ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 411A, No. 9, pp. 1439–1441. © Pleiades Publishing, Inc., 2006.
Original Russian Text © V.A. Golubev, V.S. Zubkov, 2006, published in Doklady Akademii Nauk, 2006, Vol. 411, No. 4, pp. 519–522.

GEOPHYSICS

A Geothermal Model of the Lithosphere in the Baikal Rift Zone with Consideration of Advective Heat and Mass Transport by Endogenous Fluids

V. A. Golubev[a] and V. S. Zubkov[b]

Presented by Academician V.V. Adushkin, March 2, 2006

Received March 3, 2006

DOI: 10.1134/S1028334X06090236

The lithosphere of rift zones is characterized by high permeability. Therefore, discharge of endogenous fluids is confined to these zones [1–4]. Additional heat transport related to their flux should be reflected in the joint losses of heat through the Earth's surface and on the geotherm, i.e., distribution of temperature by depth. In a quantitative respect, this problem remains a bare spot in the geothermic studies of continental rifts including the Baikal Rift Zone (BRZ). In this paper, the first attempt is made to calculate the influence of fluid heat and mass (HM) transport through the lithosphere on the thermal field in this region.

The urgency of such estimates increased due to the development of the plume tectonic concept [1, 2]. According to the simplest model of the plume, melting of the mantle and transport of the melt into the upper levels of the lithosphere are related to the heat and buoyancy of fluids mainly represented by H_2O, CO_2, N_2, H_2, and CH_4 [2–4]. The existing estimates of fluxes of endogenous fluids are based on the assumption that their discharge is evenly concentrated over the Earth's surface and have been taking place uniformly since the origination of the planet. According to [5], the mean discharge rate of endogenous waters is 0.8 $cm^3/m^2 \cdot yr$ ($0.248 \cdot 10^{-7}$ $g/m^2 \cdot s$). In the regions of Alpine folding, the average fluxes of inorganic gases are CO_2 400 $cm^3/m^2 \cdot yr$ ($2.46 \cdot 10^{-8}$ $g/m^2 \cdot s$), N_2 40 $cm^3/m^2 \cdot yr$ ($1.56 \cdot 10^{-9}$ $g/m^2 \cdot s$), and H_2 10 $cm^3/m^2 \cdot yr$ ($2.80 \cdot 10^{-11}$ $g/m^2 \cdot s$) [6]. Natural discharge of hydrocarbon gases in the Earth is generally equal to $9 \cdot 10^{11}$ kg/yr [7, 8]. Not less than 20% of this amount falls on the share of endogenous methane [9]. Hence, its planetary discharge can be estimated at $1.8 \cdot 10^{11}$ kg/yr ($1.12 \cdot 10^{-8}$ $g/m^2 \cdot s$). Let us use the data in [3] to calculate the values of thermal capacities of these five fluids at *P*–*T* values corresponding to the conditions of the continental lithosphere. According to our estimates based on these data, the mean values of thermal capacities (J/g · °C) are as follows: H_2O 7.1, CO_2 5.1, N_2 6.0, H_2 47.6, and CH_4 14.5.

The integral intensity of fluid HM transport, which depends only on the discharges and characteristics of the fluid, can be expressed by the value

$$R_{1-m} = \sum_{j=1}^{j=m} \nu_j \rho_j c_j. \qquad (1)$$

Here, ν_j is the velocity of component *j* of rising fluid ($m^3/m^2 \cdot s$), ρ_j is its density (kg/m^3), and c_j is thermal capacity of a mass unit (J/kg · °C). Substituting the values of discharges of the five gases given above ($\nu_j \rho_j$) and the values of their c_j to this sum, we get $R_{1-m} = 0.475 \cdot 10^{-6}$ $W/m^2 \cdot °C$.

In addition to R_{1-m}, the model should contain data about the thickness of the lithosphere (*h*) and the temperature of its base (T_h). Independent estimates of *h* and T_h for the BRZ that are the least indirect were obtained from magnetotelluric soundings (MTS) and mineralogical thermobarometry. According to the MTS data, the BRZ base is located at a depth of 100 km and coincides with the roof of the anomalous mantle, which is in the state of fraction melting at ~1200°C [10]. We note that under the pressure corresponding to a depth of $h = 100$ km, the melting temperature of dry basalt is close to 1400°C. Low temperatures of basalt melts in the upper mantle substrate of the BRZ are explained by the presence of fluids [2, 10]. According to [11], the presence of even a few percent of water in the rocks decreases their melting temperature by 300–400°C. Ther-

[a] *Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences, ul. Lermontova 128, Irkutsk, 664033 Russia; e-mail: golubev@crust.irk.ru*

[b] *Vinogradov Institute of Geochemistry, Siberian Division, Russian Academy of Sciences, ul. Favorskogo 1a, Irkutsk, 664033 Russia*

mobarometry of xenoliths from volcanic basalts in the BRZ and adjacent regions yields temperatures of ~1100–1200°C at a depth of 90 km [12]. These values of h and T_h almost coincide with their estimates based on the MTS data. According to other investigations, the lithosphere in the axial BRZ is as thin as 40 km, which is the thickness of the Earth's crust [13]. Taking into account all these estimates, we assume that the values of h and T_h are equal to 70 km and 1100°C, respectively.

A 1D equation of heat balance, which describes stationary distributions of temperature in a geological massif heated from below, can be used to solve this problem. Radiogenic sources are active inside this massif. In addition, the massif is penetrated by an advection of fluids with velocity v. The solution implies that all heat contained in the fluids in the Earth's interior is completely transferred to the rocks; i.e., it transforms to the conductive form of heat transport, while the fluids flow to the Earth's surface. The corresponding heat flux through the Earth's surface (q_{es}) is found from relations

$$q_{es} = q_0 + q_{hf} + q_{adv}, \tag{2}$$

$$q_{adv} = R_{1-m}(T_h - T_{es}). \tag{3}$$

Here, q_0 is conductive heat flux through the lithosphere base; q_{hf} is heat flux generated by radioactive elements.

Let us present the lithosphere in the BRZ as the number N of plane-parallel horizontal layers. Any layer i can have its own values of heat conductivity and radiogenic heat generation (λ_i and A_i). The temperature at the base of layer n can be calculated from relation

$$T(z_n) = T_{es} + \sum_{i=1}^{i=n} \Delta T_i, \tag{4}$$

in which ΔT_i is the temperature increment in each layer i, whose width is Δz_i. The heat flux through the roof of the upper layer (at $z = 0$) is assumed known. Using this reference q_{es} value, it is possible to calculate the value of conductive heat flux through the base of the first layer ($i = 1$). After this, heat flux through the underlying layers can be calculated. Heat flux through the base of layer i is determined from relation

$$q_i = q_{i-1} - \Delta q_{i,\,hf} - \Delta q_{i,\,adv}. \tag{5}$$

where q_{i-1} is heat flux through the base of layer i, equal to the heat flux through the roof of layer i; $\Delta q_{i,\,hf}$ and $\Delta q_{i,\,adv}$ are increments of the flux caused by radiogenic heat generation and advection of fluids. The ΔT_i value can be calculated from a relation similar to Eq. (5)

$$\Delta T_i = \Delta T_{i,\,pc} - \Delta T_{i,\,hf} - \Delta T_{i,\,adv}. \tag{6}$$

Here, $\Delta T_{i,\,pc}$ is temperature variation during the transition from the upper to the lower boundary of layer i caused by pure conduction, i.e., variation without account for radiogenic sources of heat A_i and heat emission by rising fluids:

$$\Delta T_{i,\,pc} = \frac{q_{i-1}}{\lambda_i}\Delta z_i. \tag{7}$$

In Eq. (6), the $T_{i,\,pc}$ value is positive and related to the temperature increment, which depends on the power of radiogenic heat generation A_i (W/m^3):

$$\Delta T_{i,\,hf} = \frac{A_i \Delta z_i^2}{2\lambda_i}. \tag{8}$$

The $T_{i,\,adv}$ value in Eq. (6) is also positive and represents the increment of the temperature of rocks caused by cooling of rising fluids during their percolation through layer i:

$$\Delta T_{i,\,adv} = \frac{\Delta q_{i,\,adv}}{2\lambda_i}\Delta z_i. \tag{9}$$

The increment $\Delta q_{i,\,hf}$ in Eq. (5) is calculated from the relation

$$\Delta q_{i,\,hf} = A_i \Delta z_i. \tag{10}$$

The advective increment of heat flux in layer i in Eqs. (5) and (9) is found with the account of the R_{1-m} value discussed above and increments $\Delta T_{i,\,pc}$ and $\Delta T_{i,\,hf}$ calculated from formulas (7) and (8):

$$\Delta q_{i,\,adv} = (\Delta T_{i,\,pc} - \Delta T_{i,\,hf}) R_{1-m}. \tag{11}$$

The layer-by-layer calculations of temperature should start from the upper layer. First, we find increments $\Delta T_{i=1,\,pc}$ and $T_{i=1,\,hf}$ from Eqs. (7) and (8), which allows us to calculate the power of advective heat release ($\Delta q_{i=1,\,adv}$) in this layer from Eq. (11). Next, using Eq. (9), we can calculate the advective increment of temperature ($T_{i=1,\,adv}$), which is the third addend in Eq. (6). This sequence of calculations is applied to all underlying layers.

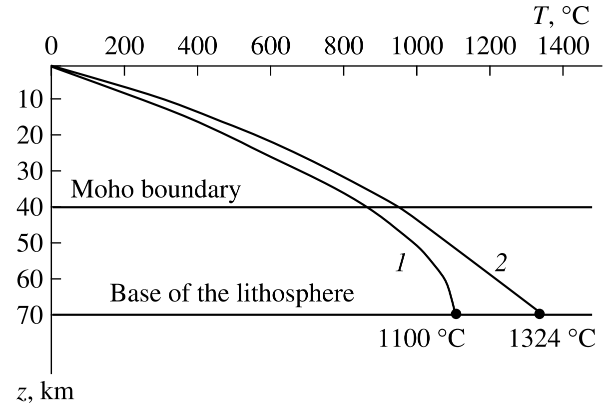
The problem discussed here belongs to the class of inverse geophysical problems and, based on the reasoning given above, is solved by the method of sorting the solutions of direct problems. At the lower boundary of the model, we choose an intensity of fluid HM transport R_{1-m}, which guarantees the actually observed heat flux through the Earth's surface at a given temperature at this boundary T_h. In our calculations, we assumed that $T_{es} = 0$, while the regional q_{es} value within the BRZ is equal to 70 mW/m^2 [14]. The λ and A values are assumed to be the same as before [14, 15]: in layer 0–15 km, λ and A are assumed equal to 2.5 W/m · K and 1 · 10^{-6} W/m^3, respectively; in layer 15–40 km, 2.7 W/m · K and 0.3 · 10^{-6} W/m^3, respectively; and in the lithospheric subcrustal layer (40–70 km), 3 W/m · K and 0 W/m^3, respectively.

The layer-by-layer calculations with $\Delta z_i = 1$ km performed with these parameters showed that temperature

T_h = 1100°C at the lower boundary of the BRZ lithosphere and heat flux through its upper boundary equal to 70 mW/m^2 are possible only if advective HM transport through the lithosphere exists in this region with intensity R_{1-m} = 17.3 · 10^{-6} W/m^2 · °C. According to Eq. 3, the heat flux due to heat release from the fluids to rocks (in the course of fluid spreading through the lithosphere) is equal to 19 mW/m^2, which is equal to 27.1% of the regional heat flux in the BRZ (70 mW/m^2). The corresponding conductive advective distribution of temperatures by depth is presented in figure (curve *1*). This figure also shows geotherm *2*, which was calculated for the case of pure conduction (R_{1-m} = 0), i.e., for the case of zero heat transport by fluids through the lithosphere. At q_{es} = 70 mW/m^2, pure conductive geotherm *2* requires 1324°C at the lower boundary. The above data of nongeothermal methods for estimating temperatures in deep zones of the BRZ suggest the absence of such high temperatures at this boundary. It should be noted that geotherms *1* and *2* at a depth up to 10 km are hardly distinguishable. The discrepancy is 88°C at the Moho boundary and reaches 224°C at the base of the lithosphere.

The estimate R_{1-m} = 0.475 · 10^{-6} W/m^2 · °C obtained at the beginning of this article was based on the information about the fluxes of endogenous waters evenly distributed over the Earth's surface and on the data on discharge of CO_2, N_2, H_2, and CH_4 in the Alpine folding zones. In reality, discharge of endogenous fluids is focused mainly in the rift zones, whose total area is many times smaller than the area of Alpine folding (more so for the area of the planet). Hence, we can consider that the R_{1-m} value of the endogenous fluid flux, which actually exists in the BRZ, is many times greater than its indicated value. Correspondingly, the value of R_{1-m} = 17.3 · 10^{-6} W/m^2 · °C, which is used for calculating geotherm *1* and is 36 times higher than the average value for the entire planet (0.475 · 10^{-6} W/m^2 · °C), becomes well grounded.

Thus, we have developed a simple method for calculating the geothermal field that takes into account advective heat transport by endogenous fluids. The application of this method showed that increased conductive heat flux observed within the BRZ can be caused to a significant extent by this advection through the lithosphere. Due to the advection of endogenous fluids, the temperature near the lower boundary of the BRZ lithosphere should be lower by a few hundred degrees than the values based on the previously developed (purely conductive) thermal models of this region. The account for advective heat transport decreases the deviation between the geothermal and nongeothermal estimates of temperatures in deep zones of the BRZ. Thus, the upper mantle of the BRZ actually contains a large amount of fluids, which rise through permeable zones to the Earth's surface and are continuously replenished by fluid fluxes from below.



Geotherms of the lithosphere in the BRZ calculated for the (*1*) presence or (*2*) absence of HM transport by fluids through the lithosphere with intensity R_{1-m}.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 04-05-64972) and the Siberian Division, Russian Academy of Sciences (integration project "Deep Structure of the Earth, Geodynamics, Magmatism, and Interaction of Geospheres", section no. 6.5.2).

REFERENCES

1. N. L. Dobretsov and A. G. Kirdyashkin, Dokl. Earth Sci. **373**, 879 (2000) [Dokl. Akad. Nauk **373**, 84 (2000)].
2. F. A. Letnikov, Geol. Geofiz. **44**, 1262 (2003).
3. F. A. Letnikov, P. I. Dorogokupets, and V. V. Lashkevich, Petrology **5**, 597 (1997) [Petrologiya **2**, 563 (1994)].
4. V. S. Zubkov, Geochem. Int. **39** (2), 109 (2001) [Geokhimiya, No. 2, 131 (2001)].
5. V. I. Vinogradov, Bull. Mosk. O–va Ispyt. Prir. **75** (5), 3 (2000).
6. G. I. Voitov Zh. Vses. Khim. O–va, No 5, 533 (1986).
7. V. V. Adushkin, V. P. Kudryavtsev, and S. B. Turuntaev, in *Global Changes in Natural Environment* (Novosibirsk, 1998), pp. 191–205, [in Russian].
8. V. V. Adushkin, V. P. Kudryavtsev, and S. B. Turuntaev, Dokl. Earth Sci. **391**, 914 (2003) [Dokl. Akad. Nauk **391**, 813 (2003)].
9. B. M. Valyaev, Geol. Nefti Gaza, No. 9, 30 (1997).
10. A. M. Popov, Pageoph. **134**, 575 (1990).
11. A. E. Ringwood, *Composition and Petrology of the Earth's Mantle* (McGraw-Hill, New York, 1975; Nedra, Moscow, 1981).
12. I. V. Ashchepkov, Yu. D. Litasov, and K. D. Litasov, Geol. Geofiz. **40**, 287 (1996).
13. Yu. A. Zorin, T. V. Balk, M. P. Novoselova, and E. Kh. Turutanov, Izv. Akad. Nauk. Fiz. Zemli, No. 7, 32 (1988).
14. V. A. Golubev, *Conductive and Convective Heat Transport in the Baikal Rift Zone*, Doctoral Dissertation in Geology and Mineralogy (Irkutsk, 2002).
15. V. A. Golubev, Dokl. Earth Sci. **390**, 558 (2003) [Dokl. Akad. Nauk **390**, 247 (2003)].