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The Thermal Field and a Thermal Model of the Ural Lithosphere in View of SG-4 Superdeep Drilling

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Abstract—Specific features of the deep temperature and heat flow distribution in the central and southern Urals and Mugodzhary Mountains are discussed. Various causes responsible for the low heat flow in the uppermost crust of the Urals are analyzed. 2D and 3D numerical geothermal models have been constructed for the area adjacent to the SG-4 Superdeep. Paleotemperatures calculated as a function of the tectonic evolution of the lithosphere in the Ural Foldbelt showed that the structural rearrangement of the lithosphere at the stage of the Ural paleoocean closure and the subsequent Late Paleozoic collision of continental blocks may serve as a possible explanation both of the low heat flow in the uppermost 2–3 km of the crustal section and of the downward increase in the heat flow.

INTRODUCTION

The history of the geothermal studies in the Urals can be subdivided into two periods. The first period that involved sporadic temperature measurements in mines and boreholes within coal basins was completed in the 1968–1970. The summary of the obtained results gave a very approximate pattern of the geothermal regional field based on unreasonably wide extrapolation. In the paper published by Ezhov [7], the temperature at a depth of 1 km was estimated based on measurements in the Foreural and Transural regions, as well as on published data on the thermal properties of rocks. The results were presented as a map at a scale of 1 : 10000000 covering the territory from the Berchogur Settlement in the south to Salekhard in the north. However, the isotherm pattern within the Ural Foldbelt remained very hypothetical. Nonetheless, Ezhov pointed out a general temperature decline within the foldbelt, which was subsequently confirmed. The principal conclusions of that paper were stated as follows: (a) geoisotherms are parallel to the general trend of the Ural Foldbelt; (b) the geothermal gradient slightly increases with borehole depth over most of the territory, that is, the thermograms are concave in shape; (c) the average geothermal gradient in holes <3 km deep is 17.3 mK/m within the Ural Foldbelt and 48 mK/m in the Transural region; (d) high temperature at a depth in the Transural region is caused by the screening effect of low heat-conductive Mesozoic and Cenozoic sedimentary rocks.

Ezhov explained a relatively low temperature in deep-seated rocks of the Urals by intense heat loss through high heat-conductive deformed rocks and ultramafic belts exposed at the surface and ignored completely any other factors that could account for the low temperatures in the Urals, for example, tectonic, geochemical, and hydrodynamic specific features in the evolution of this region. Further studies did not confirm the last three of Ezhov's conclusions. Nonetheless, this publication was extremely helpful at that time.

The results obtained at the first stage of geothermal investigations in the Urals were also summarized in the Geothermal Map of the USSR at a scale of 1 : 5000000 edited by F.A. Makarenko [4]. The schematic map of geothermal gradients in the territory of the USSR at a scale of 1 : 25000000 was presented as an inset, where the Ural Foldbelt was shown as having inferred geothermal gradient of 10–15 mK/m. In another inset map of heat flow at a scale of 1 : 30000000, the Ural Foldbelt and practically all of western Siberia were outlined by a heat flow contour line of 1.2–1.6 hfu (heat flow units), or 50–67 mW/m^2. This was the first publication of evaluative data on the heat flow in the Urals that finalized the first period of its geothermal field research.

The second period, which commenced in the early 1970s, is characterized by the obtaining of high-quality data, including temperatures in long-standing boreholes, heat conductivity values in rocks and large structural complexes, heat flows, and radiogenic heat generation in the Earth's crust of the Urals. Distorting factors that exert their effects upon the thermal field were studied and estimated, and stationary and time-dependent geothermal models developed.

These studies were initially implemented at the Institute of Geology, Bashkirian Scientific Center, Academy of Sciences (Sal'nikov and others) and focused on the southern Urals. Starting from the mid-1970s, the research teams from the Institute of Geophysics, Uralian Division, Academy of Sciences of the USSR (Yu.P. Bulashevich, Yu.V. Khachaĭ, V.A. Shchapov, etc.)

†Deceased.

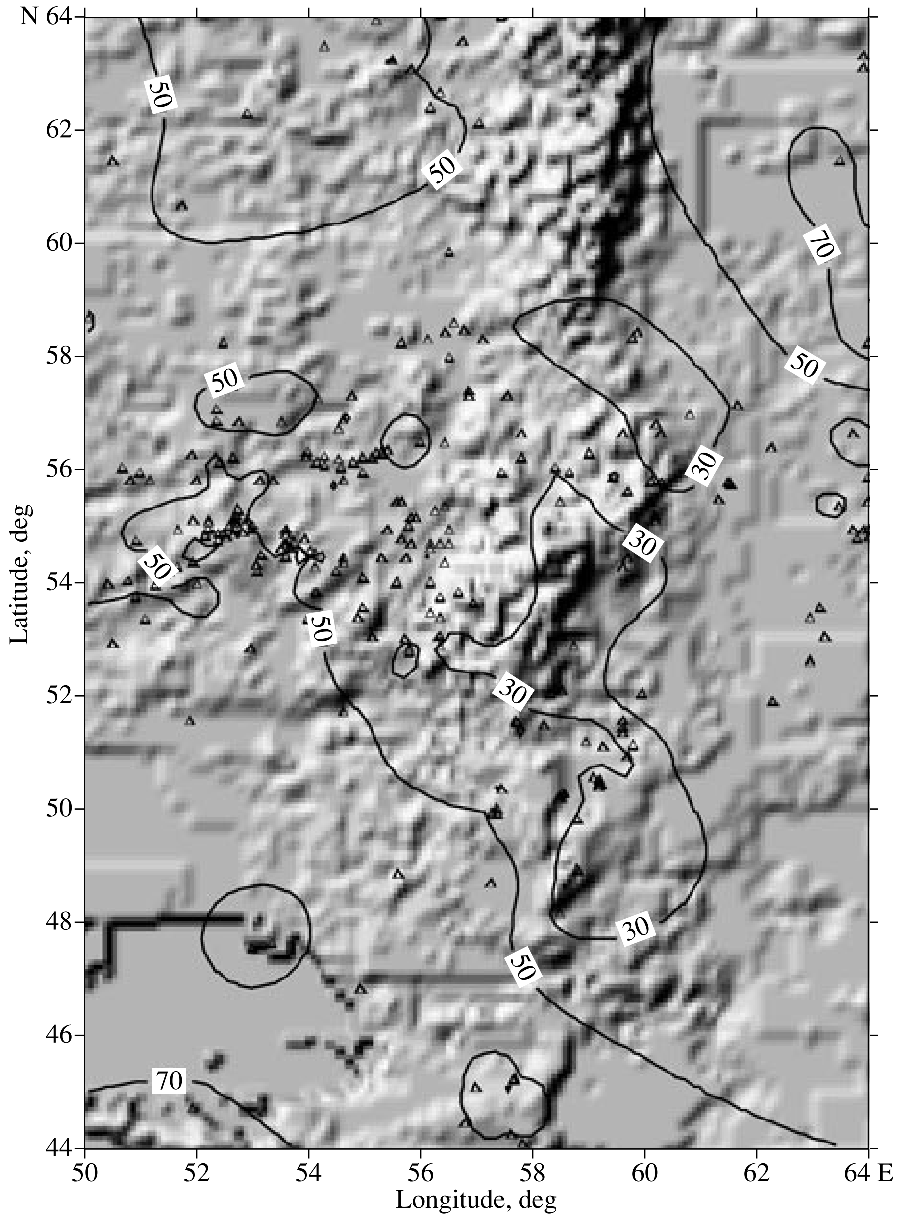


Fig. 1. Heat flow map of the Ural region (heat flow contour lines, mW/m^2). Compiled from measurements in boreholes, down to 2.5 km deep). Triangles show heat flow measurement sites.

and from the Geological Institute (GIN), Academy of Sciences of the USSR (M.D. Khutorskoĭ and others) joined these studies and expanded them over the central Urals and Mugodzhary. Virtually all of the information available to date (Fig. 1) and published in integrating monographs [9, 14, 20, 22, etc.] and numerous papers [2, 3, 13, 15 among others] had been obtained owing to the efforts of these three research teams.

REGIONAL THERMAL FIELD OF THE URAL FOLDBELT

Measurements in ancient blocks (inliers of the Russian Platform basement within Paleozoic rocks of the Urals), in the Uraltau Paleozoic zone, East Ural uplift, Denisovka–Valerianovsk zone, and in other tectonic units showed a regional heat flow decline throughout the Ural Foldbelt. The heat flow measured as 30–38 mW/m^2 is twice (!) as low as the average heat flow value in Late Paleozoic tectonic units all over the globe. The heat flow in the Tagil–Magnitogorsk Synclinorium turned out to be still lower.

The Tagil–Magnitogorsk Synclinorium, being explored by many boreholes, is the best studied in terms of geothermy in comparison with other lithotectonic zones of the Ural Foldbelt. Twenty seven areas were studied here from the latitude of Nizhnii Tagil to Orsk.

The structure and geological history of all these areas are similar, and so are the anomalously low background heat flow values of 21–27 mW/m^2 characterizing the entire territory of the synclinorium.

However, in the eastern part of the Tagil–Magnitogorsk Synclinorium (Gusikha and Ashchebutak areas) the heat flow is somewhat higher (28–33 mW/m^2). In V.E. Sal'nikov's opinion [14], this can be explained by an increase in the volume of acid rocks having higher potassium abundance [1] and, as a consequence, by increasing heat generation in the upper crust. However, even the local increase in the heat generation in the upper crust cannot explain the regional decline of the heat flow throughout the Ural Foldbelt. Evidently, the mantle component of the heat flow is also lowered here.

Thus, the low heat flow values (below 30 mW/m^2) are characteristic of all the examined structures in the Tagil–Magnitogorsk (as well as in the West Mugodzhary) synclinoria within the measured interval (down to 2.5 km). This implies that the boundaries of these synclinoria can be depicted by a heat flow contour line of 30 mW/m^2. This zone trends N–S from the latitude of Nizhnii Tagil in the north to the latitude of the Berchogur Settlement in the south.

Various factors that could explain the formation of an anomalously low heat flow were discussed in recent works, including low heat generation in the Earth's crust of the Urals, the influence of descending groundwater filtration [26], and a regional paleoclimatic impact resulting in the cooling of the upper crust [6, 25].

The authors of the papers cited above themselves note that the paleoclimatic factor cannot explain the regional anomaly, because it affects only the uppermost few hundred meters penetrated by boreholes, whereas the anomaly extends much deeper.

The radiogenic heat generation in the rocks that have been sampled from boreholes in the Urals does not differ from that in other foldbelts (Altai–Sayan region, Mongolia, Norwegian Caledonides), where the heat flow is considerably greater and fits the world average level for the corresponding age of the crust. Hence, this factor is not crucial in explaining the anomaly.

We quantitatively estimated the velocity of vertical groundwater filtration in the SG-4 Superdeep from the curvature of the thermogram [8]. The method is based on the analytical relationship between the vertical filtration velocity (v) (one-dimensional model) and the thermogram curvature:

$$v = \frac{k}{\Delta z}\ln\frac{\Delta T_{i+1}}{\Delta T_i} = \frac{k}{\Delta z}\ln\frac{T_3 - T_2}{T_2 - T_1},$$

where k is the heat conductivity of rocks within the measured temperature interval; Δz is the measurement depth interval; T_1, T_2, and T_3 are temperatures measured at three points down the hole spaced at a distance of Δz. The calculated vertical filtration velocity in the SG-4 Superdeep at an a priori known disequilibrium between the drilling mud and rocks of the hole walls is shown in Fig. 2. As can be seen from the figure, the absolute values of the velocity are equal to $n10^{-7}$–$n10^{-8}$ cm/s. At such a filtration velocity, the background geothermal gradient is distorted only by 0.015% in comparison with the measured values, and no tendency to the increasing hydrodynamic correction down the hole is observed.

We can suggest that the effect of the groundwater convection upon the temperature and heat flow in the SG-4 Superdeep is negligibly small, i.e., the heat flow must be conductive. However, only an analysis of an equilibrium thermogram can reliably prove this.

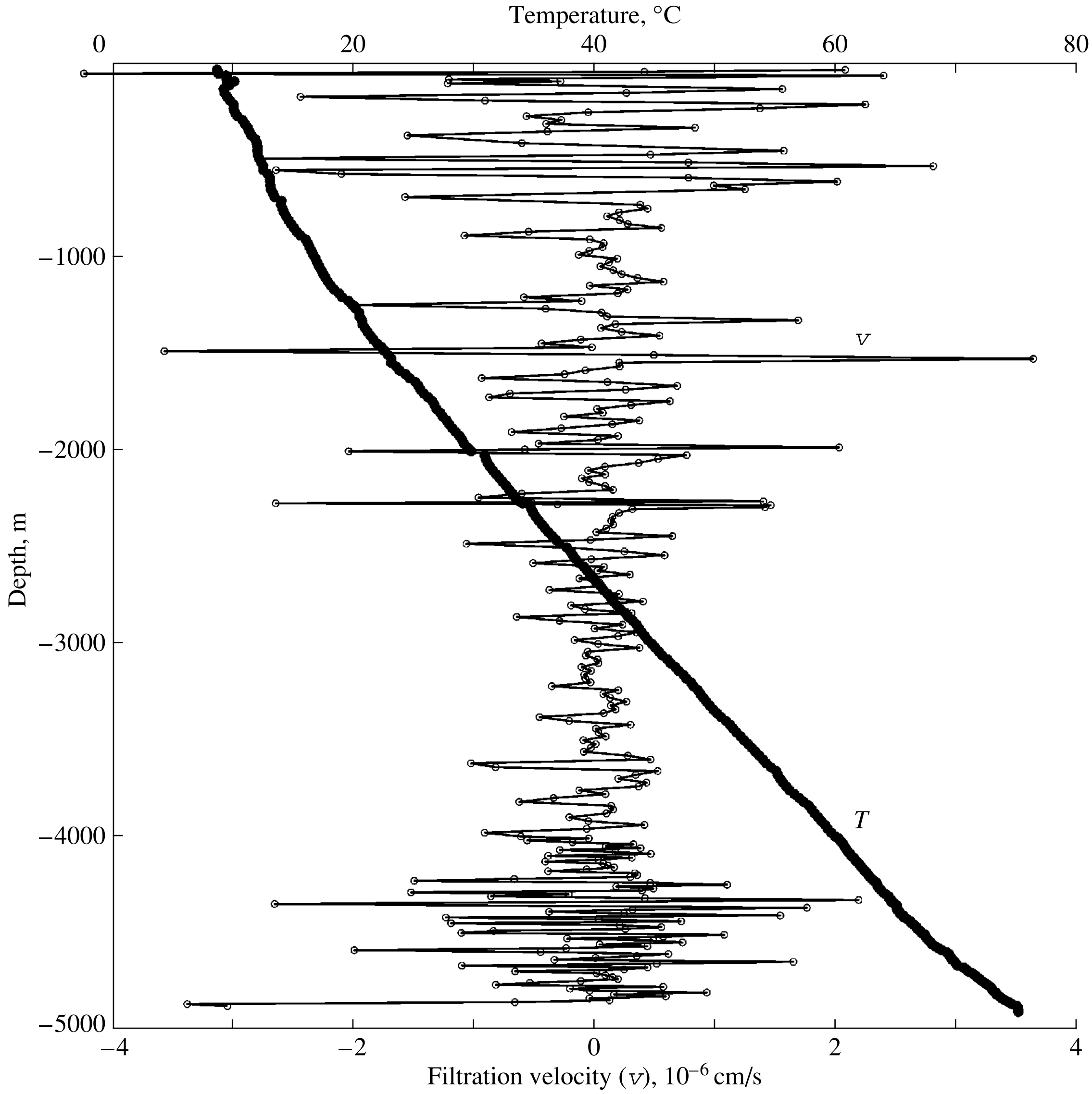
The extensive regional anomaly is obviously related to the deep-seated processes that occurred in the Ural lithosphere throughout its tectonic evolution. The nature of such processes is discussed below.

Ultramafic massifs in the Urals are distinguished for their specific heat flow. They extend longitudinally along the western margins of the Tagil–Magnitogorsk and Mugodzhary synclinoria. The Kempirsaĭ and Khalilovo massifs are the best explored in terms of their thermometry. The geothermal gradients measured in more than 30 holes sunk into these massifs vary within a narrow range of 14–17 mK/m, and this value is considerably higher than those in the Tagil–Magnitogorsk Synclinorium. The average gradient used in the calculations is accepted as 15.2 mK/m.

Consider in more detail the thermal conductivity distribution in the ultramafics of the Kempirsaĭ and Khalilovo massifs penetrated by boreholes, because of the scanty published data available for this type of rock.

A rather limited set of rocks (serpentinized dunite, peridotite, and harzburgite) was encountered in all of the examined holes. Gabbro-amphibolite dikes of the Tygashasaĭ Complex were crossed by boreholes only in the area of the Tsentral'naya Mine. These dikes cut the serpentinized dunite that crops out at the 20 let KazSSR, 40 let KazSSR, and Zapadnaya Zalezh deposits. The average values and standard deviations are 2.23 ± 0.17 W/(m·K) (n = 18), 2.37 ± 0.22 W/(m·K) (n =19), and 2.38 ± 0.13 W/(m·K) (n = 25), respectively in these areas. As can be seen from the presented data, the thermal properties of the rocks are rather uniform, and their average values are 20% below those reported in the literature for serpentinized rocks [19]. The heat conductivity of harzburgite from the holes drilled at the Malokhalilovskoe deposit is somewhat higher: 2.44 ± 0.39 W/(m·K) (n = 17). A high heat conductivity was noticed for chromite ore; a representative collection of chromite samples was taken from the Kempirsaĭ massif (20 let KazSSR deposit). The heat conductivity is 5.91 ± 0.39 W/(m·K) (n = 11).

The heat flow in boreholes drilled at the Kempirsaĭ massif varies from 35–37 mW/m^2 (Almaz-Zhemchuzhina area and Tsentral'naya Mine) to 42 mW/m^2 (20 let the KazSSR Mine). At the Malokhalilovskoe



Positive v values indicate descending filtration and negative values, ascending filtration

Fig. 2. Temperature (T) distribution (nonequilibrium thermogram) and velocity (v) of vertical groundwater filtration in the SG-4 Superdeep.

deposit, the heat flow was estimated as 37 mW/m^2, i.e., it is the same as at the Kempirsaĭ massif.

AN EVOLUTIONARY THERMAL MODEL OF ULTRAMAFIC MASSIFS IN THE URALS

Consider a possible evolutionary model of the Ural geothermal field that could explain specific features of the heat flow in ultramafic massifs and in framing rocks. The Urals is a tectonotype of linear fold zones characterized by allochthonous mechanism of crustal reorganization, i.e. by large-scale structural rearrangements within transition zones from paleoocean to paleocontinent and resulted in the formation of subduction and collision zones reliably reconstructed from geological evidence.

Numerical modeling of the thermal evolution of the lithosphere in paleosubduction zones, i.e., in the present-day linear belts, demonstrated that an anomalously low heat flow could originate owing to the transient thermal effects: the formation of very thick lithospheric thrust sheets and screening of the deep-seated heat flow. These effects do not act infinitely long, but the time-dependent event in the thermal field could last 250–300 Ma, if the total thickness of subducted lithospheric sheets was comparable with the thickness of the whole paleooceanic lithosphere (60–70 km). This implies that the present-day heat flow may reflect the geodynamic and structural rearrangement that took place in the Late Paleozoic. Calculations showed that the screening effect halves the deep-seated heat flow [21, 22]. This can explain the anomalously low heat flow in the Greenstone Zone of the Urals, which was thrust over the Central Ural Rise [11, 12]. The Paleozoic subduction zone was also deduced from geophysical data [17]. However, the origin of the relatively high heat flow in ultramafic massifs remains unexplained.

To elucidate this fact, a numerical modeling of the uplift and subsequent transformation of an ultramafic body was undertaken. The calculations were performed for two evolution scenarios. First, it was assumed that a body heated to the solidus temperature of peridotite was emplaced into the crust, and the thermal activity of the root zone persisted during a certain geological time. Then, the root zone cooled down and simultaneously the ultramafic body was shifted in the lateral direction along with a nappe, although without a complete detachment of the upper part of the body from its root. In the second scenario, the upper part of the ultramafic body was completely detached from its root and displaced separately. In other words, the visible part of the ultramafic massif becomes rootless. The further growth of the Uraltau domelike uplift and its subsequent erosion were simulated in both scenarios.

The moment of emplacement was accepted as an initial and dated as 400 Ma ago (the Early and Middle Devonian boundary as follows from the isotopic age of the ultramafics). The boundary temperature conditions were accepted based on the results of the previous (minus one) modeling step for a plane-parallel lithosphere consisting of a granite layer, 10 km thick, a basalt layer, 35 km thick, and the upper mantle layer, 55 km in thickness (down to the lithosphere sole). The thermal diffusivity of the granite layer is accepted as $5.15 \cdot 10^{-7}$ m^2/s and the thermal conductivity, as 2.5 W/(m·K). The respective parameters of the basalt layer are $9.72 \cdot 10^{-7}$ m^2/s and 2.6 W/(m·K) and of the mantle, $13.3 \cdot 10^{-7}$ m^2/s and 3.0 W/(m·K). The temperature was set as 1200°C at the base of the lithosphere, and as 5°C on the surface of the neutral layer. No paleoclimatic changes that might have occurred during the geological evolution were taken into consideration. The temperature at the base of the Earth's crust that had been derived for this modeling stage was accepted as the lower boundary condition for the next modeling stage. The emplaced ultramafic sheet was partly melted, i.e., an adiabatic temperature gradient existed within it, and the effective values, taking convective heat transfer into account, were ascribed to the thermal parameters. The thermal diffusivity was accepted as $13.3 \cdot 10^{-7}$ m^2/s and the thermal conductivity, as 10 W/(m·K). In 30 Ma after emplacement, a temperature of 1000°C was held within the modeling ultramafic sheet that, naturally, heated the upper crust. For example, a temperature of 300°C existed at a depth of 30 km at the moment of emplacement, while this isotherm shifted to a depth of 11 km after 30 Ma. At the next modeling stage, which followed 50 Ma after the previous one (320 Ma ago), a bifurcation of scenarios was examined. In the first scenario, the thrusting amplitude was such that the upper part of the ultramafic sheet was bent relative to the root zone but retained a structural connection with it, and in the second scenario, the sheet was completely detached from its lower part and became rootless. The solidus temperature was assumed at the base of the root zone in both scenarios. A more pronounced decrease in the heat flow on the ground surface was detected in the second scenario as compared to the first one due to the isolation of the cooling sheet from the root zone. The calculated values of the heat flow above the ultramafic sheet in the first and second cases are 149 and 130 mW/m^2, respectively. A domelike uplift, as high as 2 km, started to grow at the same time, and this caused a decrease in the heat flow.

The next time stage was referred to as 250 Ma ago, i.e., 70 Ma after the previous step. By that time, the active collision had been completed both in the Mugodzhary Mountains and in the southern Urals, and the continental crust had been formed. The decline in the geodynamic activity caused cooling of the root zone; 70 Ma after shutting-off the heat supply, the root zone yielded an excess of the heat flow above the background value for the crust sole only by 6 mW/m^2 and could merely be explained by a structural effect.

Lateral displacements along thrust surfaces, the formation of domelike uplifts, and their subsequent erosion were the principal factors that formed the time-dependent thermal field in the upper crust. Numerical modeling has shown that the stationary regime settled in both scenarios only 160 Ma ago, i.e., in the Middle Jurassic. However, steady heat flow remained anomalously low (32–35 mW/m^2) and was 42–44 mW/m^2 above the ultramafic body after peneplanation of the domelike uplift.

Thus, the modeling heat flow practically coincides with its observed values.

MODELING OF THE THERMAL FIELD IN THE VICINITY OF SG-4 SUPERDEEP

The 2D and 3D geothermal modeling was applied to analyze the thermal regime in the vicinity of the SG-4 Superdeep.

The modeling technique is based on solving a thermal conductivity equation with the accepted boundary and initial conditions and with the distribution of geothermal parameters through the section established as a result of direct measurements of the thermal properties and the correlation between seismic characteristics and the thermal physical properties beyond the drilling and coring interval.

The numerical calculation of the heat field was accomplished by using the TERMGRAF software package [23].

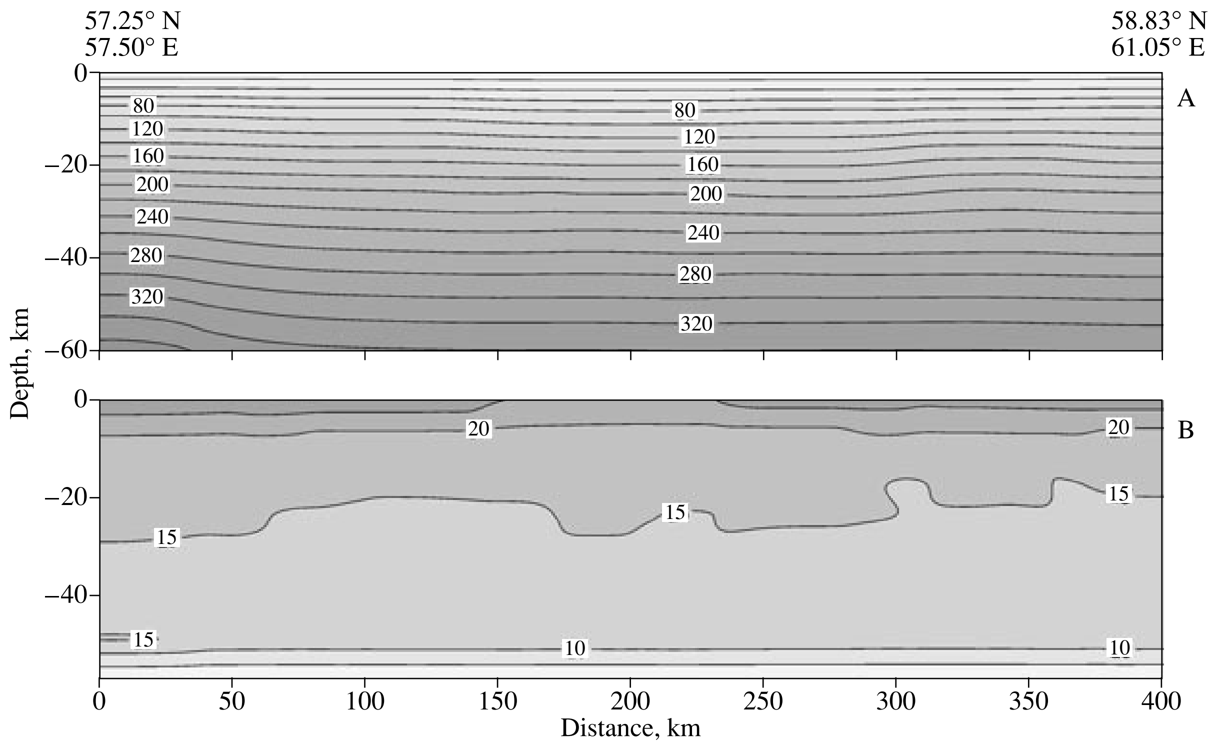


Fig. 3. (A) Distribution of temperature, °C and (B) heat flow, mW/m^2 along the GRANIT Profile.

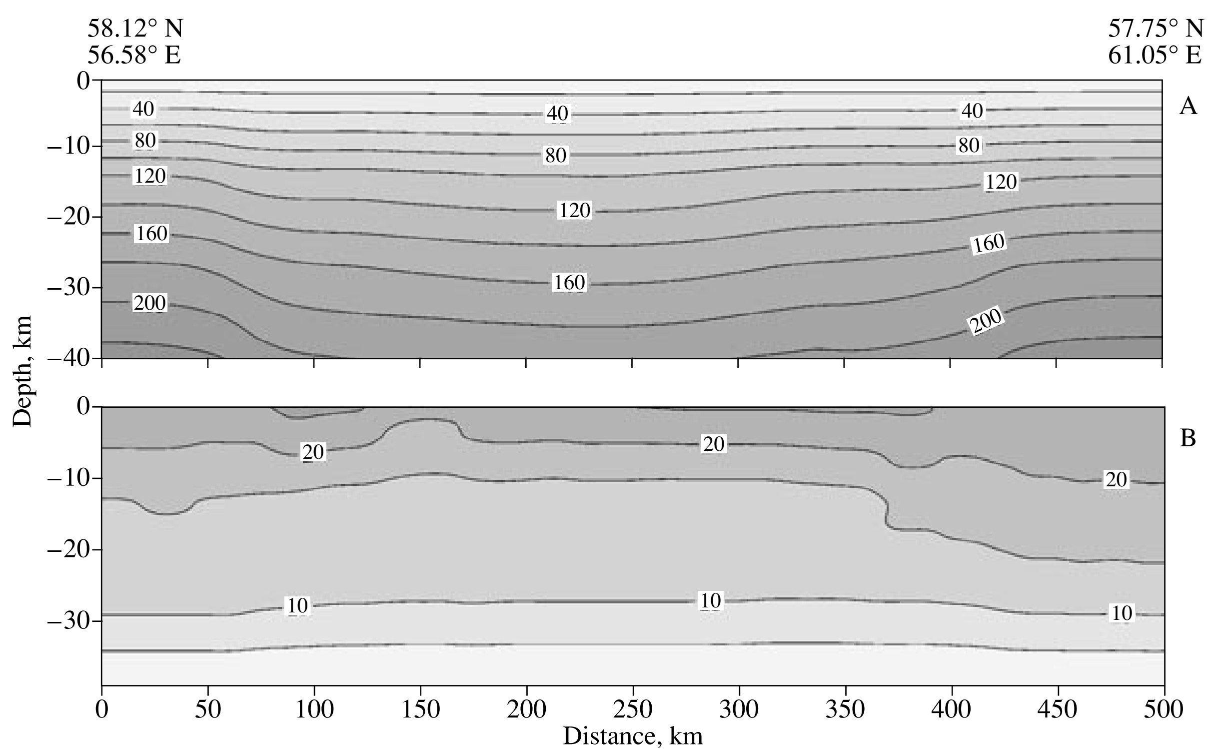


Fig. 4. (A) Distribution of temperature, °C and (B) heat flow, mW/m^2 along the Krasnoural'sk Profile.

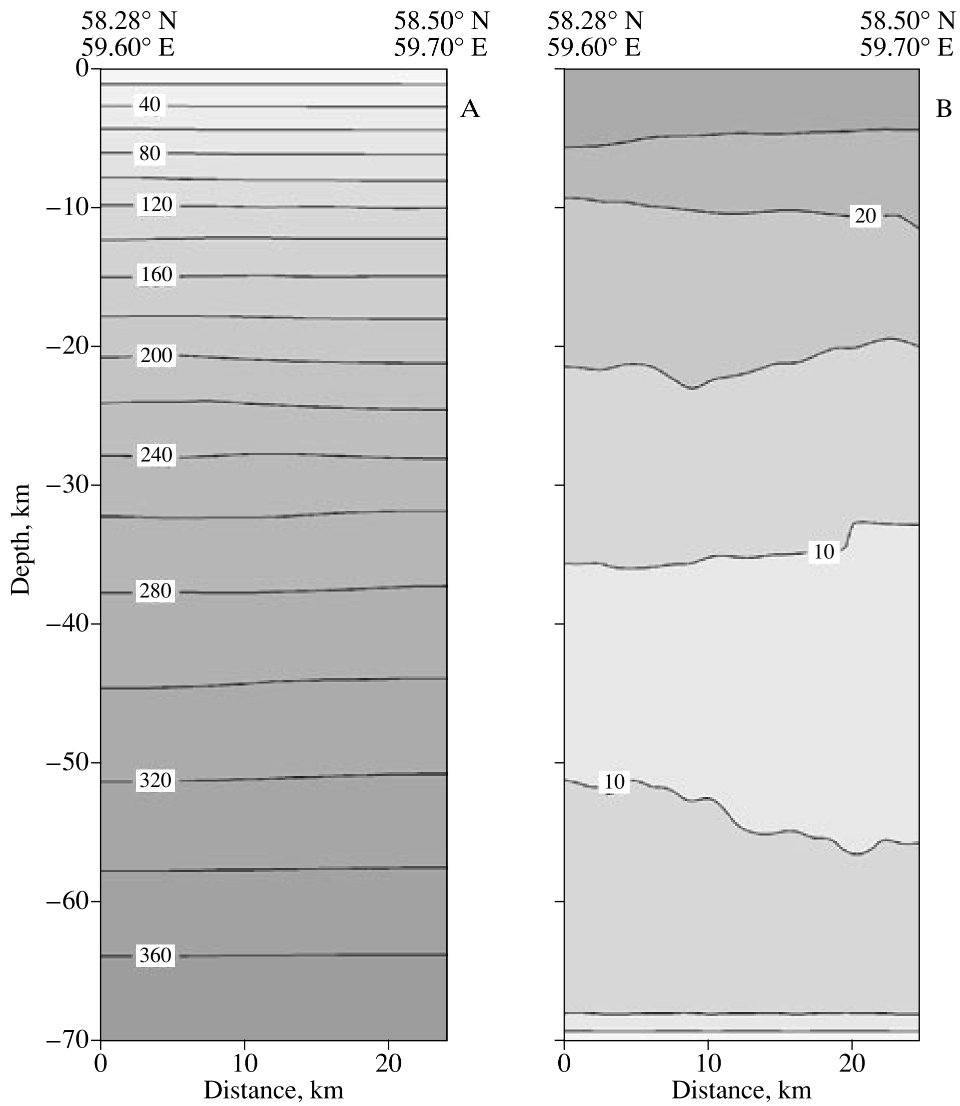


Fig. 5. (A) Distribution of temperature, °C and heat flow, mW/m^2 (B) along the ESRU-95 Profile.

The temperature and the heat flow at a specific depth were calculated from the information on the structure of the Earth's crust that had been obtained by seismic profiling along Transural geotraverses [24].

The numerical finite element method with squared approximation of the temperature function between the nodes of a rectangular network was used for solving the problem of temperature distribution in the section. A network of 41×41 nodes is envisaged in the software (i.e., a 2D problem is solved), and the linear dimensions in the network along the X and Z axes can be changed by the operator's command. Absence of lateral flow was set at lateral boundaries of the modeling region, i.e., $\partial T/\partial x = 0$. Temperature at the bottom–water interface known from meteorological data (~1°C) was set as the upper boundary condition and the heat flow, as the lower boundary condition.

Configuration of contrast media and their thermal properties including thermal diffusivity a (m^2/s), thermal conductivity k, W/(m·K), and normalized density of thermal sources $Q/(c \cdot \rho)$, K/s were set within the modeling region. The linear dimensions of the modeling region (Lx and Lz, km) that determine the linear dimensions of a node (Lx/41 and Lz/41), as well as the time interval of the solution quantization, Ma were set in the calculating part of the software package (TERM program). The program automatically selects the time step of the iteration process and calculates it as $\tau = 10^{-7}(Z^2/4a)$, where Z is the thickness of the modeling region.

As can be seen from Figs. 3–5, the calculated temperatures in the lithosphere on profiles in the vicinity of the SG-4 Superdeep are very low. For instance, they do not exceed 300°C at the M discontinuity. A temperature depression near the Tagil Synclinorium axis on

GRANIT and Krasnoural'skiĭ profiles indicates a cooling of the lithosphere beneath this tectonic unit.

The calculated heat flow coincides with the measured values on the ground surface but decreases downward due to the depletion in radiogenic elements with depth. The heat flow from the mantle is 10 mW/m^2, which is close to the 8 mW/m^2 estimated by Sal'nikov [14].

A 3D thermal model of the region was constructed using a TECPLOT v. 7.0-demo 3D-graphics software package (Amtec Engineering Inc.). This package allows the implementation of a 3D interpolation of the observed field (temperature heat flow and structural seismotomographic boundaries, in our case) in the coordinates of latitude, longitude, and depth. For preparing data files in the TECPLOT v. 7.0 format, we created a special program that transformed the text file with the results of thermal modeling into the format of the TECPLOT database after the profile beginning and end, as well as the depth quantization interval had been set. This program allows the performing of a 3D interpolation on a network of any configuration. A nonuniform network that was tied up to the trend of the seismic profiles (Fig. 6) assigned for 2D temperature calculations was used in our case.

The 3D temperature field model (Fig. 6) clearly demonstrates that the above-mentioned temperature depression trends north–south, once more testifying to the linear structure of the regional thermal field.

The 3D model of the heat flow (Fig. 7) shows that the anomalously low heat flow that was described as characteristic of the Tagil–Magnitogorsk Synclinorium, is also typical of the vicinity of the SG-4 Superdeep. The anomaly extends N–S, and the heat flow on the surface is 25–28 mW/m^2, i.e., the same as in other similar geological structures of the region.

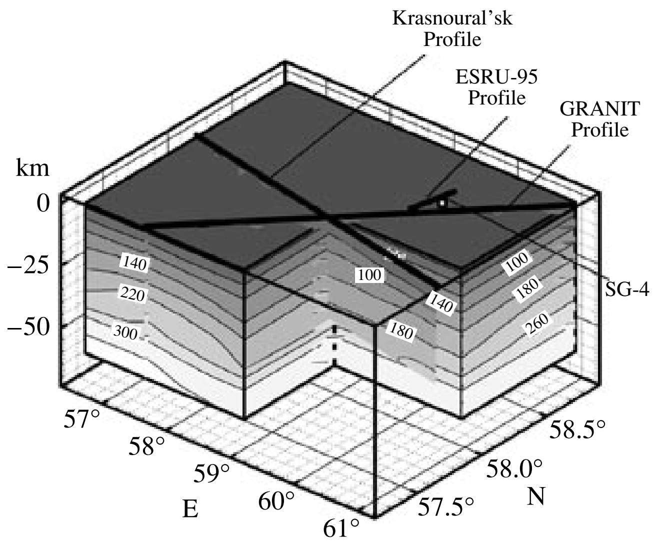


Fig. 6. A 3D temperature model (T, °C) in the vicinity of the SG-4 Superdeep.

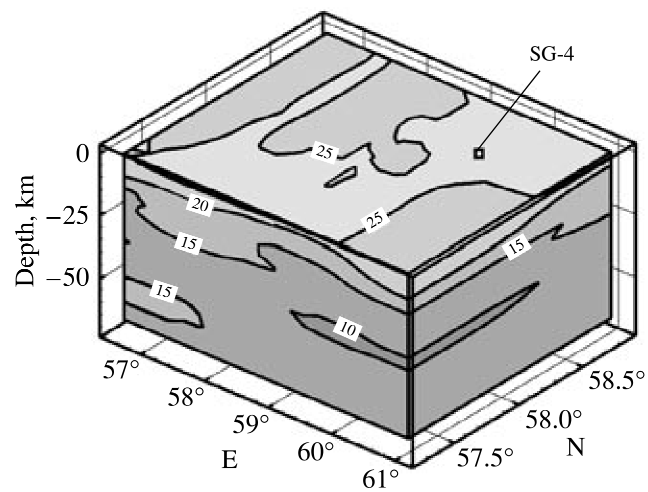


Fig. 7. A 3D heat flow model (mW/m^2) in the vicinity of the SG-4 Superdeep.

THE THERMAL EVOLUTION OF THE URAL LITHOSPHERE

The problem of the origin of heat flow and its distribution in tectonic units of various ages has important theoretical and applied implications for studying the driving mechanisms of lithosphere evolution and for assessing the feasibility of geothermal energy utilization. It is vital to understand, therefore, how the thermal evolution of the lithosphere proceeded and what was the extent of mutual effects caused by thermal heterogeneities at a depth and lithotectonic heterogeneities near the surface.

Interpretation of specific features of the geothermal field requires the construction of adequate tectonomagmatic models. If these models are elaborated with independent methods, they should be adjusted with geothermal data. However, we often cannot reconcile the observed heat flow with the specific tectonomagmatic history. A natural question arises: What are the reasons of these discrepancies? On the one hand, we have unbiased information on the deep-seated heat flow and, on the other hand, results of lithotectonic analysis. The controversy is likely related to the depth of the geosphere under consideration. While the lithotectonic analysis deals with structural rearrangement only within the Earth's crust, the terrestrial heat flow results from processes embracing the upper mantle as well. The temperature heterogeneities in the mantle that trigger the tectonic development of the Earth's crust are eventually expressed in the terrestrial heat flow, providing determinacy of the tectonic and geothermal processes. The tectonomagmatic evolution not only changes heat flow values on the Earth's surface with time, but also affects such physical characteristic as the thickness of the lithosphere.

We attribute the heat flow decrease in linear tectonic belts to the geodynamic mechanism of their evolution.

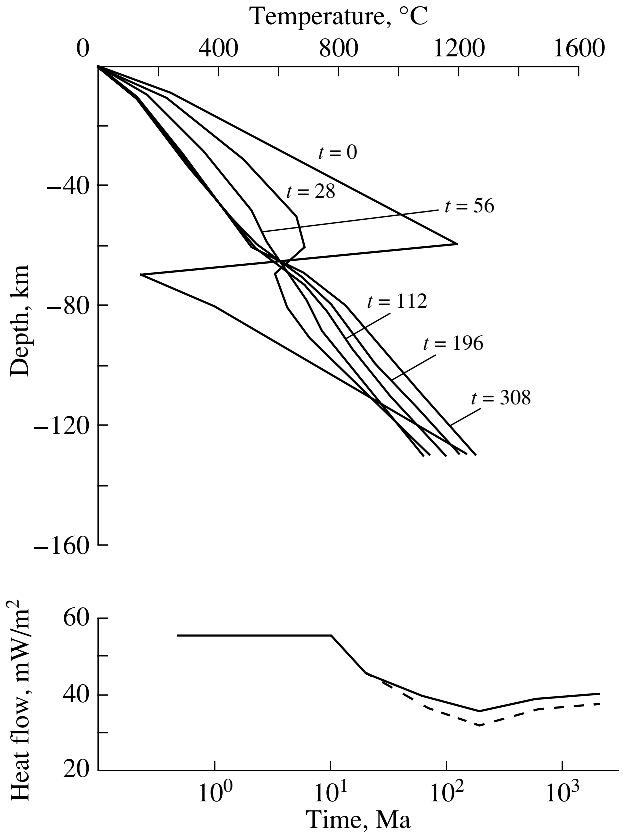


Fig. 8. Temperature (top) and heat flow (bottom) changes in time (*t*, Ma) in an overthrust model with the second-type boundary conditions on the lower edge. Dashed line shows a change in the heat flow with time (phase transition heat is omitted).

In order to support this conclusion with quantitative calculations, we undertook a one-dimensional time-dependent modeling of the thermal evolution as applied to the lithospheric structure of the Ural Foldbelt.

An overthrust (or underthrust, which is principally the same for heat transfer) thermal model was applied to the linear belts. In terms of thermal physics, the model was a sequence of layers, and specific values of heat conductivity and radiogenic heat generation were ascribed to each of these layers. The above parameters corresponded to the average statistical values characterizing the thermal physical sections of the oceanic and transitional crust [16].

The start of the solution ($t = 0$) referred to the moment of the thrust–sheet structure inception. The total paleooceanic lithosphere, 70 km thick, participated in over- or underthrusting.

A negative geothermal gradient, which existed at a depth of 65–70 km at the initial moment (Fig. 8), was related to the relatively fast, as compared to the rate of conductive heat transfer, thrusting of the lithospheric sheet having temperature of 1200°C at its sole over another sheet with a temperature of 0°C at its top. In reality, however, the temperature at the top of the lower sheet was accepted as 150°C as a result of friction heat release. This effect will be discussed in more detail below. The boundary condition of the second type, i.e., the heat flow constancy, was adhered to the lower boundary of the autochthonous sheet. The friction heat generated on the gliding surface was taken into account.

The heat of the phase transition was recalculated into an equivalent value of the heat flow density, which was algebraically summed with the mantle heat flow and then taken into account in setting the lower boundary condition.

The base of the upper sheet cooled down with time, while the top of the lower sheet warmed. The negative temperature gradient on the thrust surface vanished in approximately 25 Ma after the thrust origin, and an approximately constant temperature set in on that surface after 100 Ma. A steady temperature state is achieved throughout the entire lithosphere 325 Ma after the formation of a thrust of the given thickness. The heat flow from the Earth's surface approximately halved with time (Fig. 8). The minimum heat flow was related to the time interval of 225–275 Ma, and the steady state established both for the heat flow and temperature 325 Ma after the start of the solution.

Thus, the formation of heat flow minimums on the lower boundary is characteristic of thrust models with the boundary conditions of the first and second types, and afterwards the process proceeds along an asymptotic curve approaching the steady state. These two points are distinguishing features of the thrust model. The time when these points are attained depends on the total thickness of the allochthonous sheet: the thicker the sheet, the longer will be the time interval between the minimum and the time of steady state achievement. For example, if the thickness of the overthrusting sheet is 10 km, then this interval is 15 Ma and increases approximately up to 125 Ma for a sheet 50 km thick.

The mechanical friction between sheets during their motion, naturally, causes heating of the gliding surface. The thermal energy Q, which is released thereby, depends on the sheet thickness, i.e., the normal pressure (p) on the gliding surface, overthrusting velocity (v), and viscosity (h), which, in turn, depends on the temperature T [5]: $Q = F(p, v, h)$; $h = f(T)$.

The issue of the friction heat was discussed many times in connection with models of subduction in transitional zones [18, 27]. It was shown that friction heat release is a damping factor for the cold plate subduction into a hotter mantle. However, in the case of nearly horizontal motion adopted in our models, the friction will cause an additional heating of the gliding surface. During a long-lasting sheet motion a moment will come when this heating increases the conductive heat flow.

The rate of heating was calculated depending on the time of overthrusting. The gliding velocity of 0.4–8 cm/yr was taken as the parameter. The calculations were performed for the sheet thickness of 15 and 70 km and the respective viscosity and friction coefficients. The model assumes that the sheet motion velocity remains constant over the calculation time. It is evident that in the case of pulsatory motion the relationship will be different.

Even if improbably long overthrusting is assumed, the melting of mantle rocks induced by friction heating can occur in a 15-km plate only at a velocity exceeding 4 cm/yr. In a 70-km block, melting is possible already after 50 Ma at an overthrusting velocity of 2 cm/yr. However, there is no evidence for continuous motion of plates over such a long time. On the contrary, the results of deep-sea drilling show that the motions bear intermittent character and proceed at variable velocities alternating with periods of relative quiescence [10, 28]. In this case, the heating effect of tectonic friction will be much smaller.

Thus, the heating caused by tectonic friction plays a subordinate role in the thermal evolution of the lithosphere and cannot be a cause of large structural rearrangements.

In all of the models considered above, the surface heat flow irreversibly decreases in comparison to the prethrusting situation. If the thrust sheet is 65–70 km thick and thus comparable in thickness with the oceanic lithosphere, the minimum heat flow, twice as low as the initial value, is characteristic of the time interval of 200–300 Ma after the thrusting. This implies that, if the thrusting occurred in the Late Paleozoic, then the present-day heat flow will retain its anomalously low value.

Hence, the screening of the terrestrial heat flow by allochthonous overthrust sheets is one of the possible causes providing anomalously low heat flow in the Late Paleozoic linear tectonic belts.

CONCLUSIONS

(1) The heat flow in the southern Urals and Mugodzhary Mountains is anomalously low and lies within the measured interval of 20–35 mW/m^2, which is twice as low as the world average heat flow in tectonic units of the same age (Late Paleozoic crust) having mosaic rather than linear structural grain.

(2) The temperature distribution with depth in boreholes (including the SG-4 Superdeep) corresponds to the conductive heat transfer. As follows from the geothermal evidence, the fluid filtration velocity within the drilled depth does not exceed 10^{-7} cm/s (3 cm/year). This is a very low value, so that the convective heat transfer in the Ural lithosphere may be neglected. Nonetheless, we can estimate the bulk of fluid that should be filtered through the upper crust in the Urals to provide the observed thermal anomaly. Calculations are shown that 5×10^6 kg/s of water is to be filtered along the Ural Foldbelt, 5000 km long. In other words, the Atlantic Ocean must go through the Urals during 1 Ma.

(3) The anomalously low heat flow bears a time-dependent character due to the screening of the mantle heat flow by thick allochthonous lithospheric sheets. The heat flow from the mantle has not reached yet the Earth's surface, i.e., the sphere of our measurements, and therefore, a low heat flow is currently fixed in boreholes. The heat flow will grow as the holes are drilled deeper. If we imagine that a borehole has penetrated through the entire allochthonous sheet and entered the underlying autochthon, then we will be able to measure a normal heat flow equivalent to the age of the last tectonic (tectonomagmatic) event in the Urals.

(4) Taking into account the above suggestion, we recommend to continue both the drilling of the SG-4 Superdeep and the accompanying field geophysical investigations including thermal logging. A systematic survey of thermal parameters will cast light upon the nature of the structural rearrangement of the Earth's crust in the Urals and in other linear foldbelts.

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