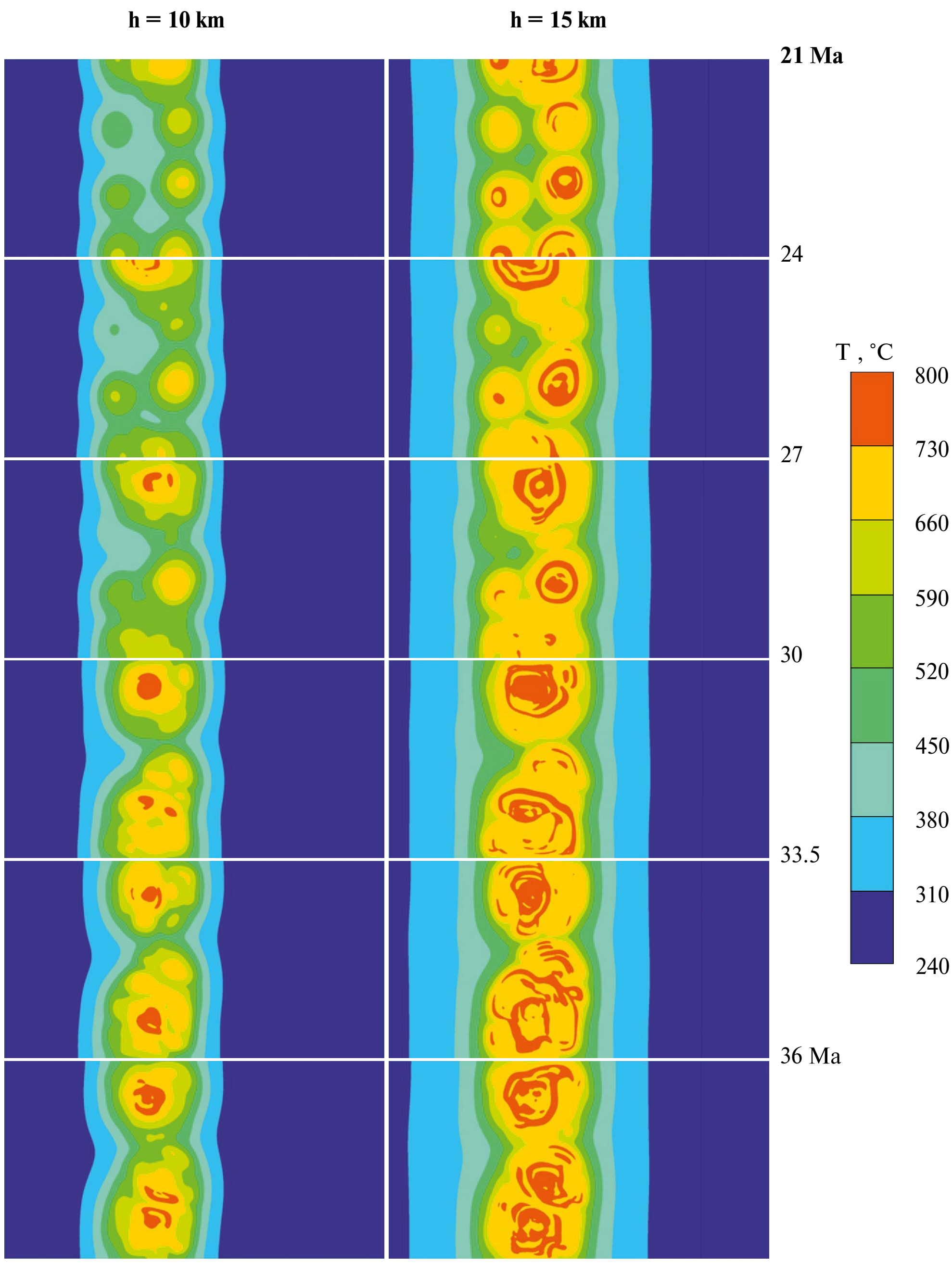

Fig. 3. Horizontal sections of the model (Fig. 2) at depths of 10 and 15 km for time points 21, 24, 27, 30, 33.5, and 36 million years, corresponding to geological time 260–245 Ma ago. Red areas with temperatures > 730°C show the shape and position of the massifs at the given moment in time.

When solving the convection problem in a 3D formulation at certain Rayleigh numbers, a stationary solution (established convection) is obtained in the form of a longitudinal temperature shaft, the axis of which coincides with the direction of the third coordinate. That is, the solutions of the 2D problem, where the third coordinate is fixed, and the solutions in 3D differ slightly [12]. However, the transition from the heat conduction mode to the convection mode is delayed in 3D calculations compared to 2D calculations, but the solutions still coincide. Also in [12], a significant influence of the spatial discretization method (division of the computational domain) of the Navier-Stokes equations on the solution is indicated. The further transition from the temperature shaft (shaft convection) to plumes (cellular convection) [16] loses meaning in a two-dimensional formulation, since we will always obtain a solution that will be invariant with respect to the third coordinate.

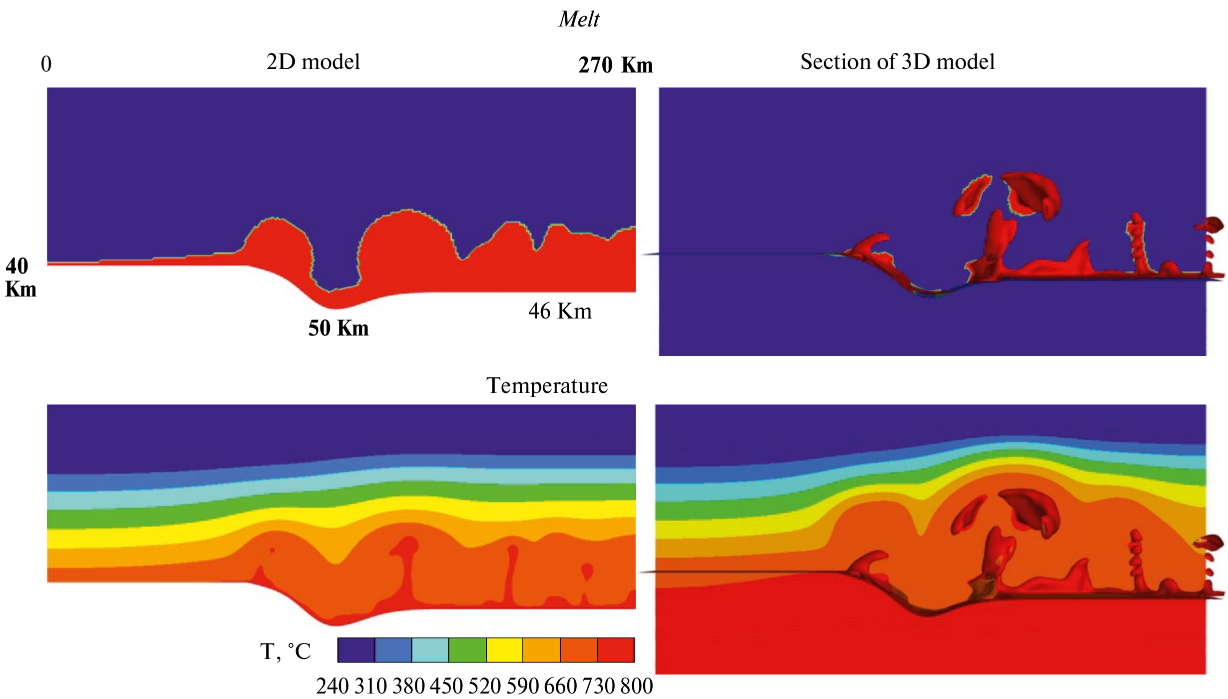

Fig. 4. Comparison of simulation results in two-dimensional (left) and three-dimensional (right) settings is given for a similar geometry of the model area. The vertical cross-section in the 3D model variant is shown in the middle of the model area, where portions of partial melt rise to different depth levels. The area of partial melt (top row) and temperature (bottom row) is shown. [3D model section]

Solutions in a two-dimensional formulation in [4] allow us to talk about melting and convective movement of magma in the form of shafts in the lower crust, but cannot explain the mechanism of formation of stock-like bodies. In this regard, the choice of a 3D formulation becomes relevant, taking into account that the geological objects considered in the work are not elongated structures, but irregularly located bodies in space.

The results of modeling in 2D and 3D problems differ significantly in the nature of the convective movement of the melt, the temperature field, and the shape of bodies containing partial melt (Fig. 4). In the 3D model, a rise to a greater height is observed (8–10 km compared to 20–25 km). In the 3D model, the formation of feeding channels and a head is observed, and the main body separates from the melt formation area. Melts due to convection are more intensively localized with the formation of separate massifs. The configuration of the temperature field also changes significantly, reflecting small-scale convective movements of partial melt masses. Thus, 3D models carry more information about the formation process and the volumetric structure of magmatic bodies.

CONCLUSIONS

Interpretation of the obtained numerical modeling results allows us to draw some petrological conclusions about the formation mechanism of post-collisional granitoids of the Kara orogen.

1. The formation mechanism of post-collisional granitoids of the Kara orogen is well described within the framework of three-dimensional models of crustal heating under conditions of increased heat flow due to the orogen collapse at the pre-trap stage of the Earth's crust evolution of the northern margin of the Siberian platform. The impact of mantle heat influences the composition, conditions of melting, and intrusion of magmas into the upper crust before the main phase of trap magmatism (251–250 Ma ago).

2. It is shown that the regime of three-dimensional cellular convection is realized when using a complete three-dimensional formulation, in contrast to the regime of two-dimensional roll convection characteristic of the 2D problem of plane deformations. Thus, 3D modeling is a more realistic and correct way to describe the corresponding magmatic processes.

3. At the base of the Earth's crust, at a depth of about 50 km, a melting zone of continental

crustal material is established, possibly with a small contribution of the mantle component, generating magma ascent and the formation of a group of spatially close granitoid massifs. The formation of massifs with a diameter of 10–20 km occurred at depths from 14 to 8 km over 15 million years, which is close to the real geological position of post-collisional stocks of the Kara orogen.

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