An Energy Appraisal of Volcanic and Hydrothermal Phenomena (On the example of Kamchatka) *

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Summary

The energy expenditure, associated with the Quaternary volcanic activity on Kamchatka is three times higher than the heat losses as result of background conductive heat flow in this region, and 17 times higher than the heat discharge by hydrothermae. The general intensity of deep heat expenditure and transformation as a result of these three phenomena proves here to be on the average 7.8 μ cal/cm² per second. This is several times higher than the average values of conductive heat losses of the Earth.

The described phenomena (conductive heat flow, volcanic activity, heat discharge by hydrothermae), however do not exhaust all the forms of deep energy expenditure of this region. Metamorphic processes, occuring in its interiors are also accompanied by tremendous energy expenditure and can be compared in this respect with volcanicity (Fyfe, Verhoogen). With due consideration to these and some other « energy capacious » geological processes, the total value of deep energy losses as direct heat withdrawal from the interiors and in other forms should be still higher. To the similar conclusion leads an analysis of the thermal history of the Earth, showing that during the period of active volcanicity, the heat supply from the upper beds of the mantle into such areas of the Earth crust, increased up to the value of the order 10 μ cal/cm² per second (Lubimova).

Such areas of active volcanicity may be regarded as positive geothermic anomalies on a planetary scale. This conclusion seems to have a common character and can be used for the whole area of recent geosynclines. This is confirmed by the space coincidence of the most intensive manifestations of tectogenesis, magmatism (volcanism), metamorphism and other « energy capacious » processes in various periods of the Earth's history. The abundance of heat influx into such areas of the Earth may result from the convective currents in the mantle or from the tectonic tension, caused by cosmic factors.

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Introduction

According to the data giving a modern point of view on the interior of the Earth, there occur about 12.10^{12} cal per second (DOSTOVALOV, JEFFREYS and others) as a result of radioactive decay, gravitational differentiation of its substance and other possible processes. The heat evacuation from the interior of the Earth is carried out both in its obvious form, *i.e.* in the form of conductive and convective transfer of the heat towards the surface, and in the concealed form as a consequence of the use of this energy, resulting from various geological processes.

The appraisal of the deep heat expenditure has been based up till now only on the measurements of the conductive heat flow in the upper parts of the lithosphere. The contradiction between the figure thus obtained, *i.e.* 6.10^{12} cal per second, (GUTENBERG and others), and the supposed scale of heat generation in the interior of the Earth is regarded by the different ways. Some researchers consider it as a proof of warming-up the depth of the Earth (LUBIMOVA, VERHOOGEN); the other believe that this contradiction is to some extent a result of the underestimate of some other possible mechanisms of heat evacuation from the interior of the Earth (LJUSTICH).

The preliminary data show that on the planetary scale conductive heat losses still play the most important role. A more differentiated analysis of the energy regime of the Earth crust, however, shows that in its mobile parts the volume of the conductive heat flow cannot be regarded as the main (and the only) index of the general intensity of deep heat expenditure. Not less important are such active « energy capacious » geological processes as orogenesis, folding, formation of the Earth crust discontinuity, metamorphism, magmatism (and volcanism, particularly). From the example of Kamchatka (one of the elements of the Pacific mobile belt), we have analized the relative importance and the summary effect of the conductive heat transfer into the lithosphere, volcanic activity and heat discharge by the thermal streams on to the Earth surface.

Conductive Heat Flow

In the space distribution of the heat flow values on the continents there is observed a certain connection with some peculiarities of the geological structure and development of either parts of the Earth crust. The maximum values of the flow — 2 and more μ cal/cm^2 per second — are now observed in the regions of Late Cenozoic and Recent volcanic manifestations. These manifestations refer to the zone of Cenozoic geosynclines, to the parts of the Earth crust rejuvenated by the latest tectonic movements and the regions of median-oceanic ridges as well. The results of the studies carried out during the last ten years in the Japan link of the Pacific geocynclinal belt, showed that the region of such heat flow values exactly coincides here with the zones of the Quaternary volcanism (HORAI, UYEDA).

We consider it very characteristic, that the same values of the heat flow are established in South-Eastern Australia (HOWARD, SASS and others) as well, where, as it is known, strong Cenoizoic epeirogenic movements were accompanied by an intensive volcanic activity. The similar features may be observed in the character of the heat flow distribution in Europe (observations in Hungary, Czechoslovakia, DDR).

The regional heat flow on Kamchatka is not studied well enough. We can only preliminarily determine its value, based on the determinations of the geothermal gradient in the wells and on the data of thermoconductivity of analogous rocks. As a result it was discovered that in the region of the Quaternary volcanism of Kamchatka the background value (value, typical for the given region) of conductive heat flow is approximately 1.7-2.6 μcal/cm^2 per second, and beyond this region — about 1.1 μcal/cm^2 per second. This agrees well with the data obtained in Japan. For the energy analysis the value of conductive heat flow in Kamchatka volcanic regions may be equal to 2 μcal/cm^2 per second.

Very characteristic of Kamchatka, as well as of other similar regions, is the abundance of local geothermic anomalies, caused by recent volcanic and hydrothermal activity. On places of anomalies the heat flow is much higher than on the surrounding territories.

Energy Effect of Volcanism

Volcanic activity is connected with a tremendous energy expenditure. Therefore the problem of the origin of volcanic heat and the role of volcanism in the thermal regime of the Earth's crust is certainly of a great interest (GRATON, LUBIMOVA, LJUSTICH, VERHOOGEN).

During recent years a quantitative apparisal was made mainly of the volcanic paroxysms (Gorshkov, Yokoyama, Minakami and others), while little attention is paid to the energy consequences of some other volcanic processes.

Based on the results of the study of the Quaternary and recent volcanic activity on Kamchatka we analized the main forms of energy expenditure observed during the true volcanic process:

a) mechanical work necessary for the magma ascent to the surface of the Earth.

b) energy expenditure during eruptions of volcanoes.

c) cooling of incandescent ejectamenta on the surface.

d) heat discharge as result of fumarolic activity of the volcanoes during the interparoxysmal stage.

e) heat loss by not deeply occuring intermediate magma chambers as result of heat conductivity of the surrounding rock masses.

For the convenience of comparison the energy effect of each of these phenomena is expressed in μcal/cm^2 per second as the mean intensity of the energy expenditure throughout the Quaternary period (generally accepted duration of 1 million years), referring to a square unit of the region of active volcanicity (92,000 km^2). As the available data are not sufficient, the main purpose of the calculations carried out was the determination of the order of the value.

Mechanical work, performed for the magma ascent to the Earth surface during the period prior to the eruption, leads, as you know, to the increase of the potential energy of displaced mass. It is determined by the product of the weight of displaced material by the height of the rise. Taking into consideration the area of distribution of the Quaternary ejected products, their average capacity, relation of lavas and loose pyroclastic formations and the fallout of a part of the product of land ejectamenta over the adjacent water areas, the total mass of the material supplied to the Earth surface as result of volcanic activity on Kamchatka during the Quaternary period, is $1.77 \cdot 10^{20}$ g. According to geophisical data, the generation zone of andesitic-basalt magma, mostly typical for the Quaternary ejected products of Kamchatka, is at the depth of at least 60 km (Gorshkov, Fedotov and others). Based on these data, the energy effect of magma ascent as a result of the Quaternary volcanic activity in Kamchatka is determined in the heat equivalent as 0.83 μcal/cm^2 per second. In the regions of the main development of acid volcanicity, in the light of the ideas about « secondary » origin of granite magmas, for the similar calculations it is recommended to take a correspondingly smaller height of melt ascent, taking into account at the same time the energy losses, connected with its origin.

Energy expenditure during the eruptions was determined according to the seismomechanichal energy eruption (we mean, the sum of kinetic energy of volcanic ejectamenta, the energy of the air wave during the eruption, and the energy of volcanic earthquake), but not according to so-called « heat power » (quantity of heat, accumulated in the ejected products), as the separated analysis of these different forms of energy expenditures is more instructive.

The comparison of the available data on the energy of various eruptions shows that for the determination of the total energy of all volcanic paroxysms, it is sufficient to take into cnosideration only the strongest (catastrophic) explosions, while the rest may be disregarded. As a standard, we took the energy of the explosion of the Bezimyanny volcano on the 30th of March 1956, equal to 5.10^{23} erg (Gorshkov). Some researchers believe (Tazieff, for example) that it was one of the strongest eruptions of the historical time. According to the data available (Gushchenko, Marhkinin and others), in our time such an eruption in Kamchatka happens not more than once during 40-60 years. If the frequency of such phenomena within the whole Quaternary period had the same order, the average energy effect of the eruptions in the heat equivalent should amount to 10^{-2} μcal/cm^2 per second.

The following comparison is of certain interest. If the total mass of the ejected products of the above mentioned explosion of the volcano Bezimianny, $2.4 \cdot 10^{15}$ g. (Gushchenko), had been thrown out for the first time to the surface of the earth during the eruption, such phenomena should have taken place in Kamchatka during the Quaternary period not less than once every 16-17 years for the accumulation of only areal volcanic formations. But as among the products of this explosion, as some investigators believe (Gorshkov, for instance), there were not less than 50 % of the material ejected before, such phenomena should have taken place once per 8 years, *i.e.* 5-8 times more frequent than now. These calculations make us think about the evolution of eruption manifestaion in Kamchatka during the Quaternary period. Relatively quiet effusions accompanied by comparatively small expenditures of seismomechanical energy with a tremendous quantity of the ejected material seemed to play a more important role in the past.

Cooling of incandescent ejectamenta on the day surface is one more form of the energy expenditure during a volcanic process. The amount of the heat discharged into the atmosphere is in proportion to the mass of all these products, to their temperature at the moment of their reaching the Earth surface, and to the specific heat capacity and crystallization heat. Taking the general heat content of the ejected material as 400 cal/g (like Bödvarsson and Verhoogen), we find out that the mean energy effect of this process is 2.54 μcal/cm² per second.

Heat discharge into the interparoxysmal stage of the volcanic activity requires as much attention as the energy expenditure during eruptions. Yet, it has been studied very poorly. In this respect only the following volcanoes are investigated: Kilauea, (Daly, Shepherd), White Island (Wilson), Niragongo (Bonnet, Delsemme) and Ebeko (Nekhoroshev). We have studied the heat power of fumarolic activity of one of the volcanoes of Kamchatka — the Mutnovsky volcano, situated in the south-east of the peninsula. Systematic geothermal studies were carried out at the north-eastern crater of this volcano in July-September, 1963.

The thermometric survey, performed by means of electrothermometric apparatus, revealed the character of the temperature distribution in the ground of the crater floor. Its maximum values (75-90°) refer to the place of the largest fumarolic activity. Direct measurements of the conductive heat flow showed that its value on the crater floor is on the average about 1000 μcal/cm² per second. In accordance with the distribution of temperature, it varies considerably, reaching its maximum (9200 μcal/cm² per second) near fumaroles and decreasing at places with low activity. The established distribution of the temperature and of the heat flow shows, that the heat regime of the crater floor is determined by the warming-up effect of steam-gaseous jets ascending to the surface along separate systems of steeply dipping fissures. The strike of these systems, determined according to the results of thermometry, agrees with the geological data.

The amount of heat, carried out by fumarolic jets, was determined according to the weight discharge and heat content of the emitted steam. To determine them, numerous measurements were made of m/sec., and of their temperature, reaching 305°. Taking into consideration deconcentrated steam yield, the specific weighed discharge of steam on the fumarolic fields is on the average 3 g/m² per second, while the specific convective heat losses are 225,000 μcal/cm² per second, *i.e.* 2 orders higher than the conductive ones. (Comparison with the data obtained on other volcanoes of the same type, shows that such relation between the convective and conductive heat losses is preserved regardless of the total intensity of fumarolic activity).

Besides the north-eastern crater, fumarolic activity on the Mutnovsky volcano is also shown on its northern slopes and very markedly in a so-called « active funnel », from which ash ejecta came out in the late 1960 and early 1961 (Kirsanov and others). Using specific indices of steam and heat discharge, we found out that on the Mutnovsky volcano during the observation time, 566 kg/sec of steam and $4.46.10^8$ cal/sec of heat were emittend into the atmosphere. As to the intensity of fumarolic activity on the interparoxysmal stage, the Mutnovsky volcano exceeds the other volcanoes of Kamchatka. Taking into consideration this circumstance and the established power indices of this process on other similar volcanoes, the mean heat expenditure in the Quaternary period of the history of Kamchatka, with 20 simultaneously acting volcanoes, is determined as 1.91 μcal/cm² per second.

Heat discharge from the shallow intermediate volcanic chambers, filled with magma melt, to the surrounding mountain rocks, causes disturbances in the regional geotemperature field. It is difficult to make geothermal measurements at such places, and the chambers themselves are detected only by indirect methods. That is why it is necessary to use the methods of calculations to determine the heat expenditure associated with this phenomena (Jaeger, Laffitte, Lubimova, Reilly, Rikitake, van Orstrand and others).

For one of the volcanoes of Kamchatka (the Avachinsky volcano), it was found by means of geophysical methods that at the depth of 2 km there is an intermediate magmatic chamber, similar in form to a sphere with the radius of 3 km (Steinberg, Zubin). Based on these data and some assumptions we made tentative estimations of the geotemperature fields on this area. It showed that on the area, adjacent to the chamber, the value of the conductive heat flow is close to 10 μcal/cm² per second, and the total heat amount discharged from the chamber through the Earth surface, is about 10^7 cal per second.

Based on the available data and general volcanological considerations, some researchers (Macdonald, for instance), believe that intermediate magmatic chambers are typical elements of the deep volcanic structure. In connection with this, we believe that, during the Quaternary period, at least 20 simultaneously acting volcanoes had such characteristic structure. Based on data obtained for the Avachinsky volcano, we can evaluate the mean intensity of the heat expenditure as 0.23 μ cal/cm^7 per second.

Judged by the size of some Kamchatka calderas, such as Ksudach, Uzon, and the volcanoes Gorely, Karimsky, Krasheninnikov, we may say that the intermediate chambers, which once had been situated under them, were considerably larger than the chamber found under the Avachinsky volcano, and discharged a larger amount of heat to the surrounding rocks. Therefore the energy value for this phenomena can hardly be regarded as exaggerated. Relation between the heat discharge by intermediate chamber and the thermal capacity of interparoxysmal stage of volcanic activity needs further studies.

The total energy effect of the described volcanic process during the Quaternary period of the history of Kamchatka amounts on the average to 5.5 μcal/cm^2 per second. 46 % of energy expenditure is connected with the cooling of the ejected products; more than 34 % falls on the fumarolic activity of the volcanoes in the interparoxysmal stage of the activity. Then follow the magma ascent towards the surface (about 15 %) and heat discharged by the intermediate chambers (over 4 %). The seismomechanical energy expenditure during eruptions is less than 1 %, showing that the eruptions play a hardly noticable role in the general energy balance of volcanicity.

Heat Discharge by Hydrothermae

According to the latest data, there are 116 groups of thermomineral sources and steam-hydrothermae in Kamchatka. There is no direct relation in their geological-structural position with concrete volcanic structures. They usually refer to the zones of tectonic disturbances, forming so-called « thermal lines ». Heat output in the places of the hydrothermal discharge is determined by the product of heat content of the discharged thermal water or steam-aqueous mixture on its yield, estimated with the consideration of concealed discharge and amounts in the region of active volcanism of Kamchatka to not less than 3.10^8 cal/sec, or on the average about 0.32 μcal/cm^2 per second.

A comparison of the heat power of the discharge of some hydrothermal systems with the regional hydrogeological and geothemal conditions sometimes can help to establish the reason of their warming-up. In certain cases the area of the formation of such systems is not large enough to supply their warming-up at the expense of background conductive heat flow. Thus, for example, for steam-hydrothermal of Geyser Valley, it should have been about 10,000 km^2, whereas according to AVERIEV, it does not exceed 40 km^2. Similar estimations show, that the warming-up of the most powerful recent hydrothermal systems occurs with the additional supply of heat from the depth associated either with the cooling of magmatic body or with an influx of a highly heated steam-gas-aqueous fluid.

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