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GEOLOGY

A Thermal Tomography Model of the Podvodnikov Basins, Northern Arctic

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The application of thermal tomography method [1] based on volume interpolation of the geothermal field demonstrated a possibility of detecting temperature and heat flux anomalies, which were not manifested in the 1D or 2D distribution of these parameters.

Greater informativity of 3D geothermal models as compared to 1D and 2D models is especially pronounced in mosaic isometric structures represented in the majority of cases by the deep basins of the Arctic region.

In our works of 2000–2004, we demonstrated the correlation of temperature anomalies with petroleum potential of the Earth's interior in the Pechora Basin (Barents Sea), South Kara basin, and southern Laptev Sea [2–4]. We went on to suggest that a thermal dome could serve as a visual manifestation of this correlation: hydrocarbon fields often coincide with thermal domes (zones of high isotherms). In addition, thermal tomography models allowed us to make accurate estimates of the background heat flux under rare sets of observations and calculate temperatures in the lithosphere, which is very important in the analysis of the degree of its tectonomagmatic activity.

The objective of the study of the geothermal field in the Podvodnikov basins (Amerasia Basin area) of the Arctic Ocean is to verify the indicators of modern tectonomagmatic activity of the mantle, which cannot be judged from the data on the structure of the Earth's crust. Only the geothermal field directly reflecting the appearance of fragments of the more heated asthenosphere in the lithosphere is capable of answering questions about modern geodynamic activity.

Structural sections obtained using the methods of seismic profiling, or sounding, and measurements of heat flux in the bottom of the basins are initial data which allow us to correctly formulate the boundary and initial conditions.

The present-day knowledge of the structure of the Earth's crust in the Arctic Basin based on seismic methods is fairly high. For example, in the Eurasian and Amerasia Basins (up to meridian 160° E), the structure of the Earth's crust was interpreted along 123 seismic geotraverses, which allows us to describe its structure at a first approximation over practically its entire thickness [5].

In 1989–1992 and 2000, investigations using the methods of refracted waves (RWM) and deep seismic sounding (DSS) within the Transarctic Program were carried out in the Amerasia Basin over a system of reversed time–distance and catching-up time–distance curves on three (two sublatitudinal and one submeridional) geotraverses, whose total length was 2300 km (Fig. 1). The distance between recorders on geotraverses SLO 8991 (De Long Islands–North Pole) and SLO 92 (Lomonosov Ridge) was equal to 10 km, and the distance on the geotraverse over the Mendeleev Rise was 5 km. The length of the hodograph with an informative record reached 200 m.

According to [6], the DSS–RWM data indicate a typical vertical and lateral layering of the Earth's crust and upper mantle in the Amerasia subbasin (the Lomonosov Ridge and Mendeleev Rise separated by the Podvodnikov basins). The upper reduced crust includes the upper gradient layer with velocities ranging from 5.8 to 6.7 km/s. The two-layer lower crust consists of the upper layer with velocities 6.8–7.2 km/s and lower crust–mantle layer with velocities 7.4–7.7 km/s. The mantle is represented by layers M (7.9–8.1 km/s) and N (8.4–9.0 km/s). The thickness of the Earth's crust in the Amerasia block varies from 22–33 km in the Podvodnikov basins to 25–26 km at the Lomonosov Ridge and 34 km at the Mendeleev Rise (Fig. 2). The evolution of the lithosphere in the paleoplatform block of the Amerasia Basin is most probably related to destruction, steplike breaking, and volcanotectonic activation [6].

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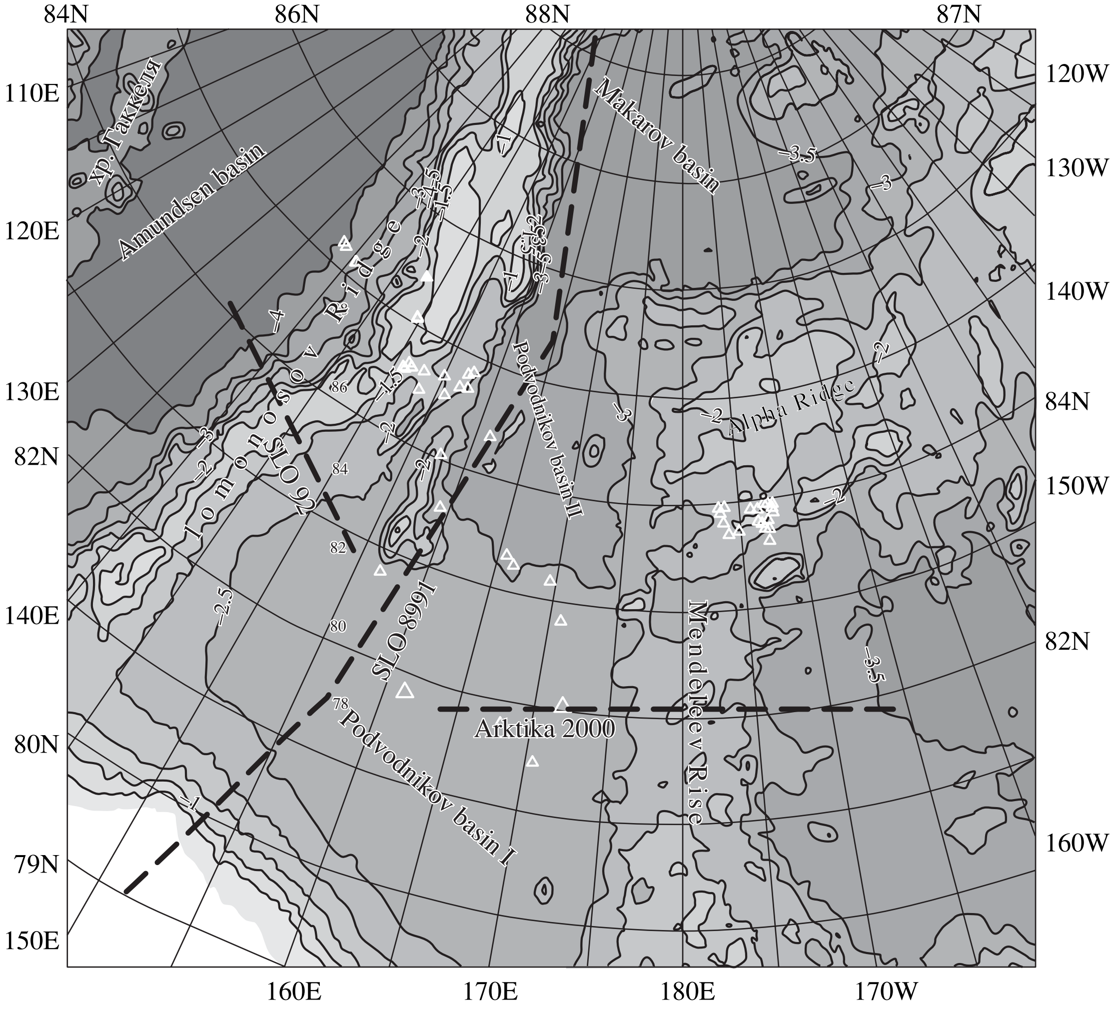

Fig. 1. Schematic location of geotraverses (dashed lines) and points of heat flux measurement (triangles) in the region of the Podvodnikov basins. The size of the triangles is proportional to the heat flux. The plot is based on the IBCAO data (v. 1.0 2001).

Geothermic measurements in the Arctic Basin are distributed extremely nonuniformly. The heat flux in the shelf part of the basin is most fully investigated in the Barents Sea (67 measurements). In the Kara Sea, only 11 measurements are available, while no measurements were made in the Laptev Sea (this region is characterized by only one station of heat flux measurements on Malyi Lyakhovskii Island). In the deep part of the Arctic Ocean, the measurements of heat flux are confined to the Gakkel Ridge, Lomonosov Ridge, and Podvodnikov and Makarov basins (more than 40 measurements).

Thus, the western part of the Amerasia Basin within the Podvodnikov basins is studied sufficiently well in the geostructural respect for the application of the thermal tomography method. Fifteen measurements of heat flux are available for the basins (the values range within 65–75 mW/m^2; however, two points exist with the values exceeding 100 mW/m^2). The measurements were carried out from drifting ice in different years by Soviet and Canadian researchers [7, 8].

We performed geothermic modeling along each of the seismic profiles using the TERMGRAF software package for calculating nonstationary heat flux [9].

The problem of temperature distribution on the section is solved by numerical method of finite elements with quadratic approximation of the temperature function between the nodes of a rectangular grid. Within the domain of modeling, a configuration of contrast media and their thermophysical properties are specified: temperature conductivity a (m^2/s), thermal conductivity k (W/m K), and normalized density of heat sources $Q/(c\rho)$ (K/s). In the calculation part of the complex, we specify linear sizes of the model area (Lx and Lz, in km), which determine the linear sizes of the node ($Lx/41$ and $Lz/41$)), and the time interval of solution discretization (in Ma). The time step of the iteration process is automatically selected by the program. It is calculated as $\tau = 10^{-7}(Z^2/4a)$, where Z is the thickness of the model area.

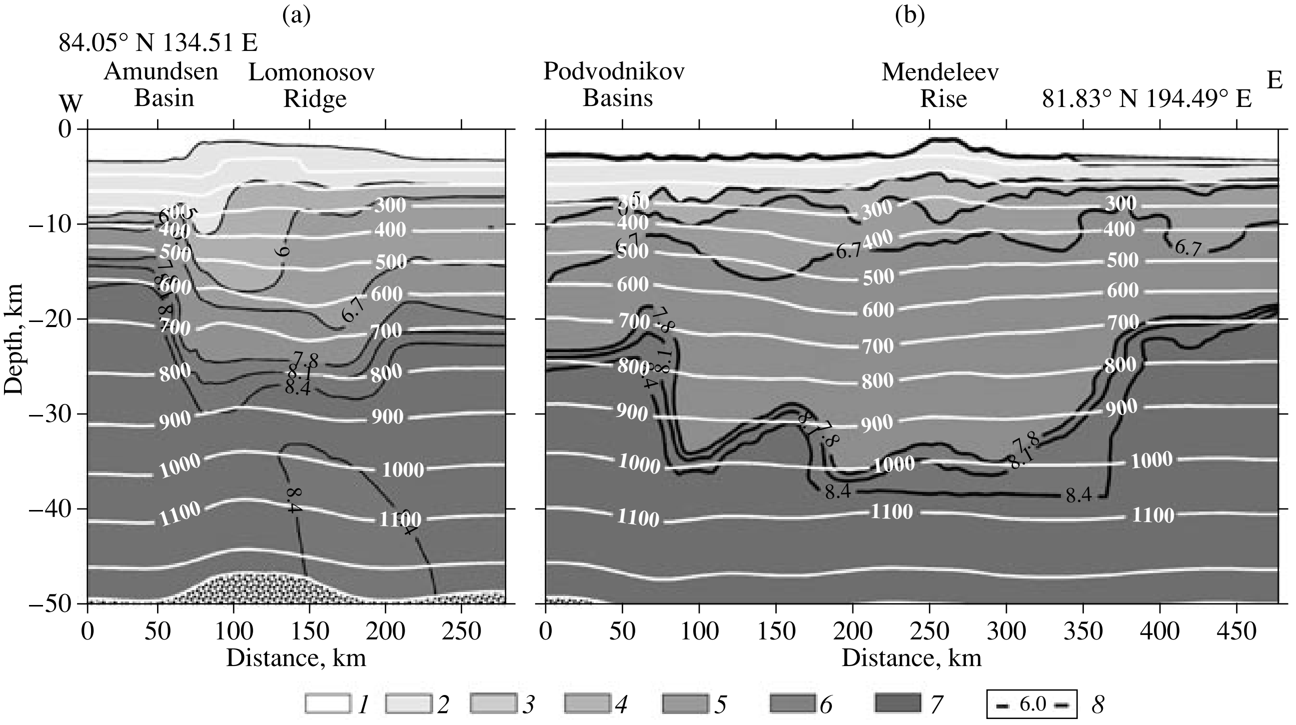

Fig. 2. Seismic (v, km/s) and geothermal (contour lines of T, °C) sections along profiles: (a) SLO-92 and (b) Arktika–2000. Dotted region denotes the area of fractional melting in the mantle. Here and in Fig. 3: Velocity layers: (*1*) water layer ($v = 1.5$ km/s); (*2*) sedimentary cover ($v = 1.5$–5.0 km/s); (*3, 4*) upper crust ($v = 5.0$–6.7 km/s): (*3*) Folded complex ($v = 5.0$–6.0 km/s), (*4*) crystalline basement ($v = 6.0$–6.7 km/s); (*5*) Lower crust ($v = 6.7$–7.8 km/s); (*6, 7*) Mantle ($v > 7.8$ km/s): (*6*) unconsolidated and standard mantle ($v = 7.8$–8.4 km/s), (*7*) consolidated mantle ($v > 8.4$ km/s); (*8*) contour lines of velocities.

The numerical solution of thermal conductivity equation

$$\left(k_x\frac{\partial^2 T}{\partial x^2} + k_z\frac{\partial^2 T}{\partial z^2}\right) + A(x, z) = c\rho\frac{\partial T}{\partial \tau}, \tag{1}$$

where k, c, and ρ are thermal conductivity, thermal capacity, and density of the lithospheric layers, respectively; $A(x, z)$ is the density of heat sources in the layer; and τ is time, yields the distribution of temperatures and heat fluxes $q(z)$ and $q(x)$ for the thermophysical medium at the final time moment of discretization. The obtained file of results is renamed to the file of initial temperatures. At the second stage, we begin the calculation from the final moment of the previous stage. The possibility of discretization of the solution is convenient if there is a necessity to change the thermophysical medium related to the lithostructural rearrangements of the geological section, to specify the distribution of new sources and sinks of heat, or to view the results of calculation of paleotemperature field.

During modeling, edge temperature at the upper boundary was specified for each profile according to the meteorological data, and heat flux was specified at the lower boundary (q_{bound}) corresponding to the measured value at the nearest stations (q_{obs}) after subtracting the heat flux generated due to spontaneous decay of long-lived radioisotopes in the layer of the Earth's crust above the lower boundary of modeling (q_{p}):

$$q_{\text{bound}} = q_{\text{obs}} - q_{\text{p}}.$$

The latter is calculated on the basis of seismic information about the thickness of the layer (z_i) and its composition, as well as from the generally accepted values of specific heat generation ($A(x, z)$) for the corresponding type of rocks:

$$(q_p)_i = A(x, z)z_i \text{ [10]}.$$

The accuracy of calculation is estimated on the basis of two criteria: (a) the coincidence of model and measured (in boreholes) heat fluxes, and (b) the coincidence of temperatures at the intersection of profiles.

Thermophysical media, i.e., configurations of contrast thermophysical layers and the values of thermal and temperature conductivity, were specified on the basis of the corresponding digitization distinguished from the seismic data of the structural complexes.

The values of thermophysical properties of the crust, which were adequate to the found limiting velocities, were used in the calculation (table).

Analysis of the geothermal field. Calculations of temperatures and density of the heat flux in the lithosphere were carried out along seismic geotraverses SLO-92, Arktika-2000, and SLO-8991 (Figs. 2, 3).

Thermophysical parameters accepted for modeling the geothermal field in the Earth’s crust

Suite	Limiting seismic velocity, km/s	Temperature conductivity, a, 10^7 m^2/s	Thermal conductivity k, W/(m · K)	Heat generation (normalized) Fi, 10^{-13} K/s
Nonconsolidated sediments	<3.7	3.0	1.3	–
Consolidated Mesozoic–Cenozoic terrigenous sediments		3.5	1.5	–
Paleozoic carbonate sediments	4.7	3.8	1.9	1.5
Granites:				
upper part	6.0	5.0	2.5	5.52
lower part	6.5	5.0	2.5	3.5
Basalts, rocks of the crust–mantle mixture	>6.5	7.0	2.9	–
Crustal ultrabasites	–	8.0	3.0	–
Mantle ultrabasites	–	10.0	3.2	–

It is well seen from these sections that the structure of the Earth’s crust under the Podvodnikov basins has a very complex and inhomogeneous character. The thickness of the sedimentary cover changes from 5 km (Podvodnikov Basin I) to 1 km (Podvodnikov Basin II). Correspondingly, the temperature at the bottom of the layer of nonconsolidated rocks within the basins decreases in the northern direction from 250 to 150°C. The thickness of the folded complex decreases in the northern direction and the thickness of consolidated crust (presumably the basalt layer) decreases in the same direction with velocities ranging from 6.0 to 7.8 km/s. The

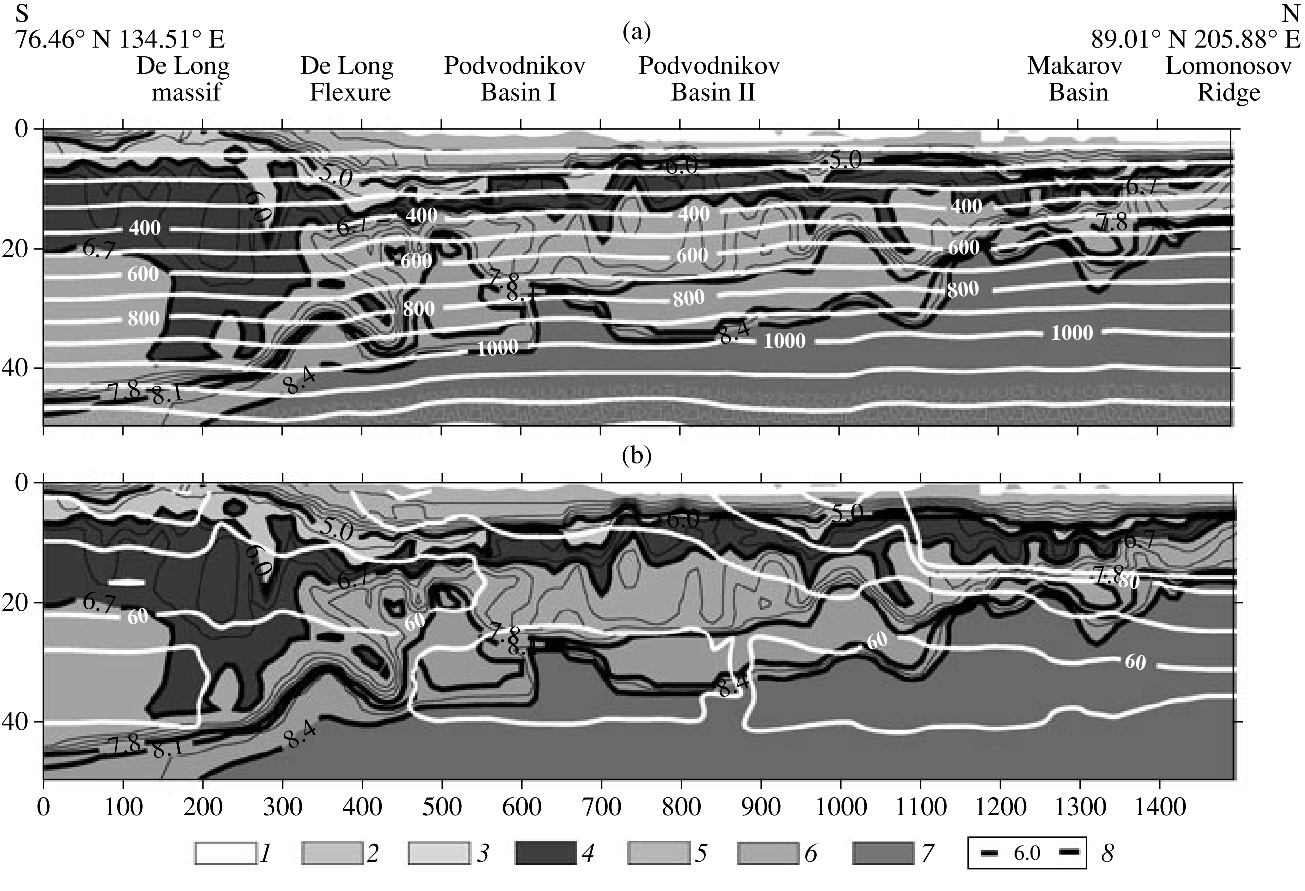

Fig. 3. Distribution of (a) temperatures (T, °C) and (b) heat flux (mW/m^2) along profile SLO-8991. Dotted region on the profile denotes thermal asthenosphere.

temperature at the bottom of the crust also decreases in the northern direction, which is unambiguously explained by a decrease in the depth of the Moho boundary. For example, the temperature at the Moho boundary is equal to 750°C in the southern Podvodnikov Basin I and 700°C in the northern Podvodnikov Basin II.

We note that the Moho boundary in the Amerasia Basin is not isothermal; i.e., the temperature at the boundary depends on the thickness of the crust. This result was obtained earlier for practically all passive transition zones of the World Ocean that differ from the active convergence zone of the Western Pacific, which is characterized by the isothermal nature of the Moho boundary [11].

In the upper mantle within the solid lithosphere, temperature gradually increases from 700–750°C at the M boundary to 1200°C at a depth of 42–45 km. The roof of the thermal asthenosphere confined at the 1250°C isotherm (with account of *PT* conditions at this depth) is manifested at a depth of 50 km.

Thus, we suppose the lithosphere under the Podvodnikov basins is 50 km thick. This thickness is slightly smaller than that of the lithosphere in abyssal basins of the World Ocean (70–80 km), but it is typical for passive continental margin of the Atlantic type. These estimates of the lithosphere thickness were obtained for the Angola, Brazil, and Canary continental margins in the investigation of the thermal field over Transatlantic geotraverses [12]. The obtained data allow us to state the absence of modern tectonomagmatic activity in the region of the Podvodnikov basins, which unambiguously would be reflected in the level of the heat flux and correspondingly in the thickness of the thermal lithosphere.

Thus, the background heat flux within the lithosphere of the Podvodnikov basins is equal to 60–70 mW/m^2 (Fig. 3). There is a tendency of a slight increase in the background heat flux across the strike of the Podvodnikov basins. For example, it reaches 80 mW/m^2 under the Mendeleev Rise. However, this is explained by the influence of the structural–thermophysical inhomogeneities, which are due to lower thermal conductivity of nonconsolidated sediments in the basins than higher thermal conductivity in the exposed folded complex of the Mendeleev Rise.

CONCLUSIONS

The available data on the structure of the Earth's crust and modeling of the lithosphere thickness suggest that the Podvodnikov basins can be considered as structures of the passive continental margin of the Atlantic type. Analysis of the thermic regime of the lithosphere in these structures does not allow us to speak about the manifestation of modern tectonic activity. It is likely that the Podvodnikov basins were formed as a result of the sagging of the upper part of the lithosphere in the place of a continental block, which existed in the geological past. We studied basins with a similar structure in the Yucatan Basin of the Caribbean Sea [13].

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