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Spreading and Rifting: Specific Character of Helium Isotopic Compositions

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Abstract—Mechanisms of the oceanic crust spreading and rifting in the continental crust are discussed in light of fluctuations of He isotopic compositions. The data on the Mid-Atlantic Ridge, East Pacific Rise, Baikal Rift Zone, Rhine segment of the North Sea–Libya Belt, and African–Arabian Belt are considered. The $^3He/^4He$ value in submarine basalts and hydrothermal solutions of the mid-ocean ridges is extremely uniform, whereas this isotope ratio for rocks and fluids widely varies along the strike of continental rifts. These variations indicate a different intensity of mantle diapirism in their particular segments, or various extent of opening along the continental rift and, hence, another mechanism of the mantle–crust interaction in zones of oceanic spreading.

INTRODUCTION

The Mid-Atlantic Ridge was discovered in the 1950s. Its clearly delineated axial valley resembles the characteristic valleys in eastern Africa described by Gregory [52] in the middle of the nineteenth century. This similarity led to the suggestion that both structures are a result of the same process of global rifting that develops on continents and on the oceanic floor. This idea is reflected in the titles of numerous papers and monographs on this subject; e.g., *Continental and Oceanic Rifting* [14], *Continental and Oceanic Rifts* [46], and *The World Rift System* [74]. However, there is no agreement among geologists in answer to the question *What are the Rifts?* [39] or about *Notions of the Rift Structure and Rifting* [3], first of all, because it remains ambiguous whether these terms define effects of the process or purport its causes.

When Gregory introduced the term *rift* into geological practice, he did not attach to it anything other than structural and geomorphic meaning, "Those valleys of subsidence with long steep parallel walls, which Professor Suess has called *Graben*… These may be conveniently called *rift valleys*" [60, p. 80]. Etymologically, the word *rift* means an "opening made by cracking or splitting; a divergence" [60]. Thus, if priority is given to the characteristics of the process result, then the term *rift* may indeed be applied to both the continental rift zones and the axial valleys of mid-ocean ridges (MOR). However, it is hardly reasonable to overstate the degree of similarity between these structures: a narrow (tens of meters) and shallow (8–15 m) axial-summit caldera of the East Pacific Rise, where I happened to work [70], may be compared with the rift of East Africa only by morphology and in no way by its size; the same can also be said about the axial valley of the Mid-Atlantic Ridge.

In the twentieth century, the term *rift* was filled with geodynamic meaning in a quite subjective manner. The study of the African–Arabian Belt as a tectonotype of continental rifts led to the belief that high geothermal and volcanic activity, seismicity, and positive gravity anomalies are inseparable features of these structures. In this respect, similarity of the belt with the mid-ocean ridges confirmed the idea of similar geodynamic settings where both types of structures were formed. This was clearly set forth by Milanovskii [23, 24], who wrote in one of his works, "Rifting develops not only at the continents,… but also largely in the oceans… The rift zones… are vast… tracts of elevated… and very high thermal regimes, where the ascent of the heated mantle material is *accompanied* (italicized by me, B.P.)… by its spreading at the base of the Earth's crust… and by penetration into its interior… along with its extension and fracturing…" [26, pp. 5, 6]. Grachev [6] and many other researchers of rift zones hold this viewpoint. Such a model of rifting was called *active*. It adequately describes the mid-ocean ridges as zones of oceanic crust spreading.

However, some other trustworthy scientists do not regard the ascent of mantle material as a cause of rifting. For example, Pushcharovsky [3, p. 3] supposes that the "principle of rifting consists in the fracturing of the Earth's crust and makes it permeable for magmatic masses, deep solutions, and subsurface heat; thereby, the fracture walls are pulled apart and the crust becomes thinner." Such a model of rifting is called *passive*, because the cleft (rift) formation in the crust is provided by "stress external with respect to the rift" [16, p. 3]. In the passive model, the cause–effect relationship of crustal deformation and mantle diapirism is diametrically opposite to that which is suggested by the active model; this rules out a direct analogy between the mid-ocean ridges and the continental rift zones.

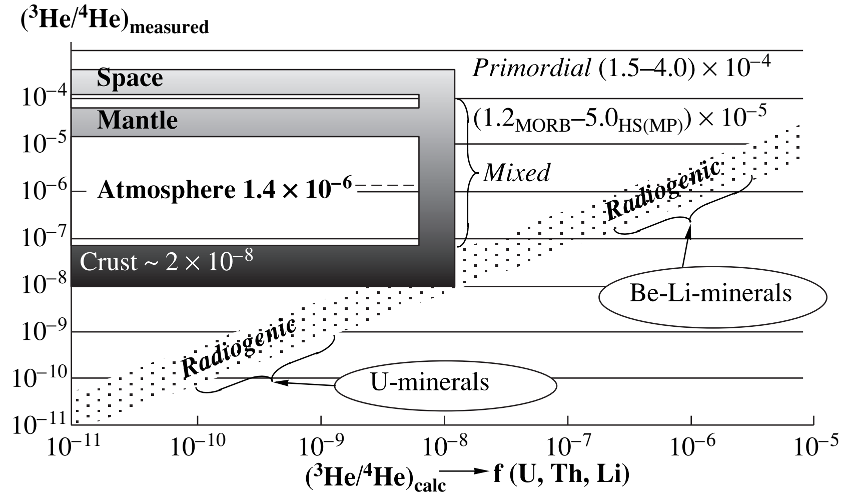

Fig. 1. Genetic systematics of helium and its reservoirs, after [20].

V.E. Khain shortly formulated the arisen dilemma in his work concerning the evolution of the Central Asian mountain belt, which poses the question "…collision or mantle diapirism?" [36, p. 317]. In this and another of his works [62], Khain was among the first to suggest the passive model of continental rifting. Thereby he assumed the possibility of transition from a passive model to an active one, and wrote in his fundamental work [37, pp. 56, 72], "…some greenstone belts could originate on the protocontinental crust under conditions of its *rifting that further could give way (but not necessarily give place) to the spreading… Spreading and the preceding rifting…*" (italicized by me, B.P.), thus clearly distinguishing these processes.

Recently, Leonov, analyzing the comprehensive geological information on the continental rifts, stated that their "properties… may be explained in terms of passive rifting and are in poor agreement with the active model" [16, p. 3]. He deems that the eventual choice between two models requires additional, in particular, petrological evidence. In this paper, an attempt is made to shed light upon the problem by examining helium isotopic composition largely of the freely circulating subsurface fluids.

HELIUM ISOTOPIC COMPOSITION AS AN INDICATOR OF HEAT AND MASS TRANSFER FROM THE MANTLE

The helium isotopic composition of geological objects is extremely diverse. The $^3He/^4He = R$ value varies in a very wide range (Fig. 1) due to the presence of two genetically distinct components of terrestrial He (see [20] and the references therein). One of these components, primordial He with $R \sim 10^{-4}$ that arose in the moment of the big bang, occurs in cosmic matter and was captured by the Earth in the process of its accretion. Another component is the radiogenic He formed as a result of U and Th decay and the nuclear reactions initiated by this process; e.g., $^6Li + n = {}^4He + {}^3H$ and $^3H - (\beta) = {}^3He$. If U, Th, and Li contents in a rock or mineral are known, one can calculate the equilibrium ration $^3He/^4He$ in the same sample. In the case when this ratio coincides with a measured value, it means that only the radiogenic He occurs, irrespective of the R value. In uranium minerals the R value may fall down to $\sim 10^{-9}$ and lower, whereas in Li-rich minerals it attains $\sim 10^{-5}$ [35]. In the case of the clarke U, Th, and Li contents in the Earth's crust, R is $\sim 2 \times 10^{-8}$; this ratio is defined as the canonical radiogenic, or crustal ratio. However, in many cases, the calculated equilibrium value $R \sim 10^{-8}$ is combined with a higher measured ratio, thus indicating that He with other isotopic composition occurs besides radiogenic He. In the present-day atmosphere $R = 1.4 \times 10^{-6}$ [21]. The contamination of He contained in the sample with an air-derived component can be accounted for, and its probable admixture may be eliminated. However, even after such elimination, the measured R values often remain greater than crustal and even atmospheric levels. This testifies to the presence of some admixture of the primordial He, which, as it turns out, is not yet lost completely by the Earth, despite its permanent dissipation into the near-Earth space environment. The values of $R \sim 10^{-5}$ were established in objects genetically related to the degassing and differentiation of the mantle; e.g., in gases of the active volcanoes, submarine oceanic basalts, ultramafic xenoliths, and some minerals from igneous rocks. This implies that the primordial component still amounts to ~10% of the bulk He content, and the rest of the He has a pure radiogenic origin.

As has been shown long ago by Gerling [4], rocks and minerals lose He which is contained and generated therein, because He escapes along with fluids. Thereby its isotopic composition is more or less averaged in compliance with contributions from all of its sources

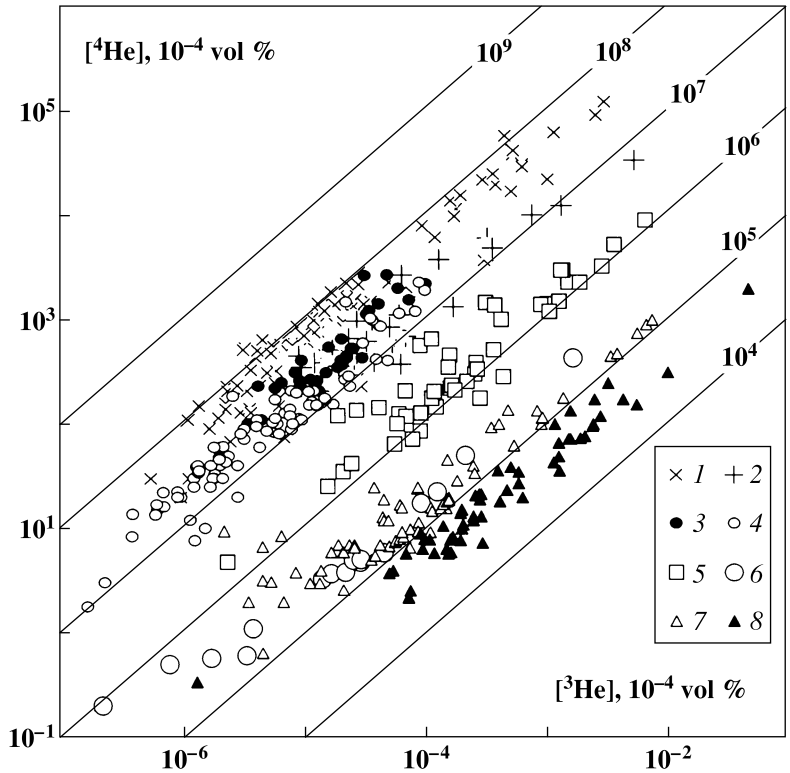

Fig. 2. Tectonic systematics of $^3He/^4He$ in the freely circulating subsurface fluids. (*1*) pre-Riphean East European Platform; (*2*) platform segments reactivated in the Paleozoic (Donets Basin, Dnieper–Donets Basin, and Pripyat Trough); (*3*) Baikalides (Timan–Pechora region); (*4*) Hercynides (Scythian Plate); (*5*, *6*) Hercynides reactivated in Cenozoic: (*5*) Greater Caucasus, (*6*) Central French Massif; (*7*) neovolcanic regions in Italy; (*8*) Iceland.

(rocks of various composition and genesis) and becomes a quasistationary regional parameter of a given geoblock. This is clearly seen from Fig. 2, which demonstrates a very wide scattering of ^{3}He and ^{4}He in the gas phase of subsurface fluids. The R value in these fluids is inversely related to the age of tectonomagmatic activity in the respective areas. Thus, it turns out to be similar in this respect to the density of the background conductive heat flow (q), which also diminishes with increasing age [31, 54, 73]. Therefore, it is not surprising that the background R and q values reveal a positive correlation [26, 32] that makes it possible to tentatively assess the heat flow density from the He isotopic composition in the fluid. This has been verified by a special study of the Okrze (Jaeger) Graben in the Bohemian Massif [30] and subsequently confirmed by studies in the Russian part of the Baikal region [19], Mongolia [38], and East China [51].

The joint analysis of the heat flow density q and the ratio $^3He/^4He$ of geological objects is reasonable because of their most important common feature: the internally consistent variation in time, owing to the cooling of the subsurface as a source of heat and to the radiogenic generation of ^{4}He. This attribute cardinally distinguishes q and $^3He/^4He$ from all the other geological, geophysical, and geochemical parameters, except the compositions of the elements, which also have radiogenic isotopes; e.g., Ar, Pb, Sr, Nd, etc.

Contrary to the ideas of autonomous flow of volatile components ascending from the mantle, and in compliance with correlation between R and q, further investigations have shown that the silicate material serves precisely as a carrier of mantle helium and heat. The correlation of isotopic compositions of atmophile helium and lithophile strontium was established for the products of recent volcanic and hydrothermal activity. Such a correlation had first been revealed in Italy [29, 68] and then in other segments of mobile belts; e.g., in the Banda arc of Indonesia [56], in the Andes [57], and in the northern Caucasus [71]. Thus, the He isotopic composition in the subsurface fluids is an extremely sensitive and unequivocal indicator of deep heat and mass flow discharge.

$^3He/^4He$ VALUES IN FLUIDS AND ROCKS FROM MID-OCEAN RIDGES

Helium with $R \sim 1 \times 10^{-5}$ that exceeds the atmospheric value was first found in 1969 in gases of the Kuril island arc [22]. At almost the same time, its traces were detected in waters of the Pacific Ocean [44] and ascribed to the supply of such He from the oceanic crust

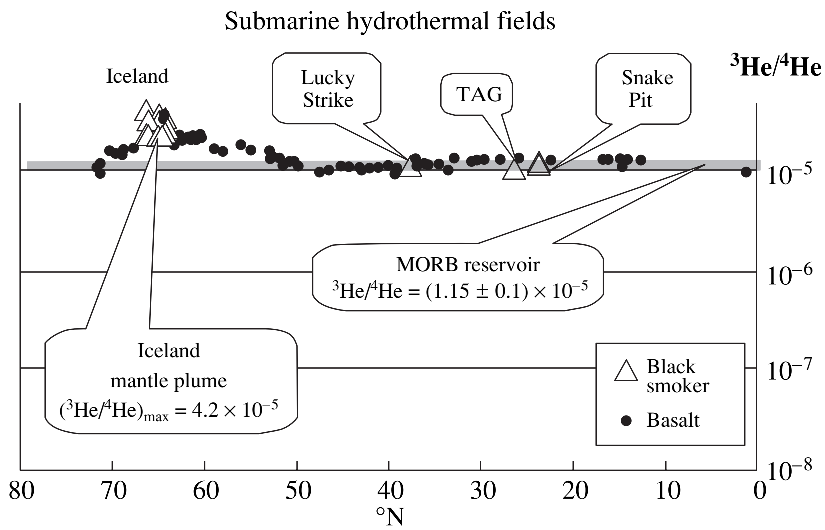

Fig. 3. $^3He/^4He$ distribution along the axis of the Mid-Atlantic Ridge, after the works by C.J. Allegre, M. Condomines, D.R. Hilton, P.J. Hooker, W.J. Jenkins, L.V. Khabarin, V.I. Kononov, M. Kurz, B.A. Mamyrin, B. Marty, R.K. O'Nions, E.R. Oxburgh, B.G. Polyak, T. Staudacher, I.N. Tolstikhin, and others.

permanently formed in the spreading zone. These findings were interpreted as evidence for the presence of residual primordial He in the Earth's mantle. Afterwards, the mid-ocean ridges became a target of detailed study with respect to the He isotopes. Submarine basalts were the main objects of this study. Helium was recovered from the dredged samples in different ways: with the complete melting, by crushing and analysis of the fractions having various sizes, and by stepwise annealing. The data obtained eventually yielded an extremely narrow range of *R*; its average value in the global MOR system is $(1.15 \pm 0.1) \times 10^{-5}$ [65]. Precisely, this value is assigned now to the MORB reservoir.

In addition to basalts, the submarine hydrothermal solutions, which are locally discharged in the axial valleys of MOR, were studied in the TAG, Snake Pit, and Lucky Strike fields of the Mid-Atlantic Ridge (MAR); in the field of 11°, 13°, and 21° N in the East Pacific Rise (EPR); at the Guaymas occurrence in the Gulf of California; and elsewhere. The helium isotopic composition in the hydrothermal solutions is everywhere completely identical to that of the submarine basalts.

As a result, it became possible to trace the *R* distribution along the MAR and, in less detail, along the EPR. Both experiments showed the extremely uniform He isotopic composition in the zones of oceanic crust spreading. At the same time, the gases from Iceland with an *R* value 3.0–3.5 times greater than the MORB level clearly stand out in the MAR profile (Fig. 3). Such values had been detected here long ago [13], soon after the first finding of the primordial He traces in volcanic emanations, and were repeatedly confirmed by later investigations.

The *R* values that resemble those in Iceland were also revealed in volcanic and geothermal gases at a few other localities: in the Hawaii Islands, Yellowstone National Park, Ethiopia [45–47], and elsewhere. Recently *R* values greater than the MORB level were found in the products of volcanic activity on Azores [66] and Canary Islands [58].

The *R* values that exceed the MORB level characterize the hot spots in the interpretation given by Morgan [67]; i.e., the ascending flows from the lower undepleted mantle where the percentage of the primordial He component probably reaches 50%. Precisely, the He isotopic composition makes it possible to distinguish such mantle plumes from the multitude of inferred hot spots; generally speaking, every volcano can be classified as a hot spot by definition.

LATERAL VARIATIONS OF $^3He/^4He$ IN CONTINENTAL RIFTS

Prerequisites of Interpretation

Besides introduction of corrections for possible air contamination into the measurement results, two other necessary conditions must be fulfilled before conducting a search for systematic lateral variations in the He isotopic composition.

First, it should be preliminarily established how stable the *R* value at the time of a given station of sampling; if this value is time-dependent, the difference may be misleading. Such an approach was realized during the study of the Baikal Rift Zone and its framework. More than 100 springs and wells were sampled here (Fig. 4). The repeated sampling over more than 20 years bore out the stable He isotope ratios at each station and at any level of *R* values [27]. It is emphasized that in most cases the samples were taken at different times by different people and analyzed in different laboratories. Therefore, the comparison of the

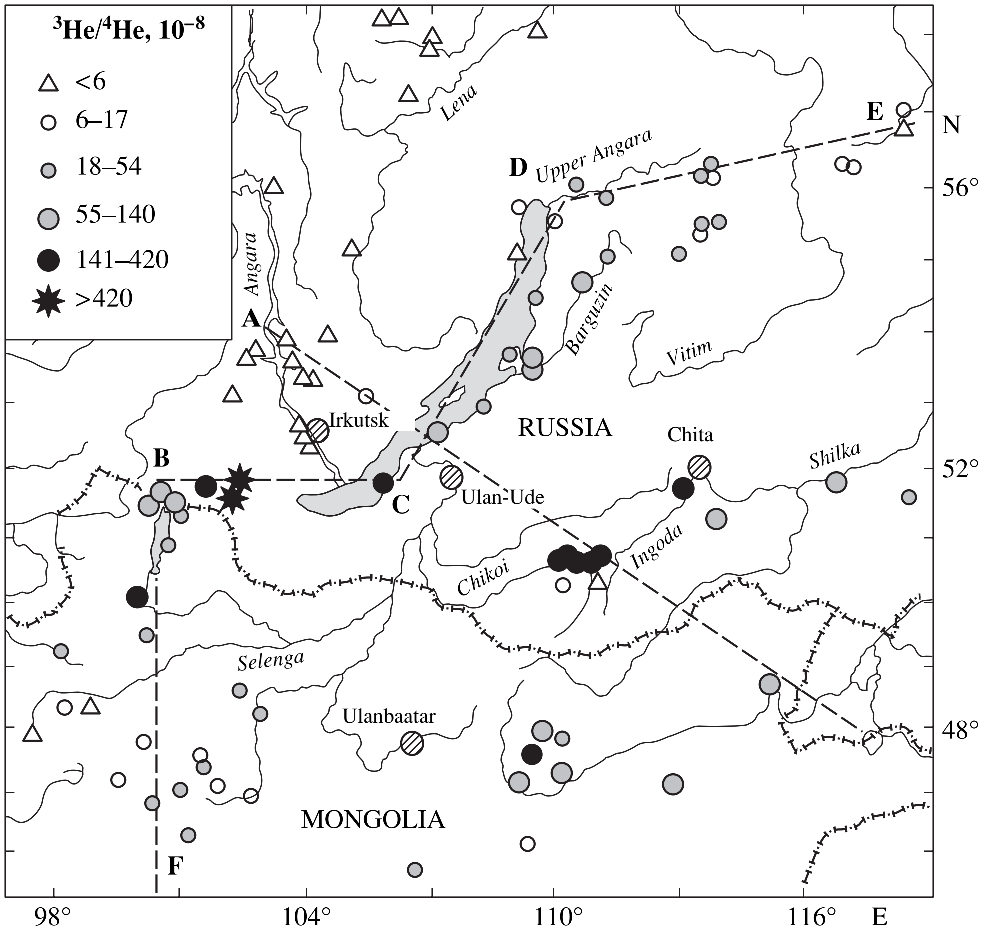

Fig. 4. Stations of the He isotopic composition study in subsurface fluids of the Baikal–Mongolia region, after [27]. The average value is ascribed to the stations, where the ^{3}He/^{4}He ratio was measured repeatedly or in different objects spatially coinciding at a scale of the map; A–E and F–G are profile lines, see Figs. 5 and 6.

results obtained is quite allowable for the study of the systematic lateral variation of *R* values in this region.

Second, the vertical variation of the He isotope ratio in fluids within the geological sections of the sampled region should be verified. It can be done only in drilled areas; e.g., the Tunka Basin of the Baikal Rift Zone, the Irkutsk Amphitheater, and the Nepa Arch on the Siberian Platform. As was established, the *R* value in all of these regions is the same in gases derived either from shallow-seated sources or from deeper intervals of the geological section, regardless of what component is predominant in the gas composition; thereby, *R* in the rift basin is greater than at the platform by almost three orders of magnitude [27]. The absence of systematic differences in the He isotope ratio within the vertical section of the drilled territories make it possible to jointly analyze the results of *R* determinations in samples taken from springs and wells.

The Baikal–Mongolia Region

The regional differences in the He isotopic composition of subsurface fluids are clearly seen on the profile across the Baikal Rift Zone (Fig. 5). A sharp contrast between the pre-Riphean Siberian Platform and the Baikal Rift is especially evident. However, a quite different distribution is displayed to the east of Lake Baikal: in the Transbaikal region, the R values are at almost the same level as in the rift zone.

This pattern is formally consistent with the deep structure of the region deduced from the geophysical data. According to this evidence (see the review in [2]), a vertical slitlike conduit localized beneath the Baikal Rift Zone rises from the asthenosphere to the Moho surface. An offset of the anomalous mantle branches out from this conduit at the Moho level; it extends to the southeast of Lake Baikal for approximately 300 km as a stratal low-velocity zone of P-waves with elevated conductivity, which indirectly indicates a higher temperature. The nearly vertical channels with conductivity of 5–10 Ω m beneath the Baikal Rift and 20–50 Ω m in the Transbaikal region localized above the low-velocity zone are interpreted as fault-controlled and fluid-saturated zones (magma feeders?).

As follows from the *R* values in fluids of the Transbaikal region, a sheetlike (?) intrusion of anomalous

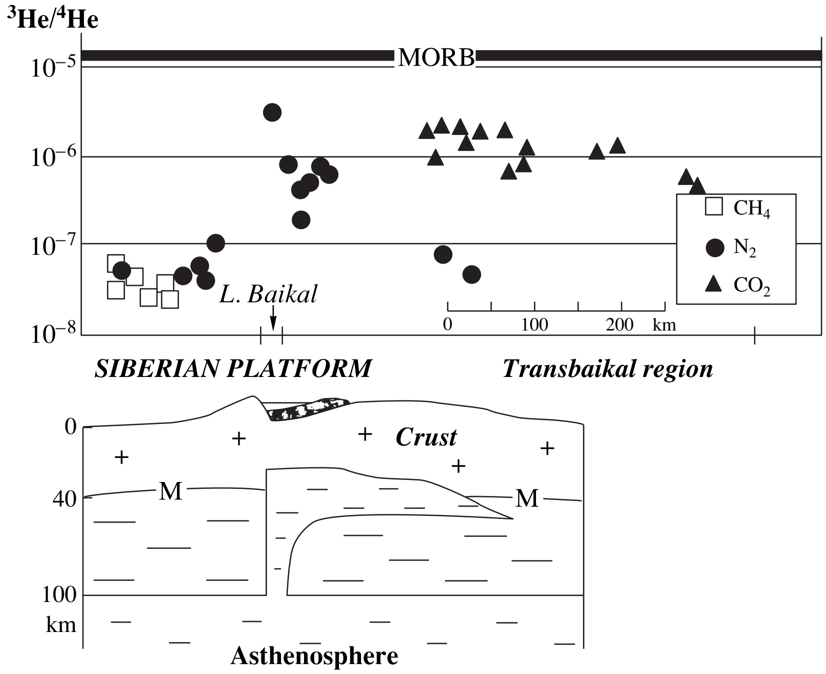

Fig. 5. $^3He/^4He$ distribution across the Baikal Rift Zone, see line F–G in Fig. 4. The deep structure of the region is shown at the bottom as deduced from the geophysical data [2].

mantle containing a few percent of melt [2] extends farther to the southeast beyond the geophysical anomaly. The explicit admixture of the mantle-derived He in gases from springs at the eastern flank of the rift zone indicates that a hidden discharge of heat and mass flows ascends from the mantle here exactly; this discharge covers a much larger area than the territory of the open discharge.

The *R* distribution along the Baikal Rift Zone is especially evident. Owing to the available data, this distribution has been traced for a distance of more than 2000 km between the Upper Chara and Khubsugul rift basins and farther to the south, approximately along 100° E, up to the Bolnai Fault. Ordering is clearly seen in the variations of He isotopic composition (Fig. 6).

The maximum *R* values reach 1.1×10^{-5}, which were measured in the eastern Tunka Basin by the first researchers [17] and confirmed by all subsequent studies, turned out to be inherent only to this segment of the Baikal Rift Zone. As is known, this basin differs from all other graben-like depressions of the Baikal Rift Zone by its high volcanic activity that lasted from the early Miocene to the Holocene inclusive. Volcanic rocks occupy a considerable portion of the sedimentary cover and make up four groups of small monogenic volcanoes at the surface.

A much lower *R* value of 3×10^{-6} was measured in the sample from the Svyatoi Klyuch Spring at the coast of the neighboring South Baikal Basin [69]. Deep fluids discharge at the bottom of this basin, as has been demonstrated by geothermal studies [5] and by the He isotopic composition of water in the lake [9].

In gases from the springs that discharge along the eastern coasts of the Middle and North basins of the Lake Baikal bath, the He isotope ratio becomes lower yet, although an admixture of the mantle component is quite detectable. However, at the western coast of the North Basin, the *R* value drops to the canonical radiogenic level, which indicates an abrupt decrease in the mantle signal toward the west; i.e., in the antirift direction.

In the studied springs of the adjacent Upper Angara Basin, the average *R* remains the same as in the North Baikal Basin. Farther to the northwest along the North Muya Range, Udokan Range, and the Upper Chara Depression, it consecutively diminishes down to the level characteristic of the ancient continental crust dissected by a rift. The record-breaking high He concentration of up to 2.2 vol. % in gases of the Upper Chara Depression also indicates the crustal origin of He.

A similar trend is revealed in Fig. 6 for the isotopic composition of He dissolved in the waters of Lake Baikal [9] and for the fluids from the Barguzin and Baunt graben-like flank rift basins that are elongated parallel to the Baikal Rift Zone [27].

The helium isotope ratio in the subsurface fluids decreases to the south of the Tunka maximum, as well as to the northeast of it [33]. In the Khubsugul Depression, this ratio coincides with that in the western Tunka Basin only in the southernmost Ulkhen-Arshan Spring and, on average, equals 0.9×10^{-6}. In the foothills of the Khangai Range, up to the Bolnai Fault, the ratio

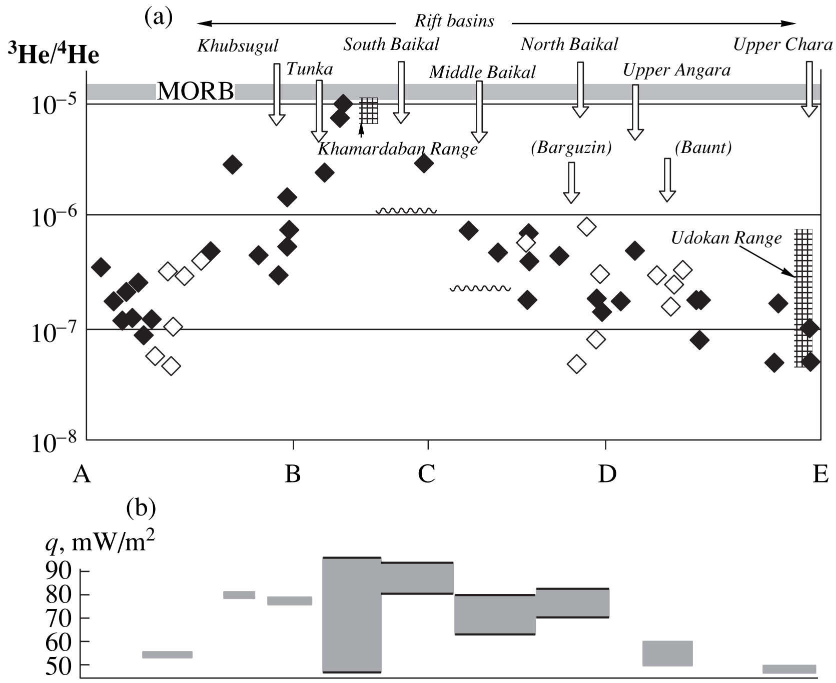

Fig. 6. (a) ^{3}He/^{4}He and (b) heat flow distribution along the Baikal Rift Zone, see line A–E in Fig. 4. The filled diamonds are *R* values of the gases from the hydrothermal occurrences near the rift zone axis; open diamonds are values of the gases from the the hydrothermal occurrences in the adjacent areas; e.g., in the Barguzin and Baunt basins. The values of rocks are shown by hatched columns; their height corresponds to the *R* ranges reported in [10]. The wavy lines indicate *R* for the gases dissolved in water of Lake Baikal, after [9].

becomes twice as low, and in the Khangai Range itself it corresponds to the level typical of the Paleozoic tectonomagmatic activity.

The decrease in the mantle signal intensity in subsurface fluids along the Baikal Rift Zone is accompanied by reduction of the basin dimensions, including their depth. So, the roof of the crystalline basement (the surface of the Cretaceous–Paleogene prerift peneplain) occurs at a depth of about 7 km in the South Baikal Basin, at 4.5 km in the North Baikal Basin, at 2 km in the Upper Angara Basin, and at 1 km in the Upper Chara Basin [25]. This fits the gravity measurements [12] and testifies to the increase in crust density beneath particular basins due to the emplacement of mafic and ultramafic intrusions that stimulate extension by virtue of isostatic compensation.

A source of deep melts is reliably identified by the He isotopic composition of igneous rocks. Such data have so far been obtained only for young basalts from the Khamardaban and Udokan areas, where this composition was determined in xenoliths of the mantle-derived spinel lherzolite and in olivine that firmly retains helium [8, 10]. These results were compared with the He isotopic composition of fluids from the Baikal Rift Zone. As can be seen from Fig. 6, the data on rocks mimic the trend for fluids: the *R* values in the Khamardaban area are much higher than in the Udokan area. This has been interpreted as evidence for the variable He isotopic composition of the mantle along the rift [8]. However, the trend observed in fluids may be explained more reasonably by a contamination of the mantle derivatives with the crustal He that gradually increases away from the Tunka Basin. If this is the case, helium contained in the Udokan samples is not of mantle origin. The geothermal data are also directly related to this problem, because the mafic melts intruding into the crust also supply heat.

It is important to emphasize that the systematic variation in the He isotopic composition along the rift is correlated with the previously established heat flow distribution (Fig. 6b). As has been shown by Lysak [18], the average density of conductive heat flow is variable in the different segments of the Baikal Rift Zone and diminishes in both directions from the South Baikal Basin, which is defined as the center of rifting. With the accuracy of the average estimation stated in the cited work [18, Table 26, p. 182], this density might be exactly the same as in the Tunka Basin.

The correlation of the He isotope ratio with the heat flow density in the Baikal Rift Zone is a particular case of a general relationship established at the scale of the entire continental block of northern Eurasia [26, 32]. The natural correlation of both the parameters mirrors an effect of the same cause; i.e., the discharge of heat and mass flow from the Earth's interior carrying primordial helium. These are manifested not only in interregional comparisons, but also at regional and sometimes local scales; i.e., not just in the aforementioned Okrze Rift dissecting the Bohemian Massif [30], but also in Japan [72], China [51], Italy [61], the Baikal

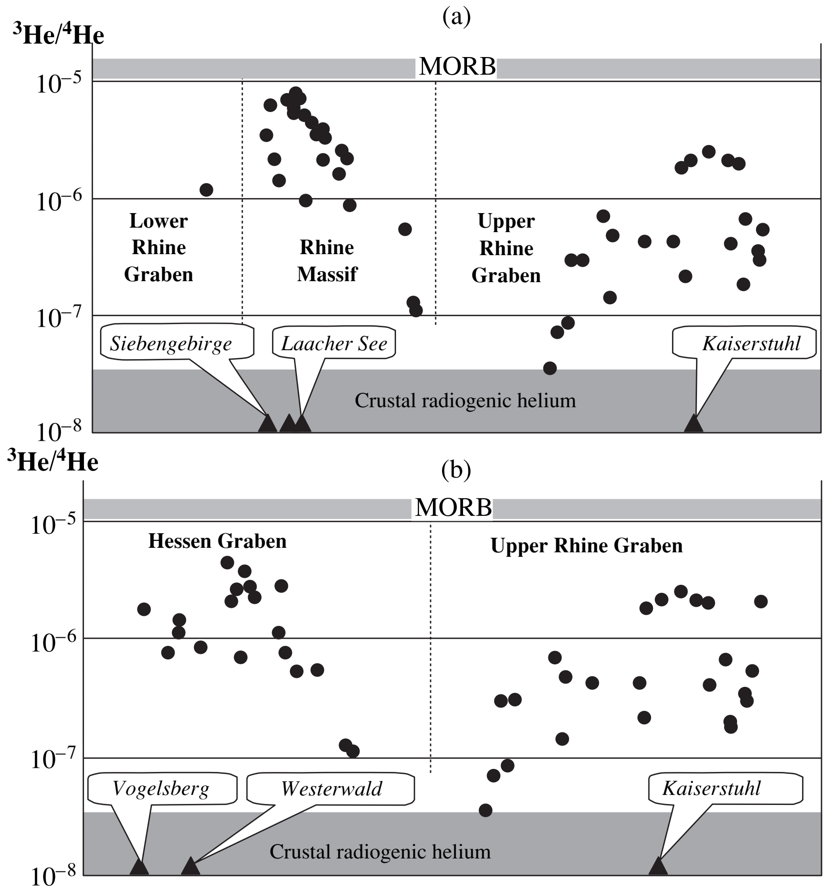

Fig. 7. Variation of $^3He/^4He$ in the Rhine segment of the North Sea–Libyan Rift Belt, after [53]: (a) Lower Rhine Graben–Rhine Massif–Upper Rhine Graben; (b) Hessen Graben–Upper Rhine Graben.

region [19], Ukraine [28], the northern Caucasus [71], and eastern Tien Shan [11].

The systematic variation of the He isotopic composition in subsurface fluids and background heat flow in the Baikal Rift Zone clearly indicates that the discharge of heat and mass flows from the mantle decreases toward the periphery of this zone.

Variable $^3He/^4He$ Ratio as a Specific Feature of Continental Rifts

Pronounced variability of the He isotopic composition in the subsurface fluids of the present-day continental rifts is a general distinguishing feature of these structures. A more or less wide dispersion of R values along their strike is observed not only in the Baikal Rift Zone, but also in other rifts of western and central Europe, in the grabens of East China, and in the African–Arabian Rift Belt, a tectonotype of continental rifts.

So, the gases in the petroleum fields related to the ancient rift systems of the North Sea contain almost everywhere helium with a low $R = (5.6–12.6) \times 10^{-8}$, which is close to the canonical radiogenic value [59]. At the same time, as has been emphasized in the referred work, the maximum values are confined to the faults that bound the Viking and Central rift grabens in the west. Recent investigations [41] have shown that in the Magnus field localized in the northern Viking Graben the R values are lower yet, $(28–54) \times 10^{-8}$, as a result of the obvious admixture of the mantle-derived helium.

In the Lower Rhine, Hessen, and Upper Rhine grabens, as on-land extensions of the grabens in the North Sea, a range of R variation is still wider and covers almost three orders of magnitude, from 1.4×10^{-8} to 0.82×10^{-5} [53]. Thereby, as in the Baikal Rift Zone, the R distribution along these structures bears a systematic character but has two maximums of different magnitude instead of one. In the Rhine grabens, these maximums coincide with occurrences of young magmatic activity represented by the Miocene Siebengebirge massif of alkaline rocks, the early Holocene Laacher See maar in the Lower Rhine Graben, and the Kaiserstuhl carbonatite complex in the Upper Rhine Graben; no such obvious spatial correlation was revealed in the Hessen Graben (Fig. 7). However, a decrease in R within the amagmatic segment of the rift zone south of the Rhine massif is quite evident.

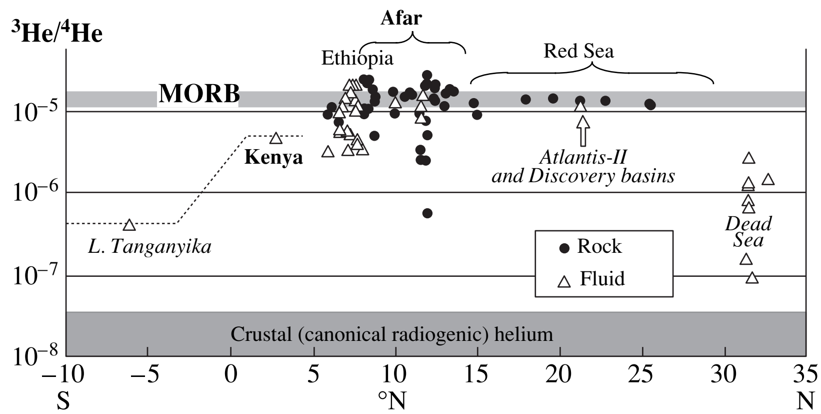

Fig. 8. $^3He/^4He$ distribution along the African–Arabian Rift Belt, after the works by C.J. Allegre, A. Bosch, H. Craig, J.E. Lupton, B. Marthy, E. Mazor, M. Moreira, Y. Sano, P. Scarsi, P. Schlosser, T. Staudacher, P.J. Valbracht, H. Wakita, and R.F. Weiss.

In the Jaeger (Okrze) Rift that cuts the Bohemian massif from the southwest to the northeast and controls occurrences of the middle Pleistocene volcanic activity [75], an R value of 0.9×10^{-5}, the record high for continental Europe, was measured in the carbon dioxide gas from the Nova Ves mofette field [55]. It is virtually equal to the He isotope ratio in gases from the Palizzi mofette south of Etna [29] and is second to that only once measured in a fumarole on the northwestern slope of this volcano, where $R = 1.12 \times 10^{-5}$ fits the MORB level [40]. R values one order of magnitude lower have also been reported from this rift [75]. It is noteworthy that, farther to the northeast in gases of the Polish Sudeten with small and sporadic occurrences of young basaltic volcanism an R value of 0.39×10^{-5} was measured [43].

The range of R values from 0.13×10^{-6} to 0.98×10^{-5} in the Songliao Depressions and in similar grabens of East China [51] is almost the same as in the European rifts.

The variable He isotopic composition along the rift zones is also naturally characteristic of the African–Arabian Rift Belt, as is evident from the summary graph presented in Fig. 8. The lowest R value was measured in the samples taken from the outer segments of this belt. In the south, the gases dissolved in water of Lake Tanganyika yield $R = 42 \times 10^{-8}$. To the north, this ratio increases for fluids and reaches 2.1×10^{-5} in a spring near Lake Chitu within the Ethiopian Rift [48]. This is much higher than that of a typical MORB. The maximum R values farther to the north remain at the same level, representing the Afar plume similar to Iceland [50]. In the submarine basalts and hydrothermal solutions of the Red Sea, apparently opened owing to this plume, the R value approaches the MORB level and drops down to 1.19×10^{-5} [63]. In the northernmost segment, the Jordan Rift, R decreases to $(0.17–0.06) \times 10^{-5}$ [42].

CONCLUSIONS

The data on the He isotopic composition are helpful to specify the processes that create continental rifts. A wide and systematic variation of the He isotope ratio along the strike of rifts is correlated with variation of background heat flow (Baikal Rift Zone, Songliao, etc.) and occasionally, as takes place in the Baikal Rift Zone, with a change of the morphology and geophysical characteristics of rift basins. This indicates that the intensity of mantle diapirism was different in each particular segment. This principally distinguishes the geodynamic settings of continental rifting and oceanic spreading (Fig. 9). The observed variability of R likely displays a different extent of the continental rift opening along their strike and, hence, a mechanism of the mantle–crust interaction distinct of that in the mid-ocean ridges.

The spreading of the oceanic crust is a response of the lithosphere to the ascent of mantle melts along the mid-ocean ridge axis that occur with an approximately equal intensity over its entire extent (as follows from the nearly parallel linear magnetic anomalies). In other words, the extension of lithosphere is driven by activity of the mantle. Precisely this process, which is defined as axial spreading (in contrast to the backarc spreading), represents the active rifting.

At the same time, the continental crust generally experiences compression, as was stated by Kropotkin [15] long ago, owing to the processes proceeding in oceans. The compression is first expressed in the stacking or amalgamation of separate crustal blocks (terranes) and eventually gives rise to the shear deformation that destroys the continuous crust (lithosphere). The arising faults serve as prerequisites for autonomous motions of divided blocks; as a result, the pull-apart basins are formed as embryos of continental rifts. These structures provide ascent of mantle diapirs, decompression melting at their fronts, and volcanic and intrusive magmatism.

Thus, the mantle activity in the course of the continental (passive) rifting is an effect of strain in the over-

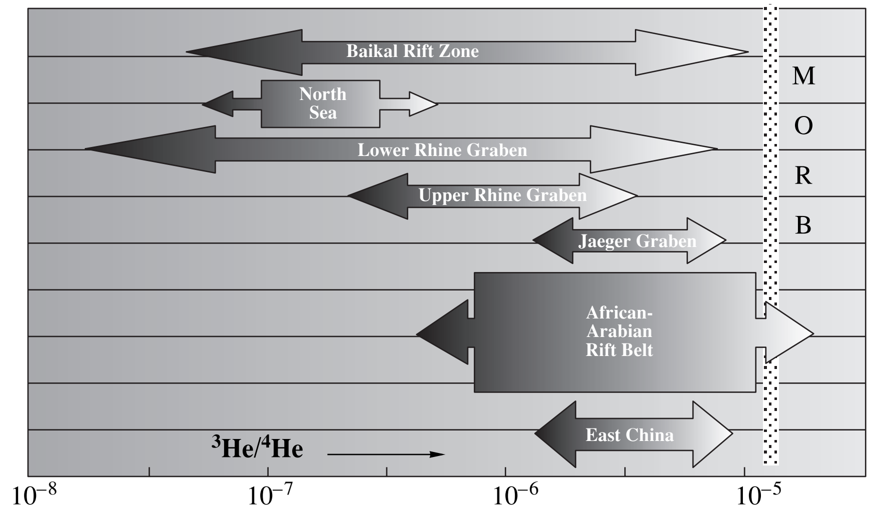

Fig. 9. Dispersion of the He isotope ratio in continental rifts, after the works by C.J. Allegre, C.J. Ballentine, H. Craig, D. Graham, E. Griesshaber, J. Heinicke, P.J. Hooker, W.J. Jenkins, H. Kämpf, M.D. Kurz, J. Lupton, B. Marty, M. Moreira, S. Nakai, R.K. O'Nions, E.R. Oxburgh, P. Scarsi, T. Staudacher, F.H. Weinlich, S. Xu, H. Wakita, and A. Zindler; MORB reservoir, after [65].

lying lithosphere, rather than its cause. The strain may be reinforced by the wedging action of mantle plumes ascending from undepleted mantle. This is the case when the plume projection on the Earth's surface coincides with a rift zone, where the magma generation is much greater than elsewhere [26]. Judging from the He isotopic composition in fluids of the African–Arabia Rift Belt, this exactly takes place in the Afar region.

Concerning the Iceland hot spot, its localization on the MAR axis is thought to be more or less accidental, because a path of mantle plume hardly depends on surface tectonics. However, it explains a paradoxical coexistence of two phenomena in the Cenozoic history of the North Atlantic that seemingly exclude each other: (1) spreading of the oceanic crust to the south of Iceland, in the Reykjanes Ridge, and to the north of Iceland, in the Kolbeinsey Ridges; and (2) formation of the Tullan (Greenland–Faroes–Scotland) trans-Atlantic threshold that inhibited the migration of arctic fauna into the Atlantic and served as a bridge connecting the flora of Europe and America [1, 64].

Some authors, like Grachev [7], regard the plumes ascending from undepleted mantle as the main cause of continental rifting. If this is actually the case, the crust (lithosphere) cannot break synchronously along the entire extent of the arising rift zones anyway, as takes place in the already existing mid-ocean ridges, but does breaks step by step from a rifting center toward its periphery, like a propagating fissure does. In extreme cases, such a sequence of events could lead to the complete destruction of the continental crust (Red Sea), opening of new oceans, and, as a result, to the rearrangement of the convection cells in the mantle.

To summarize, it can be stated that the He isotopic composition bears out the concept of passive origin of the continental rift zones. The opposite character of the mantle–crust interaction in these zones and in the mid-ocean ridges should be regarded as a much more important difference in their geodynamics than a formal similarity of the axial depressions regarded as attributes of rift structures. At the same time, these principally distinct phenomena—spreading in oceans and rifting at the continents—reveal inverse relations.

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