ON THE CHARACTER OF THE GEOTEMPERATURE FIELD IN THE REGION OF AVACHINSKY VOLCANO

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Abstract

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B. G. POLYAK

ON THE CHARACTER OF THE GEOTEMPERATURE FIELD IN THE REGION OF AVACHINSKY VOLCANO

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The study of the geothermal conditions of the subsurface near magmatic centers is necessary for solving many theoretical and practical problems. We have carried out a calculation of the geotemperature field in the region of the active Avachinsky volcano in Kamchatka.

It has been established by geophysical methods ([2]) that beneath this volcano, at a depth of about 2 km, there lies an intermediate magmatic chamber, having the form of a sphere of radius 3 km, with a temperature at its roof of not less than 600°. On the basis of these data, we carried out a preliminary predictive calculation, making certain assumptions.

The condition of the problem is to determine the character of the geotemperature field around a magmatic center with constant temperature T_0, having the form of a sphere of radius a and occurring at depth l (the vertical distance to the center of the sphere), with regional geothermal gradient B and temperature at the lower boundary of the zone of annual heat turnovers $C = 0^\circ$. The solution is sought in the form of the sum

$$T = U(x, y, z) + Bz + C, \tag{1}$$

where z is depth; $U(x, y, z)$ is the function expressing the disturbance of the geotemperature field by the magmatic center.

Analysis of materials from thermometric investigations in the surrounding regions shows that for the calculation one may adopt the value of the regional geothermal gradient $B = 35^\circ/\text{km}$. For convenience of calculation, the temperature at the lower boundary of the zone of annual heat turnovers is taken equal to 0°; its discrepancy with the true value, equal to 4.5°, as well as the thickness of the zone of annual heat turnovers, may quite well be neglected, taking into account the temperature and depth of occurrence of the magmatic center; the surface of the lower boundary of the zone of annual heat turnovers is assumed to be plane. The latter assumption is a necessary one, since taking account of the curvature of the relief rules out an analytic solution of the problem, allowing only physical modeling. It should be borne in mind here that in those cases where the depth of occurrence of the center considerably exceeds the amplitude of the relief, its curvature may be neglected without introducing appreciable errors into the calculation. Since the variation in space of the thermophysical properties of the rocks surrounding the center, and still more the regularity of this variation, are unknown, we take the thermal conductivity and temperature conductivity of the surrounding medium to be constant.

The function $U(x, y, z)$, expressing the disturbance of the temperature field by the magmatic center, for a stationary field satisfies Laplace' s equation:

$$\Delta U = \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} = 0 \tag{2}$$

and the boundary conditions

$$U\big|_{z=0} = 0, \qquad U\big|_{\Gamma} = T_0, \tag{3}$$

where Γ is a sphere of radius a.

In this case it is necessary that, at an infinite distance from the sphere, the harmonic function U tend to 0.

Applying the method of mirror images, used for solving similar problems of electrostatics and described in the literature (1), we find a solution satisfying the specified conditions in the form

$$\frac{U}{aT_0} = \frac{1}{\sqrt{(z-l)^2 + x^2 + y^2}} - \frac{1}{\sqrt{(z+l)^2 + x^2 + y^2}} +$$

$$+ \sum_{k=2}^{\infty} \frac{1}{p_k} \left[\frac{1}{\sqrt{(z-l-q_k a/p_k)^2 + x^2 + y^2}} - \frac{1}{\sqrt{(z+l+q_k a/p_k)^2 + x^2 + y^2}} \right] +$$

$$+ \sum_{k=2}^{\infty} \frac{1}{q_k} \left[\frac{1}{\sqrt{(z+l+p_k a/q_k)^2 + x^2 + y^2}} - \frac{1}{\sqrt{(z-l-p_k a/q_k)^2 + x^2 + y^2}} \right], \tag{4}$$

where

$$p_k = \frac{\alpha_1^{k-1} - \alpha_2^{k-1}}{\alpha_1 - \alpha_2} + \frac{\alpha_1^k - \alpha_2^k}{\alpha_1 - \alpha_2}, \qquad q_k = -\frac{2l}{a} \frac{\alpha_1^{k-1} - \alpha_2^{k-1}}{\alpha_1 - \alpha_2}, \tag{5}$$

and α_1 and α_2 are the roots of the equation

$$\alpha^2 - 2\left(2\frac{l^2}{a^2} - 1\right)\alpha + 1 = 0 \quad (6)$$

such that $\alpha_1 > 1,\ \alpha_2 < 1$.

The solution has physical meaning only in the region $z > 0$.

Solving equation (6) for definite values of l and a, we determine α_1 and α_2. Then from (5) we find $p_1, p_2, \ldots$ and $q_1, q_2, \ldots$. Substituting these values, we reduce equation (1) to a computational form. Analysis has shown that, in this case, terms of the series for which $k > 4$ may be neglected, since their magnitude is appreciably small in comparison with the preceding terms.

Assigning various values of z and y, we determine U at various points of the plane $(y, z > 0)$. In doing so, we assume that magmatic heat provides, at the surface of the source, a temperature 600° higher than the temperature of the regional thermal field, and we take $T_0 = 600°$. Taking into account that the temperature of molten lava is usually considerably higher, we carry out the calculation in two variants: at $T_0 = 600°$ and at $T_0 = 1000°$.

As Macdonald notes (3), indications of intermediate magmatic chambers have also been found at some other volcanoes (for example Vesuvius, Kilauea, Mihara), but the depth to the roofs of these chambers is usually considerably greater (from 4 to 7 km). Therefore we also carried out, in parallel, a calculation of the disturbance of the regional thermal field by a magmatic source of the same size and shape, but with $l = 8$ km.

Substituting the found value of U into (1) and determining Bz, we obtain, for the corresponding points, the required value of T. The results of the calculation are summarized in Table 1 and presented graphically in Fig. 1. It follows from them that the warming influence of the magmatic source, for the specified values of the depth of its occurrence l, 5 and 8 km, and an excess of the temperature of its roof by 600° and 1000° over the temperature of the regional field, is practically appreciable only in a rather limited region—for the adopted model, at distances not exceeding 12–15 km. At such a distance from the source, the temperatures of the rocks still differ noticeably from the temperatures in the regional undisturbed field at the same levels, and their increase with depth occurs at more rapid rates. At greater distances from the source, the geothermal indicators decrease and, at a plan distance of approximately 25 km, in essence already completely coincide with the indicators of the regional field (see Table 1). Apparently, the dimensions of the region in which the influence of additional heating by a magmatic source with a roof temperature of about 1000°, occurring in the depth range from 5 to 8 km, makes itself felt will coincide with those obtained by us. If the depth of its occurrence is greater, they should decrease.

Fig. 1. Calculated geotemperature field in the region of a magmatic source, for depths l of its center equal to 8 and 5 km.

1 —isotherms of the regional geotemperature field in the absence of perturbations by the magmatic body; 2 —isotherms of the calculated field when the temperature of the roof of the source exceeds the temperature of the regional field by 600°; 3 —the same when the excess is 1000°; 4 —magmatic source.

decrease. The most substantial influence on the character of the thermal field in the region of the volcano may be exerted by a refinement of the dimensions of the intermediate chamber.

The thermal field created by the source has been assumed in the calculation to be stationary. In reality it is nonstationary and, consequently, the perturbations in the regional field caused by it will weaken with time.

Table 1

Calculation of the geotemperature field around a magmatic chamber

Depth, km	Depth of occurrence of the chamber center, km	Temperature of the chamber roof, °C, without allowance for the regional field	Temperature, °C at distance in plan from the chamber, km: 0	5	10	15	20	25	In the regional field
1	5	600	291	110	53	42	38	37	35
1	5	1000	462	159	65	46	40	37	35
1	8	600	115	81	52	43	39	37	35
1	8	1000	168	112	64	48	41	33	35
2	5	600	680	217	105	83	76	73	70
2	5	1000	1095	315	128	92	79	75	70
2	8	600	235	163	106	84	77	74	70
2	8	1000	342	225	130	94	82	77	70
3	5	600		313	155	125	113	109	105
3	5	1000		451	188	138	119	112	105
3	8	600	375	245	157	126	116	111	105
3	8	1000	555	339	192	141	123	112	105
4	5	600		400	203	163	151		140
4	5	1000		573	244	179	158		140

Depth, km	Depth of occurrence of the chamber center, km	Temperature of the chamber roof, °C, without allowance for the regional field	Temperature, °C at distance in plan from the chamber, km: 0	5	10	15	20	25	In the regional field
4	8	600	558	293	208	168	155		140
4	8	1000	833	396	253	188	165		140
5	5	600		449	248	203	188	182	175
5	5	1000		632	296	222	196	187	175
5	8	600	~800	363	248	210	193	185	175
5	8	1000	~1250	488	296	233	204	191	175
6	8	600		490	302	250	230		210
6	8	1000		677	363	278	244		210
7	8	600		557	348	292	267		245
7	8	1000		776	417	324	284		245
8	8	600		609	390	332	305	295	280
8	8	1000		828	463	367	322	305	280

(if in the chamber the same temperature regime is not maintained in one way or another). Therefore, the assumption of a stationary regime leads to a certain exaggeration of the dimensions of the zone of possible warming of the rocks by volcanic heat; in reality it should be still smaller.

In the calculation only conductive heat transfer was taken into account. If, however, there is a flow of groundwater directed away from the chamber, an expansion of the zone of temperature increase caused by magmatic heat is possible. On the other hand, since the volcanic edifice is a hydrogeological recharge area, the downward movement of groundwater should lead to an increase in the thickness of the zone of annual heat exchanges (and at greater depth should cause a "pressing down" of the isotherms above the chamber). This to a certain extent compensates for the discrepancies between the calculated temperatures and the actual ones, caused by the assumption made in the calculation of a flat lower boundary of the zone of annual heat exchanges.

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Note: Figure translations are in progress. See original paper for figures.