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GEOCHEMISTRY

Helium Isotopes in the Underground Springs of East Tuva

K. M. Rychkova[a], **A. D. Duchkov**[b], **V. I. Lebedev**[a], **and I. L. Kamenskii**[c]

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East Tuva, one of the most seismoactive zones of the Altai–Sayan region, is located at its eastern flank and adjoins riftogenic structures of the southwestern termination of the Baikal rift zone (BRZ). East Tuva incorporates a volcanic area including one of the largest recent lava fields (East Tuva lava highland) in Central Asia and extended valley lava flows [1]. This zone is considered volcanically active and hazardous. The lava field is controlled by the NNE-oriented fault system, which also governed the formation of the southern present-day Bilin–Busiingol graben. The area of East Tuva and adjacent Mongolia is characterized by a sharp change in the stress-strain state of the lithosphere. Numerous thermal veins [2] and some geothermal estimates of heat flow [3] attest to high temperatures in the Earth's interior in this area.

In 2003, the authors launched a study of distribution of stable ^{3}He and ^{4}He isotopes and their ratio R (^{3}He/^{4}He) in the gas–aqueous fluids of underground springs in East Tuva [4]. The isotope geochemistry of noble gases is widely used now for studying the nature of driving forces of tectogenesis, the origin of diverse underground fluids, and sources of mantle signals. Conclusions obtained from isotope ratios are based on the following concept: the ^{3}He isotope (mantle or primary) was entrained by the Earth's matter during accretion of the planet, whereas radiogenic isotope ^{4}He is continuously forming in the lithosphere due to the decay of U and Th. The sequential migration of helium isotopes in the atmosphere and space occurs at different rates. The helium isotope ratio in atmosphere is constant at $R_a = 1.4 \cdot 10^{-6}$. Helium contained in the samples of gas or water from fluids of underground springs is a mixture of mantle isotope ^{3}He, which is supplied from the Earth's interior by diffusion or different-scale convective processes, and crustal (^{4}He-rich) helium in the lithosphere. Evidently, the higher the intensity of mantle fluxes, the higher R value. Thus, the ^{3}He/^{4}He ratio in underground fluids is an efficient tool for estimating the intensity of the present-day heat-and-mass flow from the interior of lithospheric blocks [5–7].

Up to now, helium isotopes had been studied in several tens of gas and water samples from eight underground springs of East Tuva. The helium isotopic composition was analyzed in the Geochronology and Geochemistry of Isotopes Laboratory of the Geological Institute (Apatity) on a MI-1201 mass spectrometer. The contents of isotopes of helium (^{3}He, ^{4}He), argon (^{36}Ar, ^{40}Ar), and neon (^{20}Ne) were measured to control the correctness of sampling and to interpret the obtained information [8]. The averaged results are shown in Table 1. The location of springs is shown in the figure, which also demonstrates the R values determined in the underground fluids at the western BRZ termination by other authors [7, 9].

According to our data, the highest values of helium isotopes ratio in the underground springs of East Tuva vary from $37 \cdot 10^{-8}$ to $418 \cdot 10^{-8}$. All R values are one to two orders of magnitude higher than the background values for the Paleozoic crust (for example, the average R for Tien Shan is $\sim 5 \cdot 10^{-8}$ [10]), which directly indicates the present-day influx of the mantle helium isotope in the Earth's crust of the region. The highest $R = 418 \cdot 10^{-8}$ was found in the gases of the Choigan carbonic spring located in the northeastern flank of the East Tuva lava highland at the junction of northern termination of the Bilin–Busiingol graben with the front of the Oka depression. The R values determined in the samples from the Choigan spring are higher than those in the Khubsugul depression (maximum $206 \cdot 10^{-8}$) and those

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[a] *Tuva Institute for Complex Development of Natural Resources, Siberian Branch, Russian Academy of Sciences, ul. Internatsional'naya 117, Kyzyl, 667009 Russia*

[b] *Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences, pr. akademika Koptyuga 3, Novosibirsk, 630090 Russia; e-mail: duch@uiggm.nsc.ru*

[c] *Geological Institute, Kola Sicentific Center, ul. Fersmana 14, Apatity, Murmansk district, 184200 Russia*

Table 1. Elemental and isotopic compositions of helium and other noble gases in the thermal fluids of East Tuva

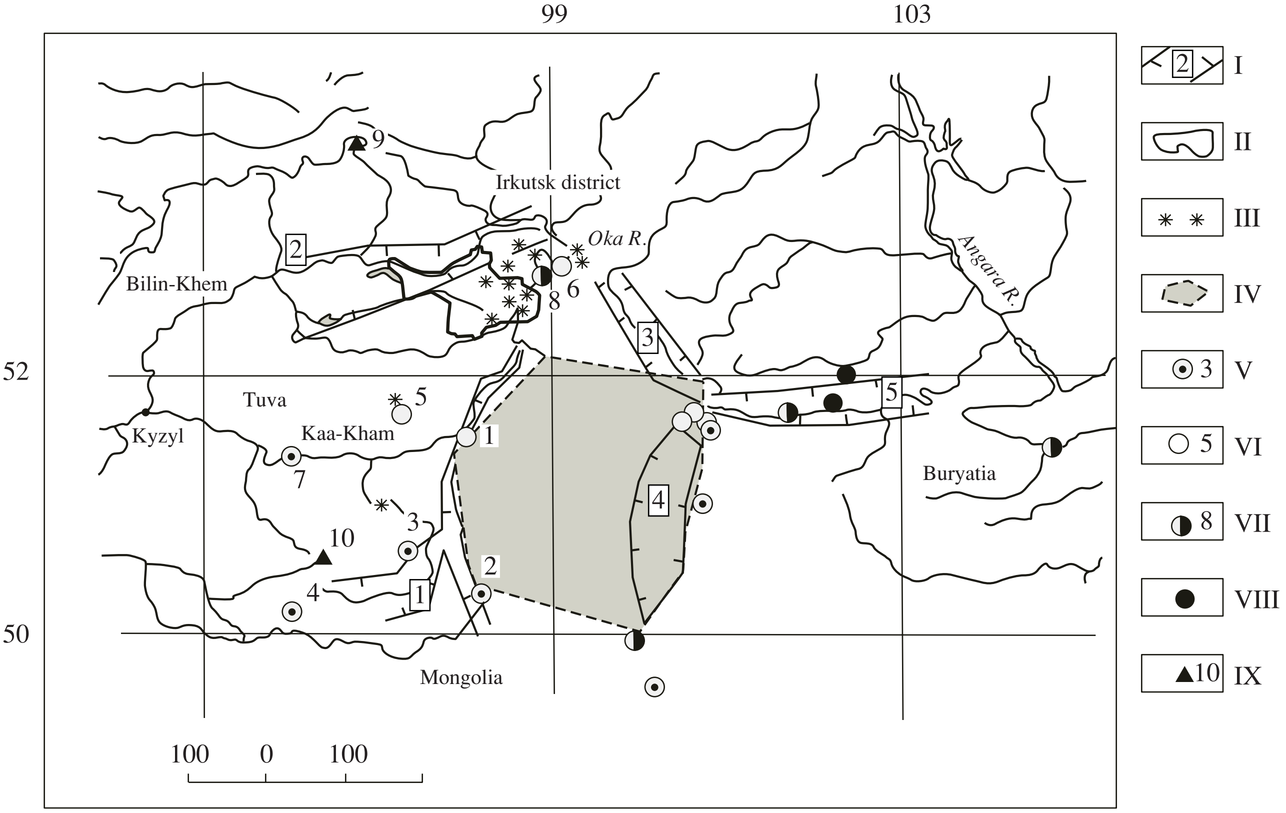
No.	Spring	Coordinates, deg		$R = {}^3He/{}^4He \cdot 10^{-8}$	${}^4He/{}^{20}Ne$	${}^{40}Ar/{}^{36}Ar$
		N	E			
1	Ush-Belídyr	51°28′	98°07′	51.5–55.6	56–235	301–303
2	Tarys	50°13′	98°12′	31.2–69.0	0.96–530	293–311
3	Saldam	50°40′	97°22′	36.8–50.2	19–59	299
4	Naryn	50°13′	96°15′	45.3	29	–
5	Maimalysh	51°40′	97°28′	121–129	28–153	297–302
6	Khoito-gol	52°40′	99°02′	61.75	91–732	300–301
7	Kara-charyk	51°24′	96°05′	37.1	1.27	297
8	Choigan	52°34′	98°45′	236–418	503–732	301

No.	Spring	Concentration in water, $3 \cdot 10^{-6}$ ncm/cmH_2O			Concentration in gas (mol % $\cdot 10^{-2}$)		
		He	Ne	Ar	He	Ne	Ar
1	Ush-Bel’dyr	11.8	0.21	–	27–29	0.14–0.15	107–117
2	Tarys	0.2–18.4	0.19–0.21	108	41–44	0.09–0.13	44–70
3	Saldam	0.89–3.9	0.21	153	–	–	–
4	Naryn	–	–	–	–	–	–
5	Maimalysh	3.13–3.44	0.12	107	28	0.20	80
6	Khoito-gol	12.7–13.5	0.13–0.16	210–276	37.1–39.0	0.059–0.082	91.7
7	Kara-charyk	0.18	0.16	242	–	–	–
8	Choigan	12.7	0.13	210	37.1–39	0.059–0.081	91.7

at the western flank of the Tunka depression with $R = (210–287) \cdot 10^{-8}$. However, these values are lower than submantle R values recorded in the central part of the Tunka depression with $R = (620–1120) \cdot 10^{-8}$ [7]. To sum up, our data indicate a northwestern continuation (possibly, even intensification) of mantle signal typical of the southwestern branch of the BRZ. The revealed anomaly is undoubtedly related to the Quaternary volcanism that is widespread in the northeastern part of Tuva. Volcanism ceased southward of the study region. The region incorporates separate older lava fields with traces of Holocene magmatic activation [1]. Helium isotopes in fluids of the Maimalysh underground spring (no. 5) were studied near the Miocene–Early Pleistocene Selig–Khem lava field located 200 km southwest of the East Tuva lava highland. Here, the R value was very high ($129 \cdot 10^{-8}$). The lowest $R = 37 \cdot 10^{-8}$ was determined in the samples from the westernmost Kara Charyk spring (no. 7) located within the sublongitudinal Shuya fault, which cuts the Ordovician granitoids. Volcanism in this area is represented by remnants of volcanic fields of the older (Late Oligocene–Early Miocene) age. Thus, one can see an evident negative correlation between R and the age of Cenozoic magmatism.

As compared to anomalous areas, the areas located south of the Maimalysh spring, in the Bilin–Busiingol graben (spring nos. 1–4), and western part (spring nos. 4 and 7) are characterized by a lower but stable mantle signal, with average R values from $37 \cdot 10^{-8}$ to $55 \cdot 10^{-8}$ (Table 1). The same relations of helium isotopes are also observed in the adjacent territories of Mongolia [9]. The preservation of relatively high R values over a vast territory can be explained by the presence of hidden present-day discharge of heat-and-mass flow in this area of East Tuva.

In addition to volcanism and helium flux, the mantle heat-and-mass transfer is manifested in the form of heat flow (q). Joint processing of a great body of samplings of R and q values showed the following relation between these parameters: $q = 18.231 \log R + 181.82$ [5]. The indicated dependence can be used for coarse estimates of heat flow if special geothermal determinations cannot be accomplished in boreholes. The helium method of q determination was tested in many regions. It was successfully applied in Mongolia [6], the Baikal rift zone [7, 9], Tien Shan [11], and other areas. We used this method to estimate the heat flow from He isotope ratios in the underground springs of East Tuva. The calculation results are shown in Table 2, which also demonstrates the geothermal determinations of q in the Aryskan and Tanzek areas [3]. These areas are also noted in the figure. The heat flow determined by the helium method varies in East Tuva from 64 to 84 mW/m^2 (average ~70 mW/m^2). Two geothermal measurements (Table 2) yielded the same average value of heat flow equal to ~68 mW/m^2. New (helium) estimates of heat



Helium isotopes in the thermal mineral fluids of East Tuva. (I) Recent grabens: (1) Bilin–Busiingol, (2) Khamsara, (3) Oka, (4) Khubsugul, (5) Tunka; (II) East Tuva lava highland; (III) volcanic eruption centers; (IV) projection of mantle plume (after [13]); (V–VIII) sites of helium isotope determination in the thermal mineral fluids (numbers are as in tables) ranked by the $R/10^{-8}$ values: (V) 30–54, (VI) 54–140, (VII) 140–420, (VIII) 420–965 (sites without numbers were taken from [7, 9]); (IX) sites of heat flow determination (adopted from [3]) (Table 2).

flow significantly improved knowledge of the heat flow field in the southeastern (most seismic) part of the Altai–Sayan region. Now it is evident that East Tuva practically does not differ from the western BRZ termination in terms of heat flow (~ 70 mW/m^2). Such high heat flows unambiguously suggest an anomalous heating of the Earth's interior in East Tuva.

Deep temperatures can be calculated by geothermal method from values of heat flow with consideration of data on the structure and composition of the Earth's crust. In this work, we used a simplified geothermal method [3], which allows approximate estimation of temperature at different depths using only heat flow data. Table 2 shows the calculated temperatures for specified depths. One can see that deep temperatures in the Bilin–Busiingol graben practically coincide with estimates for the Baikal depression [12]. Mountainous areas of Tuva are significantly more heated than ridges of the BRZ. The temperature at the lower boundary of the Earth's crust beneath East Tuva ranges from 980 to 1210°C. Partial melting zones can be formed at the lower boundary of the Earth's crust in the blocks where the Maimalysh and Choigan springs are located. The heat flow allows approximate estimation of the thickness of the geothermal lithosphere [3]. According to our data, this parameter averages 70 km in East Tuva. In other colder areas of the Altai–Sayan region, the heat flow is no more than 40–50 mW/m^2 and the lithosphere is 100–120 km thick [3]. The obtained values indicate intense heating of lithospheric blocks in East Tuva due to the higher position of the asthenospheric lens.

Thus, the study of the distribution of isotopic helium composition in the underground fluids indicates spatial variations of the present-day mantle heat-and-mass transfer in East Tuva. The intense present-day heat-and-mass transfer is observed over a much larger territory than had been established from data on the distribution of the products of neovolcanism (East Tuva lava highland). The helium anomaly revealed in the northern area continues eastward across the Oka graben and presumably joins with the western flank of the Tunka mantle helium isotope maximum. The underground discharge of heat-and-mass transfer is recorded in the southern part of the Bilin–Busiingol graben and adjacent areas. The helium isotope anomaly in the east is spatially correlated with the projection of the upper mantle plume outlined by geophysical data [13]. The estimates of heat flow and deep temperatures based on

Table 2. Geothermal parameters of the Earth's crust in East Tuva

No.	Spring	Coordinates, deg		Maximum value $R \cdot 10^{-8}$	Heat flow, mW/m^2	Deep temperatures calculated from heat flow values, °C				
		N	E			10 km	20 km	30 km	40 km	50 km
1	Ush-Bel'dyr	51°28′	98°07′	55.6	68	270	490	690	880	1010
2	Tarys	50°13′	98°12′	69.0	69	260	475	660	830	980
3	Saldam	50°40′	97°22′	50.2	67	260	475	660	830	980
4	Naryn	50°13′	96°15′	45.3	66	260	475	660	830	980
5	Maimalysh	51°40′	97°28′	129.0	74	300	550	770	980	1130
6	Khoito-gol	52°40′	99°02′	61.75	69	300	550	770	980	1130
7	Kara-charyk	51°24′	96°05′	37.1	64	240	420	590	730	860
8	Choigan	52°34′	98°45′	418	84	270	490	690	880	1010
9	Aryskan	96°42′	53°29′	–	76	260	475	660	830	980
10	Tanzek	50°38′	96°18′	–	60	360	620	840	1050	1210

the helium isotope data confirm the preliminary conclusion about intense heating of the Earth's crust in East Tuva, which was probably related to the higher position of the asthenosphere. The revealed helium isotope anomaly unambiguously indicates similarity of the processes of heat-and-mass transfer in the adjacent lithospheric blocks of East Tuva and the Baikal rift zone. Additional gas-geochemical and geothermal studies of this region are required to refine this conclusion.

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