Geofísica Internacional (2002), Vol. 41, Num. 4, pp. 485-490

Helium isotopes in subsurface fluids from the Baikal Rift Zone: An application to the problems of geodynamics

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Received: September 2, 2001; accepted: May 22, 2002

RESUMEN

Se realizó el estudio de la relación R = (^3He/ ^4He) en fluidos subterráneos de 104 sitios de la zona Baikal Rift y zonas adyacentes de Rusia y Mongolia. Los valores de la relación varían desde 1 E-8 (que es un valor típico para He radiogénico de la corteza), hasta 1.1 E-5, valor apenas por debajo del correspondiente al MORB. Se muestra que no existe variación significativa de los datos con el tiempo o con la profundidad. Los valores más bajos de R se corresponden a gases ricos en CH_4. Los datos más diversos de R se obtuvieron en fluidos ricos en N_2 y CO_2 mostrando estos últimos los valores más altos de R. Estos gases son de origen atmosférico. La relación entre f N_2/f Ne indica un exceso de nitrógeno no atmosférico. La comparación de los valores de R con las concentraciones de helio y de los componentes predominantes de un fluido en fase gaseosa muestra que esta fase se forma por el efecto del fraccionamiento controlado por la solubilidad en un sistema gas-agua y una ganancia/pérdida de gases de la corteza químicamente activos. La distribución de los valores de R en la zona en estudio indica un flujo de calor desde el manto tanto hacia la zona como hacia el este. Dentro de la zona el rango de valores de R es más amplio. Los valores de R disminuyen a lo largo de la colisión de BRZ en ambas direcciones. La disminución está acompañada de un decaimiento en el flujo de calor y muestra una disminución de éste a partir del manto en segmentos periféricos de la zona en estudio. La comparación de éstos con datos de otros rifts continentales y crestas oceánicas sugiere mecanismos radicalmente diferentes de interacción manto-corteza durante la separación de fondo oceánico y la deriva continental.

PALABRAS CLAVE: Isótopos de helio, aguas termales, rifts continentales, Lago Baikal.

ABSTRACT

The $^3He/^4He = R$ ratio was studied in underground fluids from 104 sites from the Baikal Rift Zone, BRZ, and adjacent areas in Russia and Mongolia. The *R* values vary from 1.0×E-8, typical of crustal radiogenic He, up to 1.1×E-5 just below the MORB characteristics. The repeated sampling of some sites and the comparison between the data for superficial springs and productive boreholes have shown no significant R variation in time or in depth.

The lowest *R* values belong to CH_4-rich gases. The more diverse *R* values were measured in N_2- and CO_2- rich fluids, and the latter show the highest *R*. Judging from N_2/Ar_{atm} ratio, N_2-rich gases are of atmospheric origin. The fN_2/fNe ratio value in CO_2- rich fluids indicates the excess (non-atmospheric) nitrogen. The comparison of the *R* values with He concentrations and predominate components of a fluid gas phase shows that this phase is formed under the effect of solubility-controlled fractionation in gas–water system and a gain/loss of chemically active gases within the crust.

The distribution of *R* values across the BRZ strike indicates a discharge of heat-mass flux from the mantle not only inside the BRZ but also far to the east. Inside the BRZ, the range of *R* values is widest: from 4.9×E-8 to 1.1×E-5. These variations are regular: *R* values diminish along the BRZ strike in both directions from the Tunka Basin considered as a center of rifting. The decrease is accompanied by some decay of heat flow density and shows a reduction of heat-mass flux from the mantle in peripheral segments of the rift zone.

The comparison of this trend with the data for other active continental rifts and mid-oceanic ridges suggests radically different mechanisms of mantle-crust interaction during oceanic spreading and continental rifting.

KEY WORDS: He-isotopes, thermal waters, continental rifts, Baikal Lake.

INTRODUCTION

Relation between continental rifting and the mantle upwelling still remains debatable. New light on this problem is shed with the data about He isotope composition in fluids freely circulating in rift zones. The data collected in the Baikal-Mongolian region for last quarter of XX century are considered from this standpoint.

As well-known, the $^3He/^4He=R$ value for radiogenic helium generated in old crustal rocks is of $(2\pm1)\times10^{-8}$, whereas the *R*-value in the present mantle is three orders of magnitude higher [Mamyrin and Tolstikhin, 1984]. In mid-oceanic ridges the *R*-values have appeared almost identical everywhere being close to 1.2×10^{-5} both in fresh basalts and submarine hot springs [Kononov *et al.*, 1974; Kurz *et al.*, 1982; Condomines *et al.*, 1983; Poreda *et al.*, 1986; Staudacher *et al.*, 1989; Jean-Baptiste *et al.*, 1991; Rudnicki and Egerfield, 1992]. Therefore, this value was assigned to the MORB reservoir presenting depleted mantle. The *R*-values exceeding those in MORBs were found out in Iceland, Hawaiian Islands, Afar region, and some other places where the plumes from the undepleted or enriched mantle are supposed to discharge [Craig and Lupton, 1978]. Mid-ocean ridges were thought to be similar to continental rifts. Therefore, the He isotope investigations in the rifts are of specific interest.

In the early 1970th, these investigations began in the Baikal rift zone (BRZ). The zone extends from the southern Siberia to the northern Mongolia for a distance of about 2000 km. The very first samples of gas phase in subsurface fluids collected from the Tunka graben-like Basin of the BRZ indicated *R*-values close to those in MORBs [Lomonosov *et al.*, 1976]. The following researches covered both other basins of the BRZ and its surroundings in Russia and Mongolia [Khutorskoi *et al.*, 1991; Polyak *et al.*, 1992, 1994, 1998; Pinneker *et al.*, $1995_{1,2}$; Lavrushin *et al.*, 1999; Lysak and Pissarskii, 1999].

METHODS

Most of the BRZ samples presented free gas from underground waters which discharge through natural springs or bore holes; water- and oil-dissolved gases were subordinate. Free-circulated fluids are more suitable to study regional features of He isotope distribution as compared to minerals. The latter are extremely diverse in He composition depending on their origin, structure and constitution. With time, however, He passes from minerals and rocks into circumambient fluids. In the fluids, the He isotopic composition is averaged by natural way in proportion to contributions from different sources and becomes a quasi-stationary characteristic for given hydrogeological system.

Searching for any regularity in lateral variations of *R*-values is impossible without a preliminary analysis of *R*-value fluctuations at the sampling sites with time and depth. Our studies showed that *R*-values in the objects sampled repeatedly in the Baikal-Mongolian regions were constant during many years. Except for active volcanoes, the temporal constancy was noted in other regions too, e. g., in Iceland, Italy, Mexico. There are no trends in the *R*-value variations along the depth in the drilled areas of the Baikal region, whereas these areas differ from each other in *R*-values. So, an individual fluid specimen could be generally considered as a representative one for given locality to search for lateral variations of He isotope composition.

RESULTS AND DISCUSSION

There is no strict universal relation between He isotope composition and major component of a gas phase in the region under study. Nevertheless, the total data set shows that the lowest *R*-values are peculiar to CH_4-rich gases (Figure 1). Other gases show more diverse *R*-values, CO_2-rich gases being locally marked by the highest *R*-values.

A negative correlation between He isotope compositions and its concentrations in gas phase of fluids is displayed on Figure 1. The correlation reflects a mixing of two end-members. The first one corresponds to the MORB reservoir in line with the recent estimation by Marty and Tolstikhin [1998] for the $CO_2/^3He$ ratio in this reservoir. The second end-member is the reservoir of crustal He with equilibrium radiogenic ratio. The slope band represents mixing between the mantle MORB-like reservoir and crustal He. The mixing causes the vertical scatter of data-points.

The horizontal scatter from this band originates from other possible reasons. One of them is solubility-controlled fractionation of the mantle-derived He and CO_2 in the gas–water system. The other reasons could be generation or consumption of major gases within the earth crust. This problem was examined in more detail somewhere else [Polyak *et al.*, 2000], and we turn to the analyses of the *R*-value variations in the tectonic context.

A comparative analysis shows that the tectonic units of this region differ from each other in the *R*-values. On the Precambrian Siberian platform, the mean *R*-value is close to the canonic crustal radiogenic one. The higher *R*-values observed in the Hangayn Range are inherent to Paleozoic crust where the traces of the mantle-derived He are noticeable up to the present. The Transbaikalian area was reactivated in the Mesozoic and Cenozoic and now is locally characterized by the further enhanced *R*-values. The proper BRZ is distinguished by a widest spectrum of *R*-values amounting to the highest MORB-like magnitudes discovered, as noted above, in the Tunka basin.

The distribution of *R*-values along the BRZ strike is especially informative (Figure 2). Despite a very wide scatter of local *R*-values, this distribution as a whole is regular: the *R*-values descend more or less monotonically in both directions from the Tunka Basin which differs from its counterparts in high Neogene–Quaternary volcanic activity. Such a trend evidently indicates progressive contamination of the mantle derivatives by crustal radiogenic helium away from

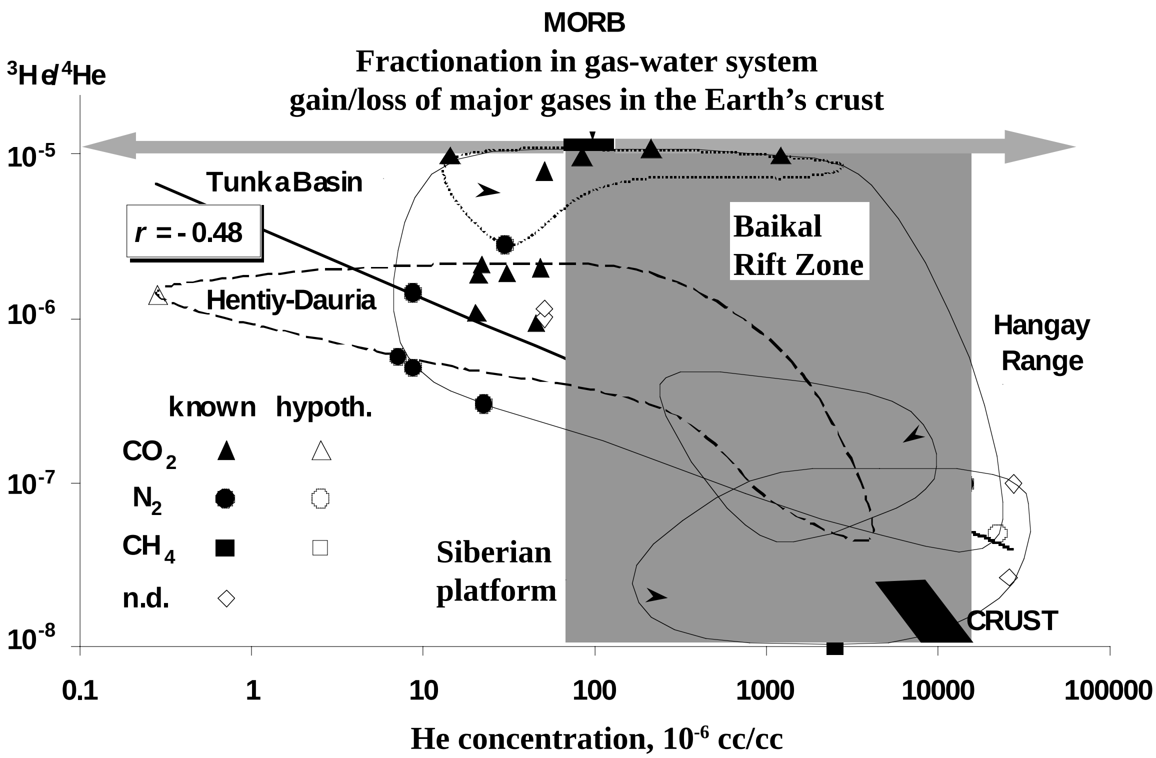

Fig.1. $^3He/^4He$ vs. He concentration in subsurface fluids of the Baikal Rift Zone.

the Tunka Basin. The fall of *R*-values is accompanied by decrease in the sizes of riftogenic grabens.

Within the grabens, local gravitational maximums are observed. They are explained by intrusions of mafic and ultramafic melts. The melt sources can be identified by the use of He isotopes. In this respect, however, the host rocks in the Baikal region were studied worse than underground fluids. *R*-values were measured only in recent basalts from the Khamar-Daban and Udokan areas [Drubetskoi and Grachev, 1987; Grachev, 1998]. These data characterizing xenoliths of spinel lherzolite in basalts, as well as olivine which is a good keeper for He, are shown on Figure 2 as shaded rectangles. The rectangle positions agree with the trend observed in fluids. It is very strange, since xenoliths are considered to be extracted from the mantle, and, if so, the mantle should be heterogeneous in respect to He isotope composition. The arising problem stimulates an analysis of the heat flow data, because the mantle-derived magma should transfer into the crust not only volatiles including He but the heat accumulated in melts as well.

The heat flow data generalized in [Lysak, 1988] display the same trend along the BRZ strike as *R*-values show: the mean of conductive heat flow density decrease along the rift zone in both directions from the southern Baikal – Tunka basins (Figure 2). So, the spatial variations of *R*-values in fluids and background heat flow density in the BRZ are similar. The similarity observed in BRZ is a particular (regional) manifestation of the general (global) regularity expressing a paragenic relationship of these parameters owing to a single underlying cause. This common cause can be only the discharge of heat-mass flux out of the mantle into the crust.

Similar lateral variations in both mantle-derived He input into subsurface fluids and deep heat loss in the BRZ indicate that heat-mass flux from the mantle (the mantle diapirism) occurs in different segments of rift zone with an unequal rate.

The same pattern of the *R*-value distribution along the strike of rift zone is observed in underground fluids of the BRZ counterparts from all the continents including the African-Arabian belt [Lupton, 1977; Craig and Lupton, 1978; Marty *et al.*, 1993, 1996; Moreira *et al.*, 1996; Scarci and Craig, 1998]. In the latter, He isotope composition distinguishes the Afar mantle plum with the extra-MORB *R*-values, young Red Sea with the MORB-like *R*-values, and the rift segments with lower *R*-values progressively decreasing both northward (in coastal springs of Dead Sea and Tiberias Lake) and southward (in Gregory Rift and Tanganyika Lake) because of a mixing with crustal radiogenic He. It may be inferred that the wide and regular *R*-variations in subsurface

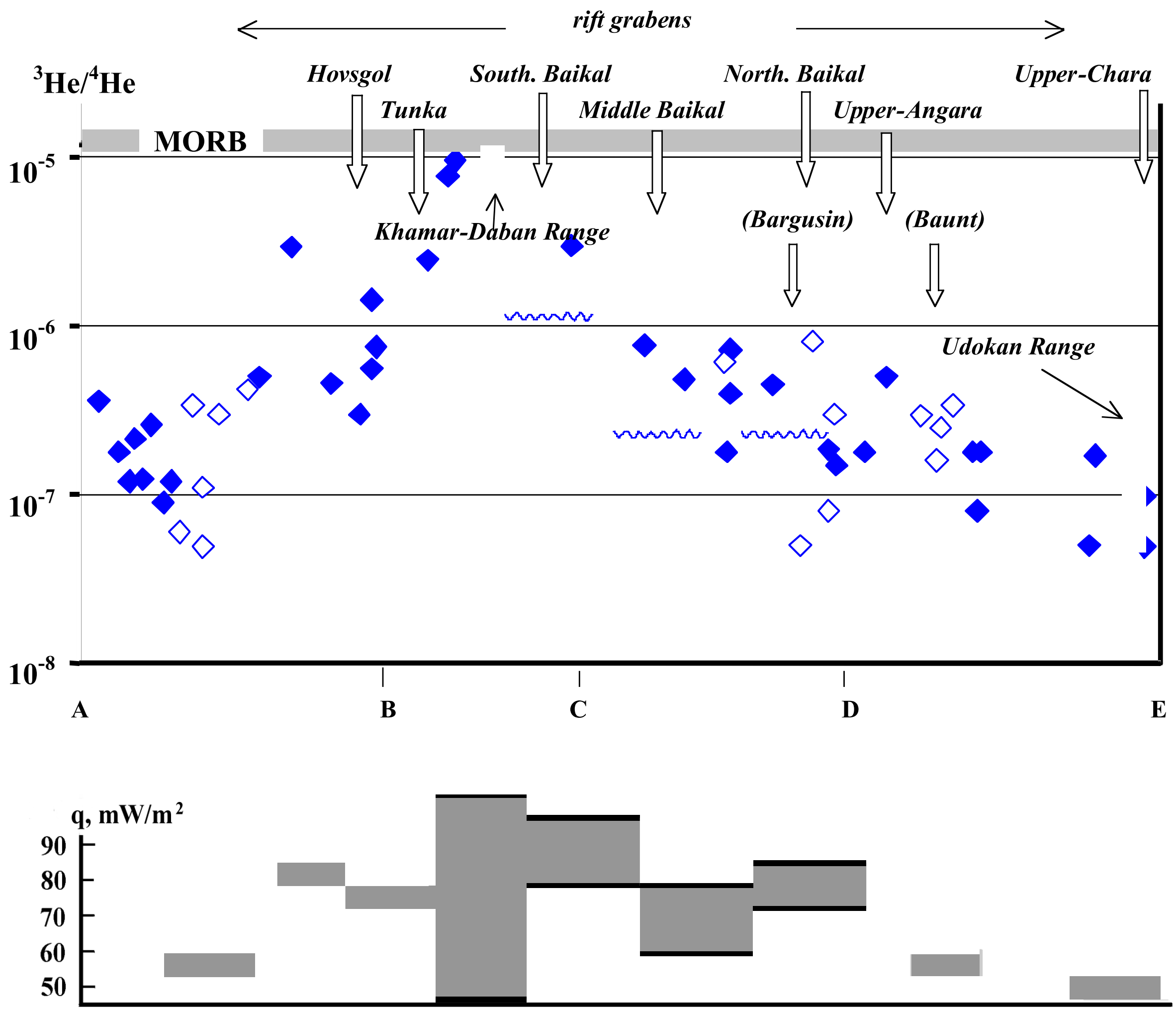

Fig. 2. $^3He/^4He$ in subsurface fluids and the background heat flow density (*q*) along the strike of the Baikal Rift Zone.

fluids from axial rift zone represent a common feature of the continental rifts, which radically differ in this respect from the mid-oceanic ridges. This contrast apparently indicates different mechanisms of the mantle-crust interaction in the oceanic spreading zones and continental rifts.

Spreading of the oceanic crust represents the lithosphere tension as a response to the mantle-derived melt upwelling with equal rate along the whole ridge axis. Contrastingly, the continents originated from accretion of collided crustal terrains, are under compressive strain. It provokes brittle deformations permissive autonomous movements of newly separated blocks and an occurrence of the pull-apart structures (embryos of continental rifts). The mantle upwelling, decompressional melting, and magmatism could occur in these structures. So, the mantle upwelling in continental rifts (and, probably, in back-arc spreading zones too) is not a cause but an effect of rupture deformations in the overlying lithosphere.

In the limiting case, riftogenic deformations (especially intensified by the mantle plums) can result in break-up of continents, opening of new oceans, as observed in the Red Sea, and with rearrangement of convection cells in the mantle. Therefore, it may be concluded that spreading and rifting are related by a cause-effect feedback.

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