ANNALS OF GEOPHYSICS, VOL. 48, N. 1, February 2005

Heat and mass transfer from the mantle: heat flow and He-isotope constraints

Boris G. Polyak
Geological Institute, Russian Academy of Sciences, Moscow, Russia

Abstract
Terrestrial heat flow density, *q,* is inversely correlated with the age, *t*, of tectono-magmatic activity in the Earth's crust (Polyak and Smirnov, 1966; etc.). «Heat flow-age dependence» indicates unknown temporal heat sources in the interior considered *a priori* as the mantle-derived diapirs. The validity of this hypothesis is demonstrated by studying the helium isotope ratio, $^3He/^4He = R$, in subsurface fluids. This study discovered the positive correlation between the regionally averaged (background) estimations of *R*- and *q*-values (Polyak *et al.*, 1979a). Such a correlation manifests itself in both pan-regional scales (Norhtern Eurasia) and separate regions, *e.g.*, Japan (Sano *et al.*, 1982), Eger Graben (Polyak *et al.*, 1985) Eastern China rifts (Du, 1992), Southern Italy (Italiano *et al.*, 2000), and elsewhere. The *R-q* relation indicates a coupled heat and mass transfer from the mantle into the crust. From considerations of heat-mass budget this transfer can be provided by the flux consisting of silicate matter rather than He or other volatiles. This conclusion is confirmed by the correlation between $^3He/^4He$ and $^{87}Sr/^{86}Sr$ ratios in the products of the volcanic and hydrothermal activity in Italy (Polyak *et al.*, 1979b; Parello *et al.*, 2000) and other places. Migration of any substance through geotemperature field transports thermal energy accumulated within this substance, *i.e.* represents heat and mass transfer. Therefore, only the coupled analysis of both material and energy aspects of this transfer makes it possible to characterise the process adequately and to decipher an origin of terrestrial heat flow observed in upper parts of the earth crust. An attempt of such kind is made in this paper.

Key words *heat flow – helium isotope ratio – geothermal energy – mass transfer*

1. Heat flow-age dependence

A long time ago, regional research showed that the background (regionally averaged) values of conductive heat flow density, *q,* are inversely correlated with the age, *t*, of tectono-magmatic activity in both continental and oceanic crust (Polyak and Smirnov, 1966, 1968; Hamza and Verma, 1969; Sclater and Francheteau, 1970). This «heat flow-age dependence» was repeatedly checked, confirmed and refined (Cermak, 1976; Chapman and Pollack, 1976; Kutas *et al.*, 1976; Chapman and Furlong, 1977; Vitorello and Pollack, 1980; etc.). Some of the *q versus t* plots are shown in fig. 1a-d.

The accumulation of the data resulted in the growing scatter of the observable *q*-values, *i.e.* the values measured at different sites or in different depth intervals. This scatter came to shade a general trend, so that some researchers began to think that this trend was «a fantasy» (Rao *et al.*, 1982). This assumption was wrong as already shown by Sclater *et al.* (1980, 1981), who emphasised the difficulties in the geological dating of *q*-values (fig. 1c).

The scatter of the individual *q*-values observed in the continental tectonic units of the same age results from many reasons. Some of them are the factors disturbing the conductive heat flow distribution near the Earth's surface. These disturbing factors are the following: i) the topography of this surface and the contrasts in thermal conductivity of rocks (thermal re-

Mailing address: Dr. Boris G. Polyak, Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, 119017 Moscow, Russia; e-mail: polyak@ginras.ru

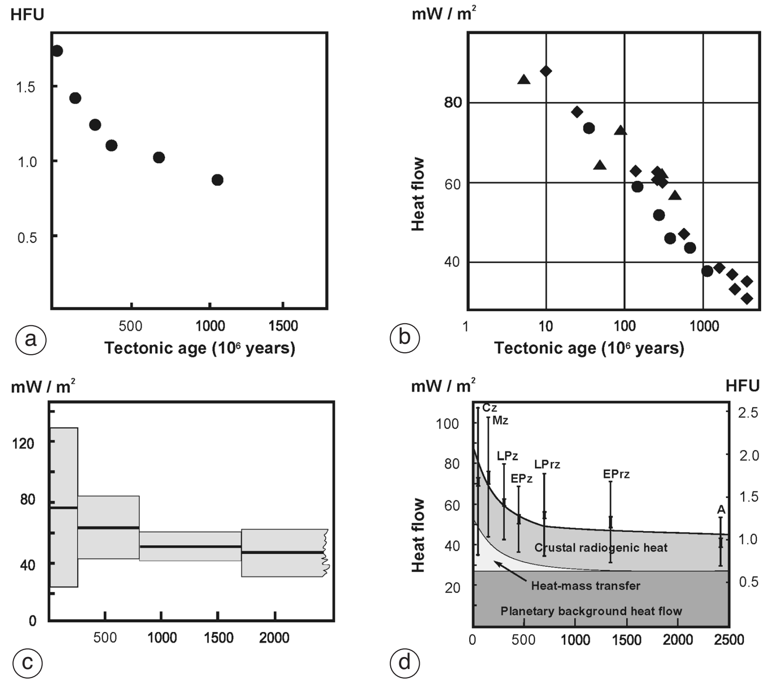

Fig. 1a-d. «Heat flow-age dependence». The plots of conductive heat flow density, q, *versus* age of tectonomagmatic activity: a) from Polyak and Smirnov (1968); b) dots from Polyak and Smirnov (1968), triangles from Cermak *et al.* (1976), diamonds from Kutas *et al.* (1976); c) reproduced from data in Sclater *et al.* (1980, 1981), the mean q-values in four age-specific provinces of continents and the relevant data scatters are shown as the lengths of straight line and shaded band, respectively; d) from Vitorello and Pollack (1980, fig.1), the data points, the standard errors of the mean and the standard deviations are shown for Cenozoic, Mesozoic, Late and Early Paleozoic, Late and Early Proterozoic an Archean provinces, the heat flow components correspond to radiogenic heat from the crust (I), effect of «transient thermal perturbation associated with tecto-genesis» (II) and background heat flow from deeper sources. HFU (heat flow unit) = 1×10^{-6} cal·s^{-1}·cm^{-2} = 41.868 mW·m^{-2}.

fraction), producing *quasi*-stationary anomalies mainly of local scales; ii) the changes in climate, *i.e.* temperature at the upper boundary of the solid Earth responsible for non-stationary anomalies; and iii) underground fluid circulation disturbing conductive heat transfer.

Besides, the abyssal heat flow can be disturbed by iv) tectonic displacements of rock masses. Heat flow anomalies of tectonic origin are similar to those generated by fluid circulation in the formation mechanism which represents advective transfer of thermal energy. These anomalies are non-stationary and, in some cases, can exist tens and even hundreds Myr (Khutorskoi, 1996).

When the individual q-values are averaged within a huge tectonic province such as Hercynides, Alpides, etc., antipodal effects of each factor can be mutually compensated to some extent. Therefore, the regionally averaged, *i.e.* background q-values approach the undisturbed values of the abyssal heat flow density.

Theoretically, thermal effects of the factors mentioned above can be quantified. However, the full set of the data needed for such calculations at each measurement site is usually unavailable. When these data are known with sufficient accuracy, the measured q-value can be corrected. These corrected individual q-values in the same region are more uniform and close to the background (abyssal) value.

There is one more reason for the local q-value scatter, namely, v) the lateral variations in radiogenic heat generation (A) in the near-surface rocks. As was shown in Roy *et al.* (1968), Lachenbruch (1970) and elsewhere, the values of q and A correlate positively with each other. At the same time, one can see some evidence for increasing A-values in the younger tectonic units (see, *e.g.*, fig. 1a-d in Pollack, 1980). The traditional concept on the downward decreasing of radioactive element abundance in the crust forces to consider the near-surface A-variations and the relevant q-variations as a consequence of the regional (local?) differences in erosion scale.

Other processes occurring within the interior (metamorphism, seismicity, etc.) are also able to distort the abyssal heat flow and, therefore, to cause a scatter in the measured q-values as well. But energy effects of these processes are difficult, if at all, to quantify because of the uncertainty of the initial data.

As a result, the relation between q- and t-values, or «heat flow-age dependence» manifests itself only when the background (average) estimations of the heat flow density in huge tectonic provinces are compared.

A cause of the dependence cannot be elucidated on the base of the heat flow data alone. The observed q-t trend discloses the presence of the unknown abyssal heat sources, which exist temporally in more or less limited fragments of the interior. The solution of inverse problems, that is a traditional approach in geophysics, cannot determine unequivocally shape, size, depth, thermal potential and residence time of such sources, allowing only to fit one or another combination of these parameters of source with the observed q-t trend. The material essence of such sources, *i.e.* their geological nature, remains a mystery.

A priori, the sources were postulated to be mantle-derived (asthenospheric) diapirs. The validity of this hypothesis can be proven only if any material evidence of mantle diapirism is found in zones of the highest heat flow. This was done by studying helium isotopes in the fluids freely circulating in the earth crust. This study discovered (i) the large difference between the values of the $^3He/^4He = R$ in the mantle, where this ratio amounts to $\sim 1.2 \cdot 10^{-5}$ in the derivatives of the MORB reservoir and up to $\sim 5 \cdot 10^{-5}$ in those of mantle plumes (hot spots) like Hawaii, Iceland, etc., and in the helium generated in the continental crust owing to radioactive decay of U and Th, where the «canonic radiogenic» R-value $\approx 2 \cdot 10^{-8}$ (see, Mamyrin and Tolstikyin, 1984, and references herein), and (ii) the positive correlation between the regionally averaged (background) estimations of R- and q-values, *i.e.*, the triple relationship between R, q and t (Polyak *et al.*, 1979a).

2. Heat flow-$^3He/^4He$ dependence

Coupled analysis of the terrestrial heat flow density, q, and the $^3He/^4He$ ratio in geologic objects (Polyak *et al.*, 1979a; O'Nions and Oxburgh, 1983; Polyak and Tolstikhin, 1985; Oxburgh and O'Nions, 1987; Polyak, 1988; etc.) is very fruitful and fully justified due to the immanent common feature of these parameters: both q- and $^3He/^4He$-values are changed in time due to cooling of the interior (heat sources) and radiogenic generation of ^4He, respectively.

This feature cardinally discriminates q and $^3He/^4He$ from any other quantitative geological, geophysical, and geochemical parameters (except for those referring to other radiogenic isotopes). Just for this reason the synthesis of heat flow and He isotope data takes on crucial importance in studying the Earth evolution.

The $^3He/^4He$ ratio values in rocks and minerals vary in a very wide range because of their genetic, structural and compositional features. However, He eventually goes away from rocks into surrounding free-circulating fluids (Gerling, 1957). There isotopic composition of He is naturally averaged in proportion to contributions from all the He-sources, and the resulting R-value represents a background characteristic of a given tectonic unit.

In itself, the presence of mantle-derived helium in underground fluids does not suggest the same origin for their other components. However, as is known, these origins can be refined due to the juxtaposition of the contents of these components with the concentration of attendant ^3He.

This approach was offered by I.N. Tolstikhin (Polyak *et al.*, 1976) and developed by H. Craig, R.K. O'Nions and other researchers in application to C-bearing gases (see, *e.g.*, Jenden *et al.*, 1993). Another fruitful approach in gas geochemistry is the juxtaposition of the *R*-values with the total helium content, (He), in gas phase of various fluids. Such analysis shows, that the variations in the ^3He / ^4He ratio reflect the mixing of crustal and mantle-derived end-members, whereas the dispersion of the [He]-values results from i) solubility-related fractionation of He and other gases in gas-water system and ii) generation or consumption of other gases (CO_2, CH_4, N_2) serving as He-carriers in the earth crust.

The studies of gas phase in various underground fluids (waters, hydrocarbons, volcanic emanations, etc.) have revealed i) an extremely wide spectrum both of the contents of He isotopes and the *R*-values and ii) tectonic ordering of the *R*-variations (fig. 2). The similar spatial variability of He isotopic composition in underground fluids and background conductive heat flow density stimulated to study the *q*-*R* relation.

Indeed, the *q*-*R* dependence was found out firstly as an inter-regional direct correlation on the territory of the FSU and Northern Eurasia as a whole (fig. 3a,b). Then the regional manifesta-

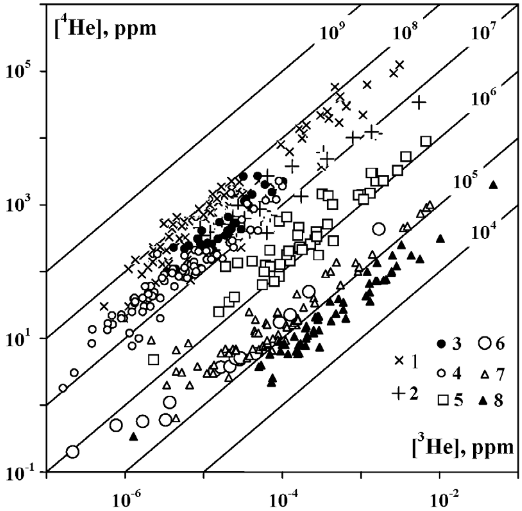

Fig. 2. The relation between the contents of [^3He] and [^4He] in subsurface fluids freely circulated in rocks (from Mamyrin and Tolstikhin (1984), added). 1 – pre-Ryphean Eastern European Platform, EEP; 2 – the EEP parts re-activated in Ryphean-Paleozoic; 3 – Baikalides (Timan-Pechora province); 4 – Hercynides (Scythian Plate, SP); 5 – the SP parts re-activated in Cenozoic; 6 – Hercynian Central French Massif re-activated in Cenozoic; 7 – Italian volcanic areas; 8 – Iceland hot spot.

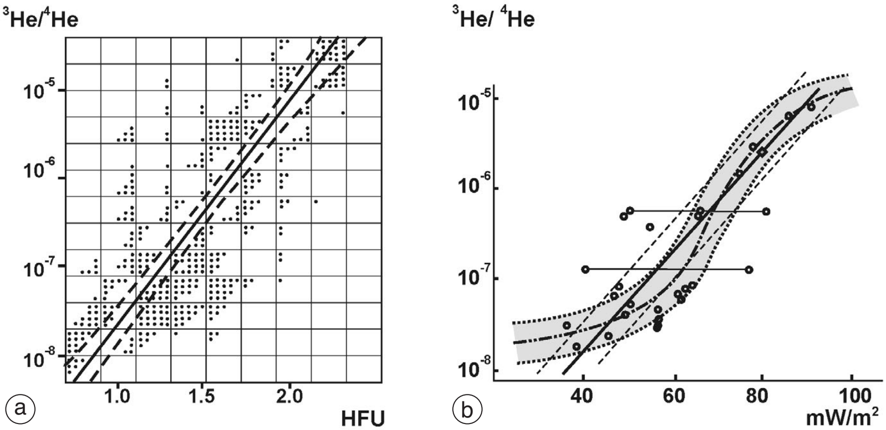

Fig. 3a,b. Heat flow - $^3He/^4He$ dependence, inter-regional juxtapositions. a) the plot of individual $^3He/^4He$ values *versus* background heat flow density in the FSU area from (Polyak *et al.*, 1979a); b) the relation of background $^3He/^4He$ and heat flow density values in different tectonic units of the Northern Eurasia from (Polyak, 1988).

tions of this dependence were demonstrated for Japan (Sano *et al.*, 1982), the Ohrje and Baikal rifts, Eastern Carpathians, Northern Caucasus (Polyak *et al.*, 1982, 1992, 1999, 2000), the eastern China rift system (Du, 1992) and Italy (Italiano *et al.*, 2000). This dependence is a typical paragenetic relation reflecting geophysical and geochemical consequences of the same cause: discharge of the ascending heat-mass flux transferring the mantle-derived helium and an excess of thermal energy to the Earth surface. What is a mechanism of this process? What is an agent of this coupled transfer?

Although helium is second only to hydrogen in thermal capacity, such an agent cannot consist of He alone, since its output from the interior is negligible in mass: the total flux of terrestrial ^{4}He to atmosphere is estimated as low as ~10^{10} atom·m^{-2}·s^{-1} (Ozima and Podosek, 1983) or even lower (O'Nions and Oxburgh, 1988).

Heat output by ascending mass flux can be quantified as excess of thermal losses, *Q*, in the flux discharge zones distinguished by higher magmatic (volcanic) and tectonic activity in comparison with stable ancient (pre-Riphean) units of continents. According to heat flow study, this excess is 40-50 mW·m^{-2} or ≥ 0.42·10^{12} W in total (Polyak, 1988). Could this *Q* really be provided by a flux of other volatiles?

$Q \geq 0.42 \cdot 10^{12}$ W could be provided by the H_2O flux with flow rate of ≥ 3 km^3/year at $\rho = 1$ g/cm^3 and enthalpy of 4180 kJ/kg ~ 10^3cal/g (similar to supercritical fluid with T~900°C). This flux would fill the World Ocean (1.37·10^9 km^3) for a period no longer than 430 Myr, *i.e.* during the post-Silurian time only.

Therefore, a coupled ascending flux of abyssal heat and mass marked by mantle-derived He cannot be identified as an autonomous flux of volatiles. It leads to the conclusion that such a flux consists of silicate substance. This deductive inference has empirical confirmation.

3. ^{3}He/^{4}He-^{87}Sr/^{86}Sr dependence

Such a confirmation resulted from the comparison of isotopic compositions of volatile (atmophile) He and lithophile Sr in products of the recent volcanic and hydrothermal activity. The expedience of this juxtaposition of these ele-

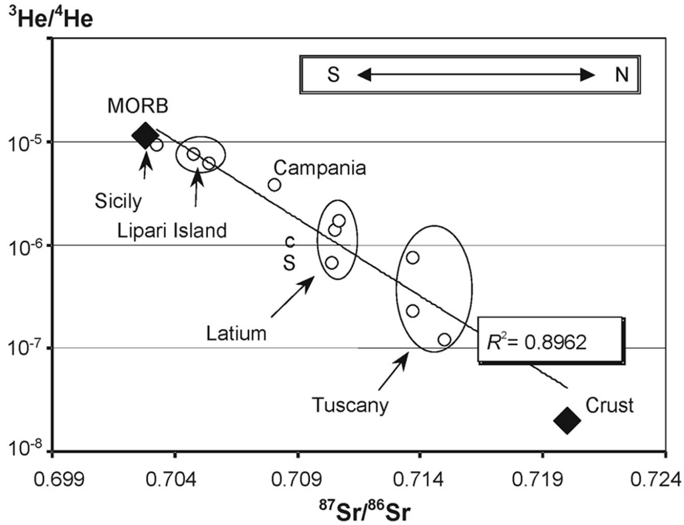

Fig. 4. ^{3}He/^{4}He-^{87}Sr/^{86}Sr dependence in the products of volcanic and hydrothermal activity in Italy (Polyak *et al.*, 1979b).

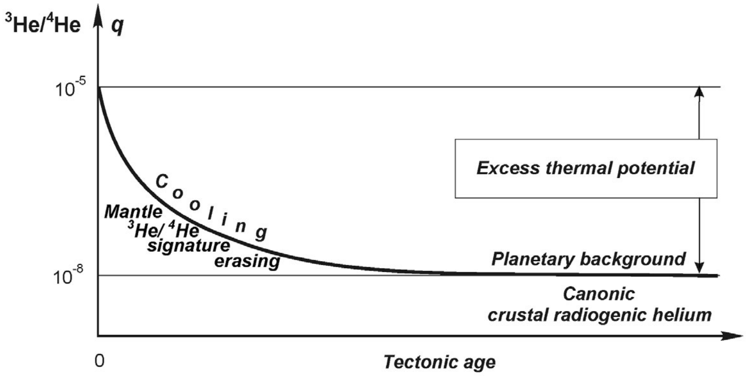

Fig. 5. The *q-t*-^{3}He/^{4}He triple relationship. See explanation in the text.

ments sharply distinguished in their properties and behaviour in the nature was already noted a long time ago by Tolstikhin *et al.* (1976). Shortly later, this approach was used in our researches of geothermal activity in Italy (Polyak *et al.*, 1979b). The comparison of the values of the ^{3}He / ^{4}He ratio in gases issued from thermal and mineral springs in Tuscany, Latium, Campania, and Sicily with those of the ^{87}Sr / ^{86}Sr ratio in volcanics of the same areas revealed the close negative correlation of these parameters. The plot shown in fig. 4 reflects the merging of the crustal and mantle-derived components. These observations were confirmed by the following researches (Hooker *et al.*, 1985; Parello *et al.*, 2000).

The inverse correlation between the ^{3}He/^{4}He and ^{87}Sr / ^{86}Sr values in products of volcanic and hydrothermal activity is seen in other places as well: in the East Sunda and Banda island arcs (Hilton and Craig, 1989), along the Pacific margin of South America (Hilton *et al.*, 1993) and in the Caucasian segment of the Alpine fold belt (Polyak *et al.*, 2000). It may be inferred that the ^{3}He/^{4}He-^{87}Sr/^{86}Sr correlation indicates the coupled transfer of these elements from the mantle into the crust.

The only agent capable of transporting both atmophile He and lithophile Sr is silicate matter. So, this conclusion supports the above mentioned postulate on relation of *q*-variations with intrusions of mantle-derived substance into the crust.

4. The coupled *q*-^{3}He/^{4}He evolution

The mantle-derived intrusions create the excess thermal potential in activated zones of the crust (fig. 5). This potential provides both enhanced heat losses observed in these zones and structural and metamorphic transformations of the interior. Subsequently, an unspent remnant of thermal energy is evacuated from the interior through overlying sequences by weakening conductive heat flow.

At the same time, the mantle signature of He, issued from cooling intrusive bodies into circumambient fluids, becomes erased gradually by generation of ^{4}He within the crust at constant dissipation of earth helium in the atmosphere and then in cosmic space. Eventually the mantle-derived matter «forgets» its origin.

5. Geothermal «age» of the continental crust

The triple *R-q-t* relationship supporting the above mentioned *a priori* postulate on asthenospheric diapirs, showed that the *q*-values measured near the Earth's surface could partially relate to the mantle-derived thermal impulses manifested in tectono-magmatic activity as well. Geological observations show that this activity manifested itself repeatedly in the history of almost any block of the continental crust. The recurrence of this activity in separate geoblocks indicates several subsequent mantle-derived impulses. Each of these impulses would influence the thermal state of the interior. The age of one or another tectonic phase dates the relevant impulse, whereas the impulse magnitude, *i.e.* rock mass and thermal energy accumulated in them, remains obscure. It is known, however, that the intensities of synchronous tectono-magmatic activity in the different regions are usually different, as well as those of its subsequent manifestations in the same region. This fact indicates the different magnitudes of the relevant mantle-derived impulses and, hence, the different duration of their relaxation.

The different intensities of both subsequent impulses in the same geological province and synchronous impulses in the different provinces seem to be the main cause for concealment of the q-t relationship. The new impulses in particular parts of the same province would change the q-values there. Hence, these impulses can be considered a primary cause of the q-value dispersion that is naturally influenced by all of the disturbing factors enumerated above.

If the magmatic activity manifests itself only once in the geological history of the given geoblock, the heat flow evolution should be described by an expression like $q^{ab} \to f\ (M_1/t_1)$, where M denotes a mass of the mantle-derived melt intruded into the crust at the time t, and q^{ab} designates a value of the abyssal heat flow density at the given site nowadays. The q-values corrected for influence of the disturbing factors must be equal to each other in all geological units formed by synchronous impulses equivalent in mass (*e.g.*, by mass M_1 in the moment t_1).

If a geoblock was reactivated by several impulses with the same enthalpy, the q^{ab} magnitude at the given site should be described by an expression like

$$q^{ab} \to f\left(\frac{M_1}{t_1}, \frac{M_2}{t_2}, \frac{M_3}{t_3}, \ldots, \frac{M_{n-1}}{t_{n-1}}, \frac{M_n}{t_n}\right).$$

If M_1, M_2, M_3 … were known, it would be possible to calculate the «average» age of tectono-magmatic activity t^{av} in the observation site as

$$t^{\mathrm{av}} = \frac{1}{\sum \frac{M}{t_i} \Big/ \sum M_i}.$$

This expression is merely a convention. Such t^{av}-values could present only the formal estimations of «geothermal age» which do not correspond to any real dates of thermal (geological) events taken into consideration. But using the t^{av}-values (if they were possible to be calculated) would decrease the dispersion of the q-values assigned to the same times of the geologic history.

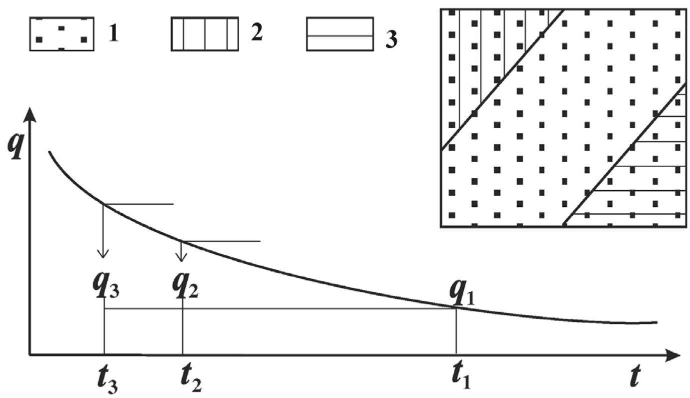

Fig. 6. Heat flow and thermal events in the earth crust. 1 – Crustal block formed by the impulse M_1 during the epoch t_1; 2 – its fragments re-activated by M_2 during t_2; 3 – by M_3 during t_3.

In the light of this approach, one can explain a specific relation of q-values determined in the geoblock formed by the impulse M_1 at the times t_1, if two parts of this block were reactivated by the impulses M_2 and M_3 at the times t_2 and t_3, respectively (fig. 6). In this case $q_2>q_1<q_3$. When $M_2/M_1 \leq M_3/M_1$, $q_3>q_2$, but if $M_2/M_1>M_3/M_1$, q_3 can be both higher and lower than q_2.

Unfortunately, the accurate estimates of the M-values are incredible. Such estimates are impossible to make without a quantification of the hidden (plutonic) discharge of the mantle-derived melts into the crust. The scales of this discharge may be much more than the traces of volcanic activity, which are more or less removed by the following erosion. But the above consideration rules out the doubts about the existence of the q-t trend in the continental crust.

6. Conclusions

Mantle-derived helium is transferred from the interior toward the Earth's surface by silicate flux along with abyssal heat. This flux is evident in the MORs, island arcs, continental rifts, etc., and supposedly exists in mature continental crust as «*magmatic underplating*» (Lachenbruch and Morgan, 1990).

This concept agrees with the triple q-t-$^3He/^4He$ relation observed in the post-Ryphean continental units. However, i) the data on the antiquity of the continental crust (McCulloch and Wasserburg, 1978; O'Nions *et al.*, 1983; Allegre and Rousseau, 1984; etc.), and ii) the ideas on intracrustal thermal activation of collisional origin (Leonov, 1993; Rozen and Fedorovsky, 2001; Yakovlev, 2002; etc.) show that the problem needs further study.

Acknowledgements

This work was supported by the Russian Foundation for Basic Researh, project no. 03-05-64869. The author is grateful to Sächsische Akademie der Wissenschaften, Technische Universität Bergakademie Freiberg and Copernicus GmbH for the invitation to attend and to present this work at 7th International Conference on Gas Geochemistry in Freiberg, 22-26 September 2003.

REFERENCES (*)

ALLEGRE, C.J. and D. ROUSSEAU (1984): The growth of the continents through geological time studies by Nd isotopic analysis of shales, *Earth Planet. Sci. Lett.*, **67**, 19-34.

CERMAK, V. (1976): Heat flow investigation in Czechoslovakia, in *Geoelectric and Geothermal Studies*, edited by A. ADAM (Akad. Kiado, Budapest), 414-424.

CHAPMAN, D. and K. FURLONG (1977): Continental heat flow-age relationships, *Trans. Am. Geophys. Un.*, **58**, 1240-1251.

CHAPMAN, D. and H. POLLACK (1976): Global heat flow: a new look, *Earth. Planet. Sci. Lett.*, **28**, 23-32.

DU, J. (1992): $^3He/^4He$ ratios and heat flow in the continental rift-valley, in *Works of Gas Geochemistry*, edited by Y. XU (Gansu Science and Technology Press, Lanzhou), 165-171.

GERLING, E.K. (1957): He migration from rocks and minerals, in *Proceedings of the Khlopin Radium Institute of Russian Academy of Science*, **6**, 64-87 (in Russian).

HAMZA, V.M. and R.K. VERMA (1969): The relationship of heat flow with the age of basement rocks, *Bull. Volcanol.*, **33** (1), 123-152.

HILTON, D.R. and H. CRAIG (1989): A helium isotope transect along the Indonesian archipelago, *Nature*, **342**, 906-908.

HILTON, D.R., K. HAMMERSCHMIDT, S. TEUFEL and H. FRIEDRICHSEN (1993): Helium isotope characteristics of Andean geothermal fluids and lavas, *Earth. Planet. Sci. Lett.*, **120**, 265-282.

HOOKER, P.J., P.J. BERTRAMI, S. LOMBARDI, R.K. O'NIONS and E.R. OXBURGH (1985): Helium-3 anomalies and crust-mantle interaction in Italy, *Geochim. Cosmochim. Acta*, **49** (12), 2505-2513.

ITALIANO, F., M. MARTELLI, G. MARTINELLI and P.M. NUCCIO (2000): Geochemical evidence of melt intrusions along lithospheric faults of the Southern Apennines, Italy: geodynamic and seismogenic implications, *J. Geophys. Res.*, **105** (B6), 13569-13578.

JENDEN, P.D., D.R. HILTON, I.R. KAPLAN and H. CRAIG (1993): Abiogenic hydrocarbons and mantle helium in oil and gas fields, *U.S. Geol. Surv. Prof. Pap. 1570*, 31-55.

KHUTORSKOI, M.D. (1996): *Geothermics of Central Asian folding belt* (RUDN Publ., Moscow), pp. 289 (in Russian).

KUTAS, R.I., E.A. LUBIMOVA and YA. B. SMIRNOV (1976): Heat flow map of the European part of the USSR and its geological and geophysical interpretation, in *Geoelectric and Geothermal Studies*, edited by A. ADAM (Akad. Kiado, Budapest), 443-449.

LACHENBRUCH, A.Y. (1970): Implication of linear heat flow relation, *J. Geophys. Res.*, **76**, 3852-3860.

LACHENBRUCH, A.H. and P. MORGAN (1990): Continental extension, magmatism and elevation; formal relations and rules of thumb, *Tectonophysics*, **174**, 39-62.

(*) English versions of Russian journals: *Doklady Earth Science Section - Russian Academy of Science Reports; Geotectonics - Geotektonika; International Geological Review - Transactions of the Russian Academy of Science, Geological Series; Geochemistry International - Geokhimiya.*

LEONOV, YU.G. (1993): Platform tectonics in the light of concepts on tectonic stratification of the earth crust, *Geotektonika*, **6**, 3-29 (in Russian).

MAMYRIN, B.A. and I.N. TOLSTIKHIN (1984): *Helium Isotopes in Nature* (Amsterdam, Elsevier).

MCCULLOCH, M.T. and G.J. WASSERBURG (1978): Sm-Nd and Rb-Sr chronology of continental crust formation, *Science*, **200**, 1003-1011.

O'NIONS, R.K. and E.R. OXBURGH (1983): Heat and helium in the Earth, *Nature*, **306**, 429-431.

O'NIONS, R.K. and E.R. OXBURGH (1988): Helium, volatile fluxes and the development of continental crust, *Earth Planet. Sci. Lett.*, **90**, 1331-1347.

O'NIONS, R.K., P.J. HAMILTON and P.J. HOOKER (1983): Nd isotope invesdtigation related crustal development in the British Isles, *Earth Planet. Sci. Lett.*, **63**, 229-240.

OXBURGH, E.R. and R.K. O'NIONS (1987): Helium loss, tectonics, and terrestrial heat budget, *Science*, **237**, 1583-1588.

OZIMA, M. and F.A. PODOSEK (1983): *Noble Gas Geochemistry* (Cambridge University Press, Cambridge).

PARELLO, F., P. ALLARD, W. D'ALESSANDRO, C. FEDERICO, P. JEAN-BAPTISTE and O. CATANI (2000): Isotope geochemistry of the Pantelleria volcanic fluids, Sicily Channel rift: a vantle volatile end-member for volcanism in Southern Europe, *Earth Planet. Sci. Lett.*, **180** (3/4), 325-339.

POLLACK, H. (1980): The heat flow from the Earth: a review, in *Mechanisms of Continental Drift and Plate Tectonics*, edited by P.A. DAVIES and S.K. RUNCORN (Acad. Press), 183-192.

POLYAK, B.G. (1988): *Heat-Mass Flux from the Mantle in the Main Units of the Crust* (Nauka Publ., Moscow), pp. 192 (in Russian).

POLYAK, B.G. and YA.B. SMIRNOV (1966): Heat flow in the continents, *Russ. Acad. Sci. Rep.*, **168** (1), 170-172 (in Russian).

POLYAK, B.G. and YA.B. SMIRNOV (1968): A relationship of heat flow with tectonic structure of the continents, *Geotektonika*, **4**, 3-19 (in Russian).

POLYAK, B.G. and I.N. TOLSTIKHIN (1985): Isotopic composition of the Earth's helium and the motive forces of tectogenesis, *Chem. Geol.*, **52**, 9-33.

POLYAK, B.G., V.I. KONONOV, I.N. TOLSTIKHIN, B.A. MAMYRIN and L.V. KHABARIN (1976): The helium isotopes in thermal fluids, in *«Thermal and Chemical Problems of Thermal Waters», Proceed. Grenoble Symp.*, August/September 1976, *IAHS Publ. 119*, 17-33.

POLYAK, B.G., I.N. TOLSTIKHIN and V.P. YAKUTSENI (1979a): Helium isotope composition and heat flow as geochemical and geophysical aspects of tectogenesis, *Geotektonika*, **5**, 3-23 (in Russian).

POLYAK, B.G., E.M. PRASOLOV and G.I. BUACHIDZE *et al.* (1979b): Isotopic distribution of helium and argon isotopes of fluids in the Alpine-Apennine region and its relationship to volcanism. *Russ. Acad. Sci. Rep.*, **247** (5), 1220-1225 (in Russian); 1981: *Dokl. Earth Sci. Sec.*, **247** (1-6), 77-81.

POLYAK, B.G., E.M. PRASOLOV, V. CERMAK and A.B. VERKHOVSKY (1985): Isotopic composition of noble gases in geothermal fluids of the Krusne Hory Mts. (Czechoslovakia) and geothermal anomaly, *Geochim. Cosmochim. Acta*, **49**, 695-699.

POLYAK, B.G., E.M. PRASOLOV, I.N. TOLSTIKHIN, S.V. KOZLOVTSEVA, V.I. KONONOV and M.D. KHUTORSKOY (1992): Helium isotopes in fluids from the Baikal Rift Zone, *Trans. Russ. Acad. Sci., Ser. Geol.*, **10**, 18-33 (in Russian).

POLYAK, B.G., V.V. GORDIENKO, A.L. CHESHKO, L.L. KAMENSKTI, E.M. PRASOLOV and V.N. TARASOV (1999): Helium isotopes in subsurface fluids of the Eastern Carpathians, *Russ. Acad. Sci. Rep.*, **367**, 244-249 (in Russian).

POLYAK, B.G., I.N. TOLSTIKHIN, I.N. KAMENSKII, L.E. YAKOVLEV, B. MARTY and A.L. CHESHKO (2000): Helium isotopes, tectonics and heat flow in the Northern Caucasus, *Geochim. Cosmochim. Acta*, **64** (11), 1925-1944.

RAO, R.U.M., G.V. RAO and G.K. REDDY (1982): A dependence of continental heat flow – fantasy and facts, *Earth Planet. Sci. Lett.*, **59** (2), 288-302.

ROY, R.F., D.D. BLACKWELL and F. BIRCH (1968): Heat generation of plutonic rocks and continental heat flow provinces, *Earth Planet. Sci. Lett.*, **5**, 1-12.

ROZEN, O.M. and V.S. FEDOROVSKY (2001): *Collisional Granitoids and Stratification of the Earth Crust* (Scientific World Publ., Moscow), pp. 186 (in Russian).

SANO, Y., T. TOMINAGA, Y. NAKAMURA and H. WAKITA (1982): $^3He/^4He$ ratios in methane-rich gases in Japan, *Geochem. J.*, **16**, 237-245.

SCLATER, J. and J. FRANCHETEAU (1970): The implication of terrestrial heat flow observations on current tectonics and geochemical models of the crust and upper mantle of the earth, *Geophys. J. R. Astron. Soc.*, **20** (5), 509-542.

SCLATER, J., C. JAUPART and D. GALSON (1980): The heat flow through oceanic and continental crust and heat losses from the Earth, *Rev. Geophys. Space Phys.*, **18** (1), 269-311.

SCLATER, J., B. PARSONS and C. JAUPART (1981): Oceans and continents: similarities and differences in the mechanism of heat loss, *J. Geophys. Res.*, **86** (12), 11535-11552.

TOLSTIKHIN, I.N., E.R. DRUBETSKOI, E.N. ERLIKH and B.A. MAMYRIN (1976): On the origin of acid volcanic rocks in Kamchatka, *Geokhimiya*, **5**, 682-695 (in Russian).

VITORELLO, I. and H. POLLACK (1980): On the variation of continental heat flow with age and thermal evolution of continents, *J. Geophys. Res.*, **85**, 983-995.

YAKOVLEV, L.E. (2002): The earth crust hydration of and generation of chemogenic heat, *Geokhimiya*, **12**, 1314-1322 (in Russian).