ORIGINAL RESEARCH ARTICLE

DOI: https://doi.org/10.18599/grs.2018.4.366-376

Heat flow from the Earth interior as indicator of deep processes

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Abstract. The energy aspects of the problem of intraterrestrial heat transfer in various forms are discussed. Endogenous causes of conductive heat flow dispersion − radiogenic heat generation, tectonic movements and magmatism (volcanism), including its latent and open discharge in the form of volcanic and hydrothermal activity are considered. The geological ordering of the heat flow in the continental crust is related to convective discharge of the heat and mass flow from the mantle, marked by the isotopic composition of helium in freely circulating underground fluids. The combined transport of heat and helium, as well as the correlation of He isotopic compositions in volcanic and hydrothermal gases and Sr compositions in young lavas, testify to the silicate nature of the heat and mass flow emanating from the mantle reservoirs of different depths.

Keywords: geothermics, heat flow, heat and mass transfer, helium isotopes, magmatism, volcanism

Recommended citation: Polyak B.G., Khutorskoy M.D. (2018). Heat flow from the Earth interior as indicator of deep processes. *Georesursy = Georesources,* 20(4), Part 2, pp. 366-376. DOI: https://doi.org/10.18599/grs.2018.4.366-376

Thermal field of the Earth among geophysical fields firstly attracted the attention of man. The most violent manifestations of geothermal activity – volcanic eruptions played an important role in the formation of mythological ideas about the structure of the world. Another form of this activity – hot springs since time immemorial have been used for household needs. But as the subject of scientific research the Earth's thermal field also became earlier than all other geophysical fields. Quantitative methods of analysis in geothermics became possible after the invention of the thermometer by Galileo in the early XVII century. Already the first measurements of temperature in mines showed that the temperature in them all year is invariable and that it increases with depth. This peculiarity of the thermal regime in the mines drew the attention of M.V. Lomonosov, who in his treatise "On the free movement of air in the mines noted" (1763-1950) wrote: "...The air in the mines at any time of the whole year retains equal dissolution" (i.e. temperature). The increase in temperature with depth indicated the existence of an upward conductive heat flow (HF), one of the two mechanisms for the removal of intraterrestrial heat.

The value of heat flow density (q), according to the fundamental law of J.-B. Fourier, is calculated as the product of the geothermal gradient and thermal conductivity (k): $q = -k\,(\mathbf{i}dT/dx + \mathbf{j}dT/dy + \mathbf{k}dT/dz)$.

In real conditions of the existence in the crust of structural and thermophysical inhomogeneities, when the horizontal components of the heat flow are not equal to zero, the deep heat flow will differ somewhat from that measured in vertical wells. This can be taken into account if the configuration of the layers and the thermal conductivity of each of them is known.

But in the overwhelming majority of cases, the approximation of a geothermal gradient only by its vertical component practically does not introduce a noticeable error in the results of observations, since dT/dz a lot more dT/dx and dT/dy. Therefore, without prejudice to the accuracy of the measurements, the HF density is determined by the formula: $q = -k \cdot grad_z T$ [mW/m^2], where k is the thermal conductivity of rocks, and $grad_z T = dT/dz$ is the vertical component of the temperature gradient measured in the depth interval opened by the mine workings. Compared with the radius of the planet, this interval is very small, so HF measurements characterize practically its "surface" value at the boundary of the solid Earth – q_s (more precisely, at the bottom of the heliothermozone, whose temperature is determined by the climatic factor). The current value of this parameter in a particular geographical point reflects the total energy effect of all past and current geological processes and thereby quantitatively limits the range of realistic geotectonic models describing the evolution of the geospheres.

Tectonic ordering of heat flow

The measured q_s value may differ from its value in the depth because of near-surface factors disturbing the geothermal field. These factors, as is well known, include

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topography of the Earth surface, the morphology of bodies with different thermal conductivity that form the geological section, the circulation of underground fluids violating the conditions of conductive heat transfer, non-stationary processes of sedimentation and erosion, as well as climatogenic temperature variations introducing geologically short-term perturbations. The data needed to quantify the effects of all these factors are rarely known in their entirety and with sufficient accuracy. But by averaging the results of particular determinations of q_s within a large homogeneous geoblock (tectonic province), the local opposite-in-sign effects of each the factors that disturb the distribution of conductive heat flow are mutually compensated to some extent. Therefore, regional average (background) estimates q_s approach the undistorted (depth) value of HF.

Analysis of such average values of q_s showed that in the continental crust, the HF decreases with age (t) of its folding (consolidation) or subsequent tectono-magmatic activation (Polyak, Smirnov, 1966, 1968; Hamza, Verma, 1969). This dependence was repeatedly tested (Sclater, Francheteau, 1970; Čermak, 1976; Kutas et al., 1976; Vitorello, Pollack, 1980; Sclater et al., 1981; and others), having received the name in English-language literature "heat flow – age dependence" (Fig. 1). The time of its manifestation in continental structures covers the Riphean-Phanerozoic stage of their history. But the relationship between heat flow and the age of the oceanic crust is no less real (Sclater, Francheteau, 1970; Smirnov, 1980).

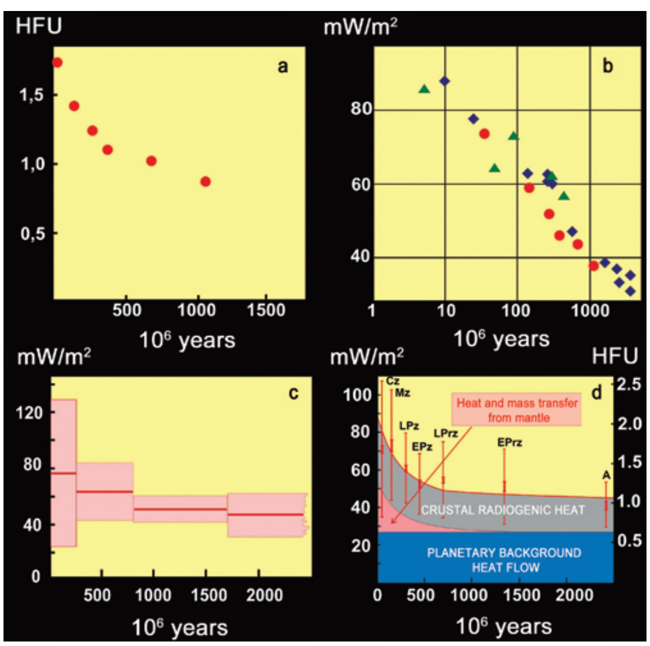

Fig. 1. Relationship of the density of the "surface" heat flow with the age of tectonic-magmatic activity in the continental crust. (a) – (Polyak, Smirnov, 1968), (b) – circles according to (a), rhombuses after (Kutas et al., 1976), triangles after (Čermak et al., 1976), (c) – after (Sclater et al., 1981), (d) – after (Vitorello, Pollack, 1980). 1 HFU is the unit of heat flow, $1{\cdot}10^{-6}$ cal/cm$^2{\cdot}$s

With the accumulation of data, the general trend in the change of HF in the continental crust was obscured by the dispersion of the particular values of q_s and the imperfection (convention) of their geochronological reference. However, the existence of a general trend was also supported by another grouping of private estimates of q_s – by the absolute age of the rocks in the areas of observation (Fig. 1c). In such samples, with a decrease in the spread of the q_s estimates, their average value, i.e. background HF value decreases as well. As a result, the reality of the relationship between q_s and t was confirmed by all later studies, including those using much more empirical q_s values – 10337 (Pollack et al., 1993) and 19775 (Vieira, Hamza, 2011).

On the continents, the "*q-t*" relationship manifests itself only when analyzing background average q_s estimates in large geoblocks, indicating the existence of temporary and relatively local heat sources in the depths. However, this relationship only shows how HF is distributed over the surface of the globe but does not explain why it is so distributed. It allows identification of deep heat sources only from the physical side, namely, traditional for geophysics by solving inverse problems, i.e. by selecting the parameters of the source that correspond to the rate of change q_s – its shape, size, depth, thermal power and time of existence (Kutas, Gordienko, 1972; Smirnov, 1972). The geological nature of the sources remained unknown. They were a priori identified with asthenospheric diapirs, and their energy effect was symbolized by a non-stationary member (Fig. 1d).

The density of the background conductive heat flow observed in the drilled depth interval is the result of a superposition of different endogenous factors, the absolute and relative effects of which are not identical at different hypsometric levels (on the surface of the crust, the Moho section, the lithosphere, etc.) and change over time. They are discussed in the next section.

Endogenic causes for the heat flow dispersion

Radioactive heat generation in the lithosphere. Almost simultaneously with the identification of the "*q-t*" dependence, another connection was found – between the "surface" values of the density of conductive heat flow (q_s) and radiogenic heat generation, RHG (A_s). The latter parameter reflects the cumulative effect of the decay of long-lived radioactive isotopes of uranium, thorium and potassium in the outcropping and/or drilled rocks. In the energy balance of the Earth, RHG is one of the sources of deep heat, weakening with time, because the half-life of ^{235}U is $0.704 \cdot 10^9$ years, ^{238}U is $4.468 \cdot 10^9$ years, which is slightly less than the age of the Earth, and ^{232}Th is $14.05 \cdot 10^9$ years (Tolstikhin, Kramers, 2008).

The extrapolation of the values of A_s into the deeper horizons of the crust led to estimates of heat loss at its upper boundary, which exceed the observed values. But the accumulation of empirical material has revealed a decrease in RHG along the depth, as well as its regional differences in the form of correlation dependences having the look $q_s = A_s \cdot D + q_{red}$ (Roy et al., 1968; Sass et al., 1981; etc.) In these dependencies D characterizes the rate of A_s descending along the depth (the lower D is, the faster this speed is), determining the thickness of the layer in which the overwhelming majority of radiogenic heat is released. The q_{red} parameter is the so-called "reduced heat flow" coming from below to the bottom of this layer (Khutorskoy, Polyak, 2016; etc.).

When analyzing these dependencies, the negative correlation "A_s-t" similar to "q-t" relationship, where t notes the geological age of tectono-magmatic activity (TMA), was observed. The "A_s-t" connection became to be considered as a reflection of the regional scale of erosion of the continental crust after its consolidation (stabilization), which removes its upper parts richest with radioelements from the geological section of this geoblock. Although the geothermal effect of this phenomenon is qualitatively indisputable, implying a decrease in q_s, its quantitative estimates are contradictory. Thus, according to the results of a study of 28 regions of different continents, the A_s value decreases with increasing age of the last tectonic thermal event (the last phase of TMA), as shown in Fig. 2.

This was attributed to the influence of erosion of the crust, which reduces the geothermal effect of RHG over 1600 million years by half. But the removal of material from the surface into sedimentary basins occurs much faster. With an average erosion rate of 0.5 mm/year, the 10-kilometer layer of the Earth crust will erode over 20 million years, so that the effect of erosion in the Paleozoic and more ancient folded belts in estimating the share of radiogenic heat generation in the structure of HF can be ignored. In addition, erosion of the continental crust can create not only negative anomalies of the background HF, but also positive ones due to the shortening of the distance between the supposed source of heat and the heliothermozone bottom.

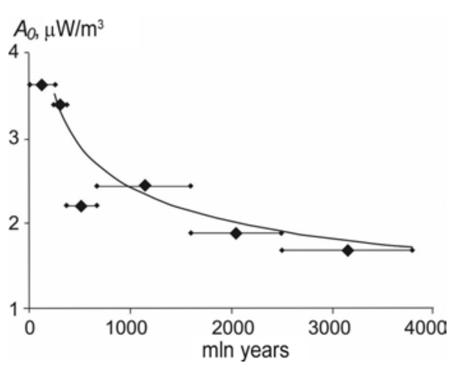

Fig. 2. Radiogenic heat generation (A_0) on the surface of the continental crust (Vitorello, Pollack, 1980)

But RHG is capable of determining local positive anomalies of HF. A striking example is the enriched uranium Hercynian granite plutons of the Cornwall peninsula in southwestern England (Table). In them, the density of the ascending conductive heat flow is 104-128 mW/m² (Gregory, Durrance, 1987), which is much higher than the average for the UK 55 mW/m² (Wheildon et al., 1980).

Cornwall batholiths	Number of HF measurements	Average value of q and average ± σ, mW/m²	Heat generation, μW/m³
Carnmenellis	10	115±7	4,0±0,5
Bodmin	5	116±5	4,2±0,9
Lands End	3	125±3	5,1±0,2
Saint Austell	2	126±0,5	4,2±0,9
Dartmoor	6	113±9	5,3±0,5

Table. Heat flow and heat generation in Cornwall batholiths (Gregory, Durrance, 1987)

In general, despite the long-term study and the undoubted geothermal significance of RHG in rocks, it cannot explain the trend of decreasing background conductive heat flow established in the Phanerozoic folded regions of the continental crust.

Tectonic movements

After the discovery of the q-t bond, some geologists assumed that the cause of the increase in heat flow in tectonically mobile belts as compared with stable areas of the crust is its frictional heating during tectonic movements. At the same time, the root causes of these movements themselves and their role in the planetary energy balance were not discussed. But in themselves, tectonic movements need an external source of energy, representing the movement of mountain masses, during which the heat accumulated in them is also transferred.

In young mobile belts, vertical motions create geothermal anomalies of a different signs. Positive anomalies can occur, not counting those caused by friction in the narrow contact zones of the displaced blocks, at relatively rapid erosion of uplifting arrays heated more strongly than their surroundings. Negative anomalies are formed during descending movements, accompanied by the accumulation of sediments and their heating up to temperatures corresponding to the geothermal background at the depth of their subsidence. Subhorizontal movements, which provoke the formation of thrusts in collision situations, also create negative thermal anomalies due to shielding of the deep heat flow by subducting slabs. Tectonogenic geothermal anomalies (except for local frictiogenic) are much longer-lived then those caused by near-surface "distorting" factors. According to (Khutorskoy, 1996), the decrease of q_s in the Pliocene-Quaternary foredeeps and intermontane depressions, downwarping at ~1 mm/year, is felt for the first tens of millions of years, while the negative thermal anomalies arising from the thrusting of large plates of the lithosphere in linear folded belts (Ural, Appalachians, etc.), do not have time to fully relax even for hundreds of millions of years (Fig. 3).

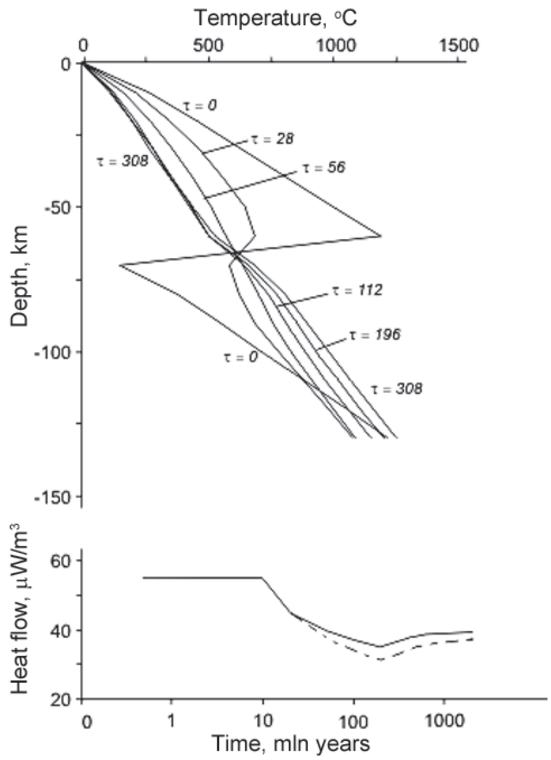

Fig. 3. The change of the geothermal field in the conditions of thrust under the boundary conditions of the second kind at the lower boundary (Khutorskoy, 1996). Above – temperature change after the formation of a thrust in time τ; below – the change in heat flow in time, taking into account (solid line) and excluding (dashed line) heat release at phase transitions

Magmatism. This phenomenon is related to the second transport mechanism of deep heat – heat and mass transfer, which, unlike thermal conductivity, consists in the transfer of heat when the heat carrier moves. It is implemented mainly in the convective currents of the mantle. In the crust it accompanies intrusions of deep melts and ascending tectonic movements. As follows from geological observations, in almost any block of the continental crust, tectono-magmatic activity (TMA) was manifested repeatedly. The multistage nature of magmatic activity in a specific geoblock indicates the sequential manifestation of several deep-seated heat impulses in geoblock, each of which influenced the geothermal field. The age of one or another phase of magmatism reflects only the time of the impulse, but does not characterize its power. It is unclear to what extent this power is reflected by the exposure of intrusive bodies – manifestations of latent discharge of deep melts in a given geological epoch, and all the more volumes of volcanics – traces of open discharge of such melts on the surface of the crust, effaced by subsequent erosion. However, multi-temporal and/or multi-scale mantle pulses responsible for individual phases of magmatic activity in different regions of one tectonic province created different HF values in these regions in the upper horizons of the geological section, i.e. the variance of the private values of q_s. Accounting for this effect could minimize the dispersion of local values of q_s attributed to the same stages of geological history and explain their estimates in geoblocks affected by several heat impulses (M_1, M_2, ...) in certain geological epochs (t_1, t_2 ...). The q_s values should also depend on the morphology and depth of each intrusion and generally reflect the cumulative effect of all consecutive pulses in one area, so quantitative estimates of the geothermal effect of individual pulses are unlikely.

At the same time, the effect of open discharge of the mass flow from the mantle in the form of evacuation of intraterrestrial heat immediately into the atmosphere can be more or less accurately evaluated by mapping the products of volcanism. Such estimates, which differ in different areas, to a certain extent reflect the energy potential of the interior. Considering that "... systems of volcanic areas have a clearly expressed linear structure ... with a length of thousands of kilometers ..." (Luchitskii, 1979, p. 5), for such a comparative analysis it is most objective to use estimates of "linear" productivity of volcanism in km³/km·year (or t/km·year). In this way, the geoenergetic specifics of various tectonic settings are clearly revealed (Fig. 4).

The same approach to the analysis of the history of individual areas of the region of modern volcanism

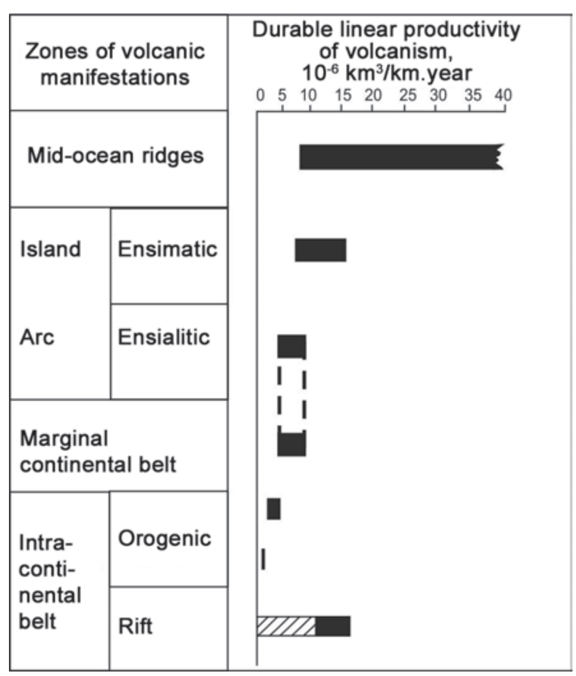

Fig. 4. Linear productivity of volcanism in different tectonic conditions (Polyak, 1988)

allows us to establish both regular variations in the intensity of volcanism over time and its variations along the strike of mobile belts (Fig. 5, 6).

So, Figure 5 shows the inadmissibility of extrapolating data on the productivity of volcanism in a geologically short period (the maximum in Kamchatka during the Holocene) for a much longer period (for example, the Pleistocene period in the same Kamchatka). But the intensity of volcanism is no less variable along the strike of its linear belts in the same stages of their history. For example, in Kamchatka, the total (taking into account the effect in each of the areas of volcanic activity) linear productivity, or thermal power of Quaternary volcanism varies more than three times along the strike of the peninsula. This is clearly seen in Fig. 6. The peak of this power is confined to the segment of the peninsula where the Klyuchevskaya group, the main supplier of volcanism products on the peninsula, is located and practically coincides with the peak of heat outflow by hydrotherms, including the largest Uzon-Geyzernaya hydrothermal system. North of this "high-energy" segment of the peninsula, the maximum frequency of earthquakes in the period 1906-1967 is noted, which indirectly indicates the heterogeneity of the geothermal field along the Kamchatka strike. This segment of the peninsula lies on the strike of the Aleutian arc, and the oldest segments of the Imperial Range adjoin it, which, in combination, speaks of its geodynamic specificity.

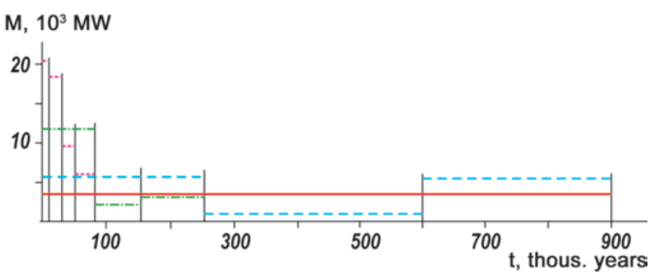

Fig. 5. The thermal power of Kamchatka volcanism in different time-intervals of the Quaternary period (Polyak, Melekestsev, 1979)

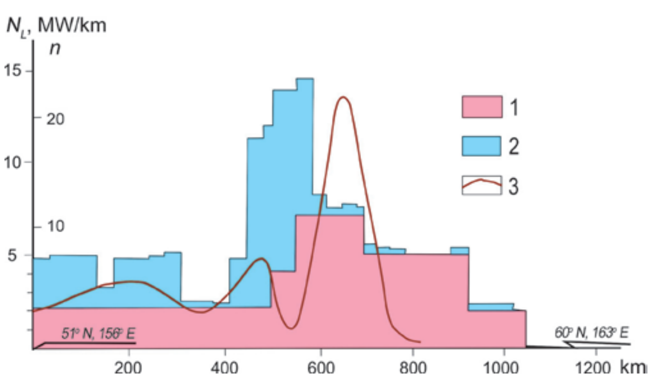

Fig. 6. The distribution of convective loss of the intraterrestrial heat (the effect of open discharge of heat and mass fluids from the depths) along the strike of the Kamchatka peninsula (Polyak, Melekestsev, 1979). 1 – the effect of volcanism, 2 – the effect of discharge of hydrotherms, 3 – the frequency of earthquakes (n) in the period 1906-1967 according to (Tokarev, 1970)

Hot spots and singularity of HF. The discovery of a global system of mid-ocean ridges (MOR) gave rise to the concept of plate tectonics. Divergent boundaries of the plates representing most of the spreading zone of the seabed, are distinguished not only by volcanic and hydrothermal activity, but also by the maximum particular values of the density of conductive HF. These values in the axial valleys of MOR (Gulf of California, Red Sea) are much, an order of magnitude or more, higher not only typical of ancient abyssal basins, but also measured in island arcs and marginal mainland mobile belts. The solution of the inverse problem of geothermics in such zones shows that the surface of the fractional melting of the mantle material coincides with the bottom of the oceans. This creates an idea of the singularity of HF in these zones (Lyubimova et al., 1976).

But the values of q_s are almost as great in the other tectonic settings, for example, in the zones of destruction of the continental crust or in the zones of areal (diffuse) spreading. As shown by field observations (Fig. 7), on

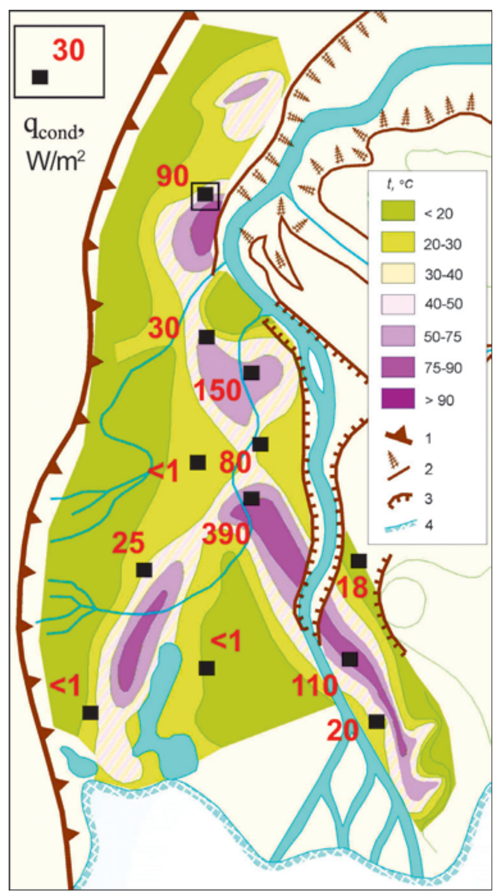

Fig. 7. Temperature variations at a depth of 20 cm and conductive heat flow density (W/m²) on the surface of the Bottom fumarole field in the Lower (northeast) crater of the Mutnovsky volcano (Kamchatka) according to (Muravyev et al., 1983). Measurement points are black squares, the digit beside is the measured q_s value in W/m²

land such and even higher q_s values characterize the sites of high-temperature hydrothermal system discharge and the fumarole fields of active volcanoes, i.e. in the areas where the heliothermozone is pinched out.

Besides the MOR, in the World Ocean there are volcanic ridges of other origin, which are formed when plates move relative to the mantle sites, which are considered to be fixed and called “hot spots” (HS) or “mantle plumes” (MP). The first name does not give an idea of the cause of this phenomenon, since this name is suit for any active volcanic apparatus, around which the deep temperatures gradually decrease. But the latter adequately determines the geodynamic nature of such points (Morgan, 1971) and is therefore preferable. According to modern concepts at such points the melts rise from layer D” on the border of the lower mantle with the outer core (Tolstikhin, Kramers, 2008), forming a chain of volcanic edifices on the ocean floor, as in the Hawaiian-Imperial Ridge – a tectonotype of similar structures (Wilson, 1963; Morgan, 1971).

In the south-eastern end of the Hawaiian Ridge (Fig. 8), volcanoes erupted 5.6-3.8 million years ago (Kauai Island), 3.3-2.2 (Oahu Island), 1.8-1.3 (Molokai Island), <1 – present time (Maui), 0.7 – present time (Hawaii Island). On the southern submerged slope of Hawaii is the currently active volcanic apparatus Loihi Seamount.

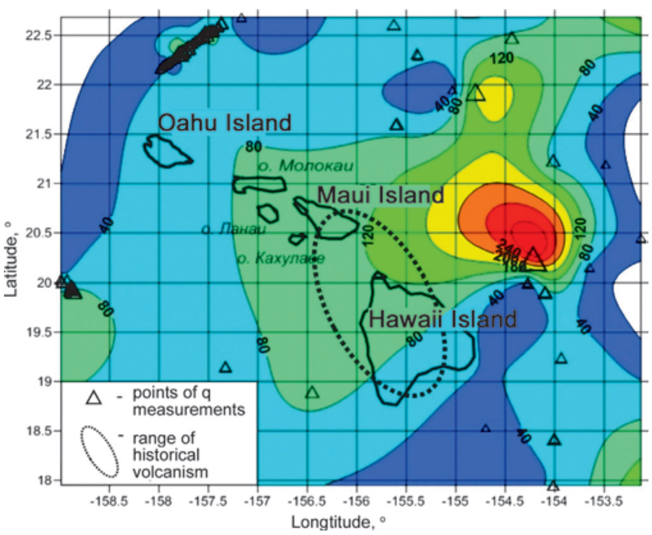

Fig. 8. Density of conductive heat flow and the range of volcanism in historical time in the south-east of the Hawaiian archipelago. Triangles – points of heat flow measurements by (Von Herzen et al., 1989)

In general, the area of recent volcanism extends from Hawaii Island far northwest. It includes not only Haleakala volcano (Maui Island) erupted in 1750, but also underwater volcanoes that erupted in the twentieth century: on the northern slope of Oahu Island (~1906) and in the points with coordinates 21° 39’N – 158° 51’W and (outside Fig. 8) 23° 35’N – 163° 50’W (Gushchenko, 1979).

The connection of mantle plumes with positive anomalies of the heat flow is ambiguous. In the southwest of the Hawaiian Ridge, this connection seems obvious, although in this case the maxima of the HF values are shifted to the northeast relative to the position of active volcanoes (Fig. 8). The latter, however, seems to be the result not so much of a real discrepancy between the material and geothermal traces of the mantle plume discharge, but rather conventional character of HF mapping at limited number and uneven distribution of measurement stations in this part of the Pacific Ocean. But in other places (Yellowstone, Afar) such a relationship is not expressed (probably due to the large influence of various factors distorting the heat flow in the continental crust).

The formation of the seabed as a result of the mantle material discharge is manifested not only in the MOR (axial spreading), but also in almost all back-arc basins, or marginal seas (diffuse spreading). As a rule, these zones are also characterized by an abnormally high heat flow. The geothermal anomaly is most pronounced and well studied in the Tyrrhenian basin (Della Vedova et al., 1984). In different parts of this basin the geodynamic situation is not the same: its western part is characterized by compressive stresses, from Tortonian time up to now whereas the eastern part over the same 11 million years is stretching (Khutorskoy et al., 1986). This eastern part of the Tyrrhenian Sea is a region of high heat flow, large horizontal temperature gradients and submarine basalt volcanism (Fig. 9).

The maximum HF values 515 and 490 mW/m^2 were measured in the rear part of the Aeolian island arc, whereas in this part of Tirrenian Sea the mean HF value is equal 155 mW/m^2. The thickness of the “thermal” lithosphere in the eastern part of the Tyrrhenian Sea was estimated as 17-23 km (Khutorskoy et al., 1986).

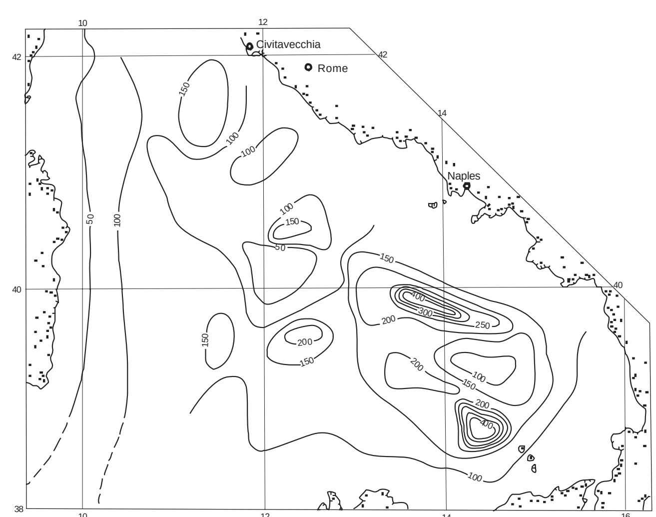

Fig. 9. Map of heat flow in the bottom of the Tyrrhenian Sea. The value of isolines is mW/m^2 (according to data (Della Vedova et al., 1984) with the addition of authors)

The same estimations of the "thermal" lithosphere were obtained in the MOR vicinities.

The high heat flow, basaltic volcanism and low thickness of the lithosphere of the Tyrrhenian basin indicate the introduction of mantle material, which "wedged out" the previously existing blocks. These blocks apparently had a reduced viscosity due to the increase in temperature at their sole and, as a result, did weakly resist the intrusion of the substance. Thus, high heat flow marks areas of ascending advection of mantle material.

Another vivid example of the penetration of mantle material into the upper horizons of the crust is the area of destruction of the continental crust in the north of the Svalbard Plate. In this part of the Barents Sea, the object of our research was the Orly trough (or Störe trough) extending from the archipelago of King Charles in the south to the beginning of the continental slope of the Nansen basin in the north (Fig. 10). The trough is a hollow of meridional strike ~ 50 km wide and almost 200 km long. The height of its sides is up to 400 m, and the bottom lies at depths of 470-520 m and even deeper on the continental slope. In the trough and on its continuation within the continental slope, 28 measurements of heat flow density were carried out from the R/V "Akademik Nikolai Strakhov". Their results were to be unexpected: the HF values ranged from 300 to 520 mW/m^2 (Khutorskoy et al., 2009). Such values are almost 10 times higher than the level of background heat flow through the bottom of the Barents Sea and are similar to the observed in the axial zones of MOR.

An abnormally high heat flow is observed in the whole Orly trough and in its continuation on the continental slope up to the isobath 1200 m (Fig. 10). Extrapolation of temperatures to the lower half-space shows that subsolidus temperatures can be met at a depth of 6.5-7.0 km below the sea floor in the trough (Fig. 11).

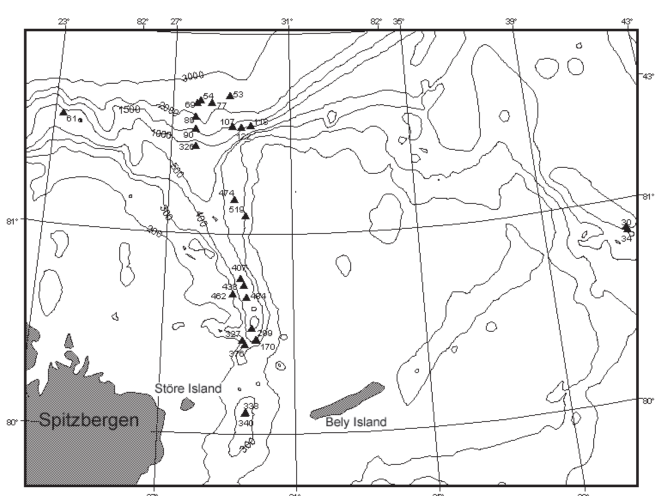

Fig. 10. Heat flow in the Orly (Störe) trough. Values of heat flow are in mW/m^2. The isobaths were carried out 100, 200, 400, 500, 1000, 2000 and 3000 m

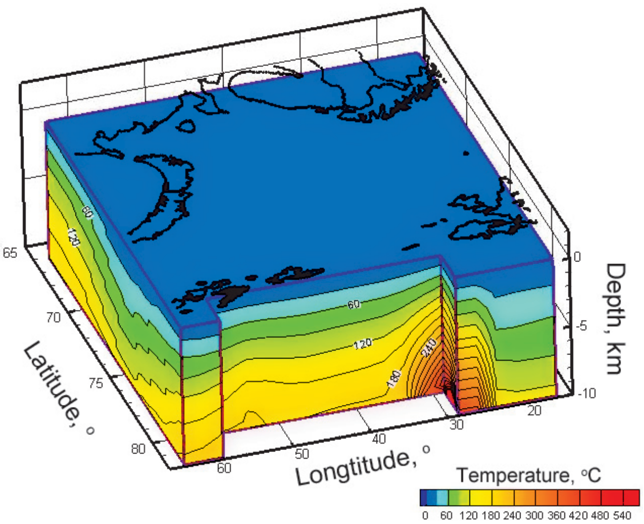

Fig. 11. 3D geothermal model of the Earth's crust of the Barents Sea, view from the north (Khutorskoy et al., 2009)

This suggests the destruction of the continental crust over its entire thickness and the penetration of the hot (mantle?) substance into the basement and, possibly, into the lower layers of the sedimentary cover. At the same time the material signs of disharge of the deep heat and mass flow on the bottom do not found.

The morphology of the trough and especially the geothermal data obtained there for the first time show that this structure has a tectonic nature. Most likely, this is a rift, which has cut the Earth's crust to its full capacity and is now in the active phase of development.

The material nature of the heat and mass transfer from the depths

So, the conductive heat flow observed in the continental block is formed by a complex superposition of non-stationary processes, different in nature, localization, scale and rate of manifestation.

How realistic is the view explaining the *q-t* dependence in the continental crust on the relation between the distribution of the density of conductive heat flow on the continents and the invasion of the asthenosphere diapirs into the lithosphere? Although this view was justified by the fact of volcanic (open) discharge of deep melts in tectonically mobile belts with a conductive HF increased relative to the continental background, it remained quite natural, but an assumption. This hypothesis could be proved only by the detection of direct material (substantial) signs of the presence of mantle derivatives in such zones of high geothermal activity. However, attempts to detect these signs, i.e. juvenile, according to E. Suess (1831-1914), components in the elemental composition of igneous rocks, volcanic emanations, or groundwater were unsuccessful, since the entire set of chemical elements is present both in the mantle and in the crust. The problem was solved only with the help of isotopic studies.

An unequivocal geochemical sign of the presence of juvenile substance in crustal objects turned out to be the isotopic composition of helium in freely circulating underground fluids, since this composition is different in different geospheres due to the presence of genetically different components in terrestrial helium. One of them is radiogenic He, formed in the Earth due to the decay of U and Th; in this helium the ratio between the concentrations of light and heavy isotopes, $^3He/^4He = R_{rad} \sim (2 \pm 1) \times 10^{-8}$. The other component arose during the formation of the Universe, is generated by thermonuclear reactions in the depths of the stars and therefore is present in the "solar wind", which irradiated protoplanetary matter during the formation of the Solar System. It is such a helium, in which the $R_{SOLAR} = \sim 1 \times 10^{-4}$ was captured by the Earth during its accretion (Tolstikhin, Kramers, 2008).

As it turned out, traces of solar helium (about 10% of its initial quantity due to constant dissipation into near-Earth space) are still preserved in the Earth's mantle and are present even in today's atmosphere, where $R_{ATM} \approx 1.4 \times 10^{-6}$ (Mamyrin, Tolstikhin, 1981) with a very low concentration of He (5.24×10^{-4} % vol.). But since $R_{ATM} \approx 100\,R_{RAD}$ (R_{RAD} is often referred to as R_{CRUST}), the contamination of crustal gases with air helium exaggerates the estimate of R. But the "superatmospheric" values of R in terrestrial gases (and rocks) clearly indicate the presence of solar helium in such objects, which today on Earth could be preserved only in the mantle.

At the present stage of the evolution of the Earth, the maximum values of R in free underground fluids are observed in the products of volcanism both on land and in the World Ocean. In the mid ocean ridges system the R values almost the same in the bottom basalts and submarine hydrotherms ("smokers"), averaging $^3He/^4He = (1.15 \pm 0.1) \times 10^{-5}$ (Marty, Tolstikhin, 1998). This value was taken as the global characteristic for the reservoir of MORB (mid oceanic ridge basalts). But in the areas of mantle plumes (Afar, Yellowstone, etc.) the magnitude of this ratio is even greater, so $R_{MP=HS} > R_{MORB}$. It reaches its maximum in Iceland. In its north-western peninsula in the gases of one of the thermal springs, the value $R_{MP} = 3.45 \times 10^{-5}$ was measured in 1973 (Kononov, Polyak, 1977). Later, in the gases of a neighboring source, an even higher R_{MP} value $> 4.2 \times 10^{-5}$ was measured (Hilton et al., 1998), and also similar (3.36×10^{-5}) in the basalts of Iceland (Condomines et al., 1983).

The discovery of traces of solar helium on Earth (Mamyrin et al., 1969; Clarke et al., 1969) occurred almost synchronously with the discovery of the pattern of distribution of conductive heat flow in the continental crust. The obvious importance of this discovery stimulated the rapid development of regional isotope-helium researches. As a result, it turned out that the distribution of the $^3He/^4He$ ratios in the free underground fluids of the continents showed the same tectonic ordering as the distribution of the background conductive heat flow (Polyak et al., 1979a). This analogy is observed both in regional and pan-regional scales. Europe is one of the largest areal manifestations of the conjugate variability of both parameters (Fig. 12).

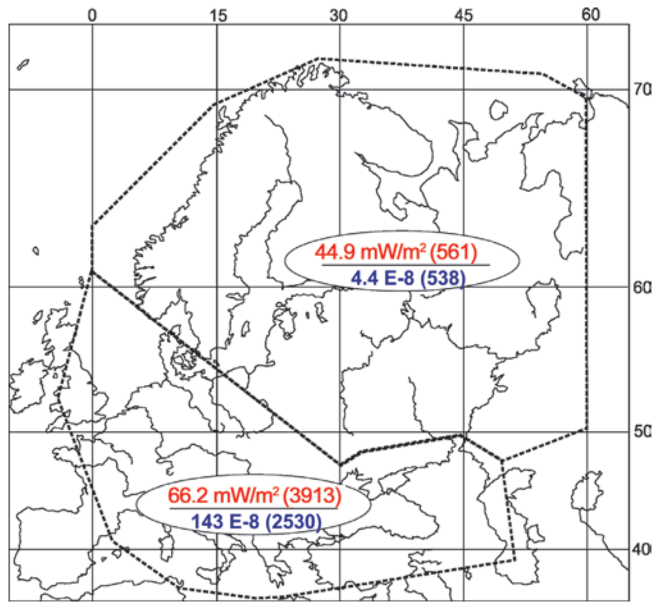

Fig. 12. Average values of conductive heat flow density (q, mW/m², numerator) and helium isotope composition in underground fluids (³He/⁴He, E-8, denominator) in the "pre-Riphean" and "Phanerozoic" parts of Europe. In brackets – the number of measurements in polygons, limited by a dotted line. The average R values in these samples differ by 30 times, whereas the average q values are differ only one and a half times

The linear manifestation of the $^3He/^4He$ and *q* bond in the Andes mountain chain is just as clear (Fig. 13).

The relationship of the isotopic composition of helium in underground fluids and the background conductive heat flow in the continental crust indicates a common cause of their variations, i.e. intake of deep heat and juvenile substance marked with mantle helium into the crust. Some researchers postulate the possibility of an autonomous flow of volatile from the depths that is not supported by magmatism. However, the carrier of mantle helium is of a different nature, which was revealed by related investigations of the isotopic compositions of He and Sr in the products of volcanic and hydrothermal activity. The investigations showed that there is a close correlation between the values of the $^3He/^4He$ ratios in the gases of the areas of active volcanism and $^{87}Sr/^{86}Sr$ in its solid products. It was discovered after determining the isotopic composition of helium in the gases of volcanoes and hydrotherms in

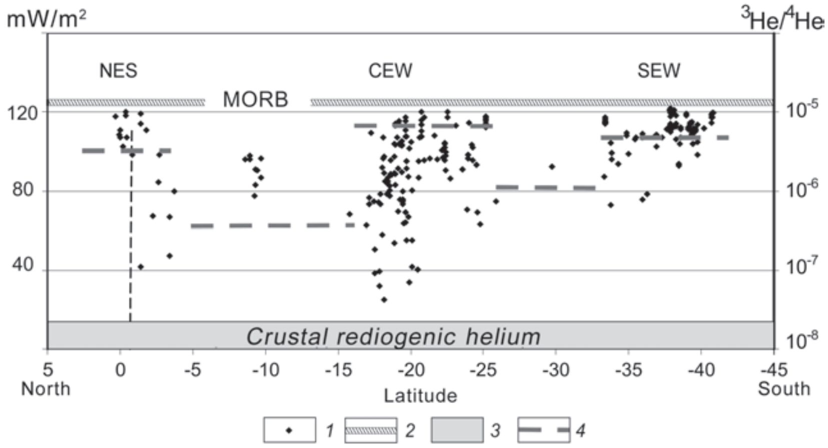

Fig. 13. Relationship between regional conductive heat flow (q) and the composition of helium in gases of volcanoes and hydrotherms in the Andean belt by (Newell et al., 2015; Hamza, Muños, 1994). NVZ, CVZ and SVZ are Northern, Central and Southern volcanic zones. 1 – $^3He/^4He$ measurements in the gases of volcanoes and hydrotherms, 2 – He isotopic composition in the MORB reservoir, 3 – the same, in the ancient continental crust, 4 – q (mW/m²)

the Apennine peninsula and Sicily Island and comparing it with the composition of strontium in N_2-Q volcanites, which are common in the same areas. The participation of the mantle and crustal components is evident in the compositions of both elements (Fig. 14). The proportion of mantle strontium decreases to the north along the Apennine peninsula and is consistent with an increase in K_2O content in volcanic rocks, thus characterizing the specificity of the Pliocene-Quaternary igneous reservoirs in Italy (Polyak et al., 1979b).

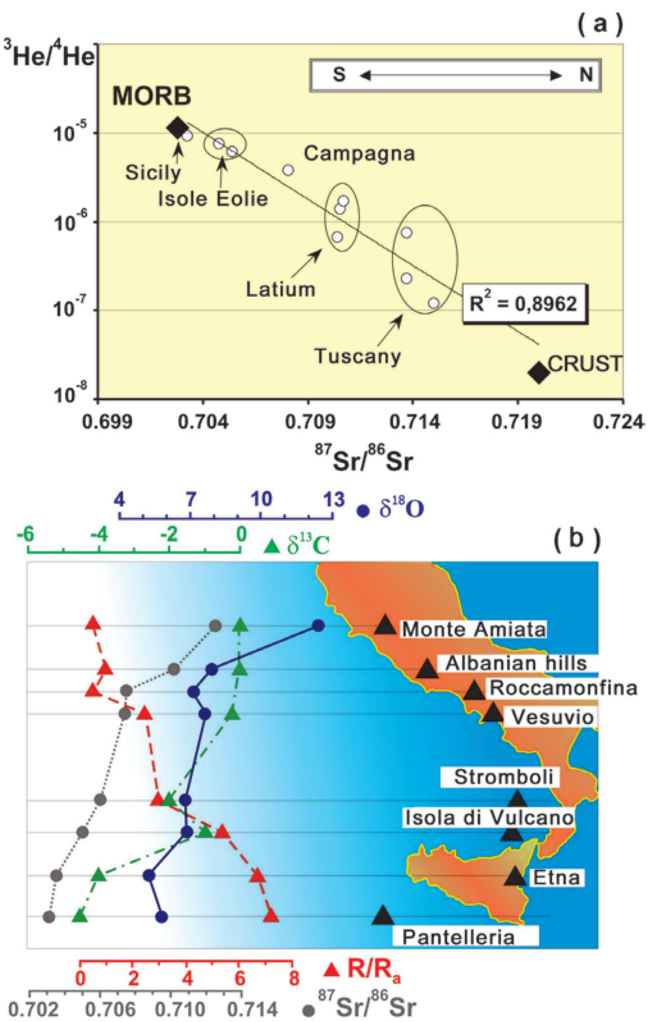

Fig. 14 Relationship of He and Sr isotopic compositions in geothermal activity products in Italy: (a) according to (Polyak et al., 1979b), (b) according to (Parello et al., 2000)

This relationship of He and Sr isotopic compositions in geothermal activity products was confirmed once more in Italy (Parello et al., 2000), and found out in the island arcs of Indonesia (Hilton, Craig, 1989) and other parts of the world. It clearly indicates the transfer of volatile He and Sr into the crust from the mantle by a common carrier agent constituting a silicate substance.

Thus, the "surface" density of conductive heat flow, q_s, and the isotopic composition of helium in geological objects, $^3He/^4He$, respectively, characterize both sides of the heat and mass transfer process in the geological environment – its energy (geothermal) and material (geochemical) aspects. These parameters, as two sides of the same coin, are related by the most important common feature: internally caused variability in time. Therefore, a joint analysis of q and $^3He/^4He$ plays a key role in solving the problems of the evolution of the Earth.

Acknowledgements

The work was carried out as part of the State Budget Theme No. 0135-2015-0021 with the financial support of the Programs of the Presidium of the Russian Academy of Sciences No. 47 and 49.

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Manuscript received 20 July 2018;
Accepted 16 September 2018;
Published 30 November 2018