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Helium Isotope Ratios in Spring Waters of the Tunka–Oka–Sayan Rift (East Sayan Area): Correlation with Heat Flow

K.M. Rychkova✉, O.D. Ayunova

Tyva Institute of Sustainable Subsoil Use, Siberian Branch of the Russian Academy of Sciences, ul. Internatsional'naya 117a, Kyzyl, 667007, Russia

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Abstract—Studies of helium isotope ratios in groundwaters discharging as springs within the Tunka–Oka–Sayan rift in the East Sayan area reveal an anomaly extending for 350 km along the East Sayan fault on the extension of the Tunka anomaly in the southwestern flank of the Baikal rift system. The calculated heat flow values (qR) agree with the measured ones (qT), and the heat flow anomalies correlate with those in the $^3He/^4He$ ratios throughout the Oka–Sayan and Bilin–Busiyn-Gol rifts. The correlation of the geophysical and geochemical parameters confirms that both are controlled by heat and mass transfer. Both mantle helium and heat apparently originate from a mantle plume beneath the South Baikal volcanic province (SBVP). The concordant $^3He/^4He$ and heat flow patterns in the Oka–Sayan fault record ongoing rifting and magmatism along the East Sayan Fault zone. The helium isotope and heat flow anomalies are consistent with the presence of low-velocity zones in the upper 200 km beneath the southwestern Baikal rift zone as far as the southern edge of the Siberian craton, which are detectable in seismic tomography images. Magmatism in the extreme southwest of the Baikal rift zone was maintained by active tectonic movements in the Pliocene and by the activity of the SBVP mantle plume. The obtained helium isotope data and high heat flow values indicate that rifting and magmatism propagate northwestward along the East Sayan Fault zone. This pattern fits the geothermal model for continental rifts implying that magmatic activity in the western end of BRS has been controlled by lithospheric deformation. The geothermal model for the Baikal–Mongolia region covers the area northwest of the system of three rift basins along the East Sayan faults.

Keywords: $^3He/^4He$ ratio, heat flow, anomaly, volcanism, magmatism, faults, rifting, Baikal rift system, East Sayan Fault, Tunka basin, Oka basin, Bilin–Busiyn-Gol basin

INTRODUCTION

The study area, located in the southwestern end of the Baikal rift system (BRS), within 96°–103° E and 50°–53° N, includes the western flank of the South Baikal volcanic area (SBVP). The origin of SBVP is controversial, being attributed either to a plume of the Central Asian mantle hot field (Yarmolyuk et al., 2003) or to rifting-related magmatism controlled by activity in the Tuva–Mongolia highlands and their surroundings (Rasskazov et al., 2007). Seismic tomography reveals low-velocity zones at the SBVP base, which may record an upwarp of the asthenosphere reaching the crustal base (Mordvinova et al., 2007) or an ascending mantle plume fed by excess heat flowing from beneath the dense and thick cratonic lithosphere (Mordvinova et al., 2015). A plume at the base of SBVP was discussed also in (Zhao, 2009).

Isotope ratios ($^3He/^4He = R$), which are in a range of $\sim n \times 10^{-5}$ to $\sim n \times 10^{-8}$ in terrestrial objects, can provide reliable constraints on the genesis of heat and mass reservoirs involved in magmatic and rifting activity. The helium isotope ratios are the lowest ($R_{crust} \sim (2 \pm 1) \times 10^{-8}$) in old cratonic crust where ^4He was generated as a result of U and Th decay and dissipated into the air and into the extraterrestrial space. The R values increase at greater contents of ^3He leading to $R_{mantle} \sim 10^{-5}$. Mantle helium rises to the crust with mantle melts (Polyak, 1988), releases into crustal fluids that flow around igneous bodies, and mixes with crustal helium to different proportions. Thus, the crustal-to-mantle helium ratio can be a regional proxy of tectonic processes, like heat flow. $^3He/^4He$ ratios are related with conductive heat flow (q_R) as $q_R = 18.23 \lg R + 181.82$, and the correlation between the geochemical and geophysical parameters indicates that both are controlled by the same heat and mass transfer mechanism. The correlation has been confirmed by numerous studies and is used for reference in obtaining and updating heat flow data worldwide (Khutorskoi et al., 1991; Du, 1992; Lysak and Pisarsky, 1999; Italiano et al., 2000; Gordienko and Tarasov, 2001).

As part of heat flow studies, we sampled 28 springs in Tuva, out of which 17 springs within the Oka and Bilin–Busiyn-Gol rifts in the western flank of BRS. $^3He/^4He$ ratios measured in thermal mineral springs were used to estimate heat flow values and revealed a helium isotope anomaly on the extension of the Tunka mantle helium high reported pre-

✉Corresponding author.
E-mail adress: tikopr.sbras @mail.ru (K.M. Rychkova)

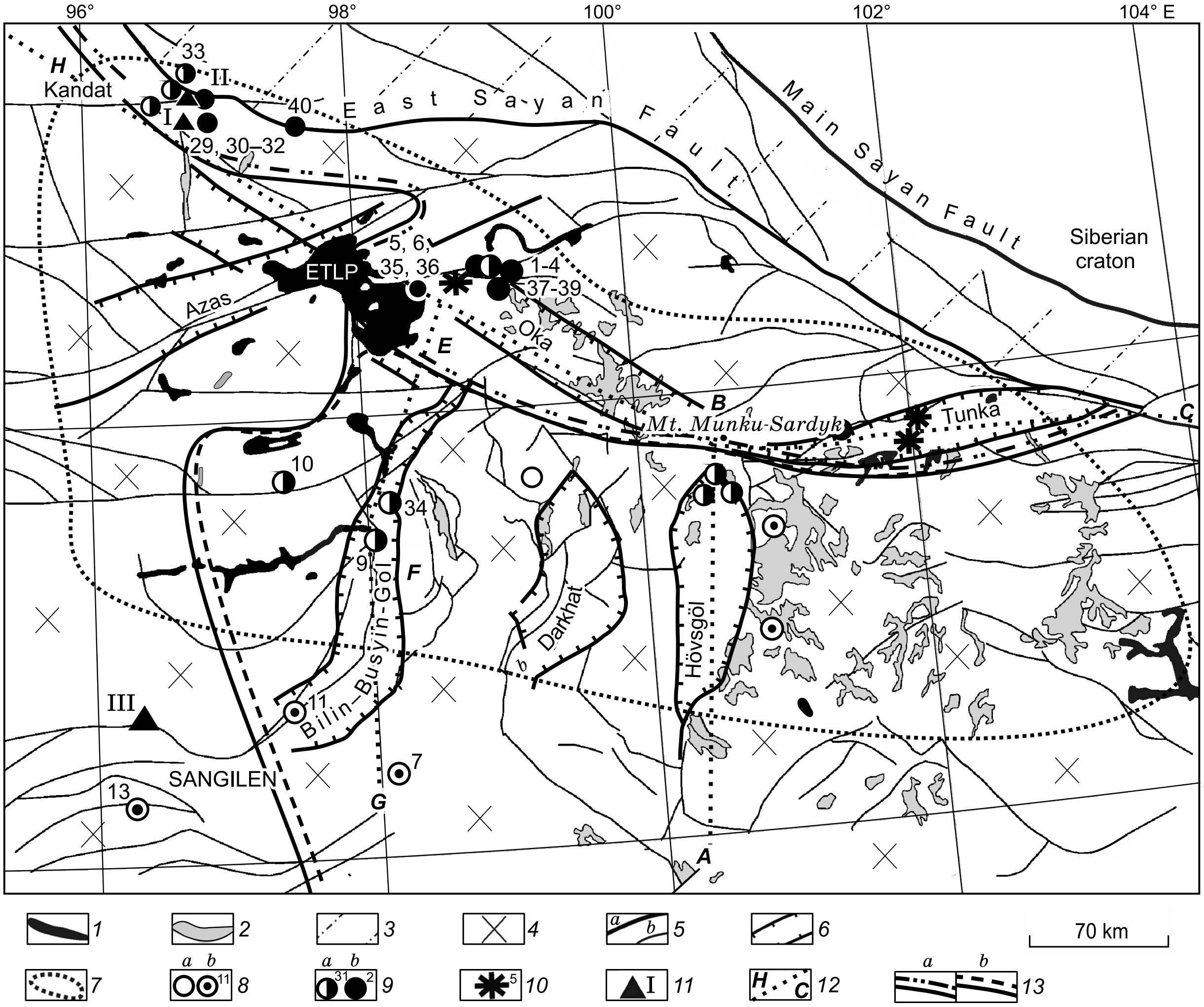

Fig. 1. Helium isotopes in spring waters of the East Sayan Range (Yarmolyuk et al., 2003), an atlas of GIS 1:500 000 geological maps of the Krasnoyarsk region, Khakassia Republic, Tyva Republic, and Evenki Autonomous District, http://atlaspacket.vsegei.ru. *1*, *2*, Late Cenozoic basalts: Late Pliocene–Holocene (*1*), pre-Late Pliocene (*2*); *3*, Riphean–Vendian metamorphic complex with Early Cambrian intrusions; *4*, Vendian–Cambrian rocks with Early Paleozoic intrusions; *5*, superregional (*a*) and regional (*b*) faults; *6*, rift valleys; *7*, contour of South Baikal volcanic province; *8*–*10*, sites of $^{3}He/^{4}He$ measurements and their values: (6–17) × 10^{-8} (*8a*), (18–50) × 10^{-8} (*8b*); (51–140) × 10^{-8} (*9a*), (141–420) × 10^{-8} (*9b*); >420 × 10^{-8} (10); *11*, site of borehole heat flow measurements; *12*, axial line of helium isotope distribution along rift zones (numbers of springs in the map correspond to their numbers in Table 1); $^{3}He/^{4}He$ distribution along line *ABC* is after (Polyak, 2000); *13*, East Sayan (*a*) and Hovsgol (*b*) hydrothermal provinces. ETLF, East Tuva lava field.

viously (Rychkova et al., 2007). The heat flows q_R retrieved from the helium isotope ratios of spring water were checked against direct measurements at three sites in the western BRS flank (Rychkova et al., 2007; Duchkov et al., 2010).

The $^{3}He/^{4}He$ and heat flow patterns in oceanic and continental rifts record the difference between the two settings: extension in mid-ocean ridges results from mantle processes while magmatism in continental rifts is controlled by lithospheric deformation (Polyak, 2004; Khutorskoi and Polyak, 2014). In 2011–2016, we additionally studied seven occurrences of issuing groundwaters in the northwestern direction along the Oka rift. This paper summarizes the new and earlier $^{3}He/^{4}He$ data from springs in the Oka–Sayan fault zone in the western end of BRS (Fig. 1).

METHODS

Helium was sampled following a reliable method and analyzed at the Laboratory of Geochronology and Isotope Geochemistry of the Geological Institute (Kola Science Center, Apatity) on an *MI–1201* mass spectrometer. Vacuum degassing of water samples and gas phase analysis were performed using a Khlopin-Gerling-type glass system with a mercury pump. The samples were analyzed for the concentrations of He and Ne, and Ar in some cases, as well as for the $^{3}He/^{4}He$, $^{4}He/^{20}Ne$, and $^{40}Ar/^{36}Ar$ isotope ratios. All $^{3}He/^{4}He$ variations were assumed to represent lateral patterns, as repeated sampling of springs in several groups for 2–7 years showed no time dependence.

Table 1. Helium isotope ratios and heat flows in the East Sayan area

No.	Spring No.	Spring name	$R_{meas} \times 10^{-8}$	$^4He/^{20}Ne$	$R_{corr} \times 10^{-8}$	He_{mantle}, %	q_R, q_T, mW/m^2	Reference
1	2	3	4	5	6	7	8	9
Oka rift								
1	1	Holun-Ugun	155	68	156	13	76	(Rychkova et al., 2007)
			140	–	–	12.5	75	(Badminov et al., 2013)
2	2	Shutkhulai	210	6	214	18	78	(Rychkova et al., 2007)
			180	–	–	16	77	(Badminov et al., 2013)
3	3	Hoyt-Gol	62	732	62	5	69	(Rychkova et al., 2007)
			68	–	–	7	69	(Badminov et al., 2013)
4	4	Krasnye Kamni	162	7700	162	13	76	(Rychkova et al., 2007)
		Dargal	140	–	–	12.5	75	(Badminov et al., 2013)
5	37		64	–	–	5.7	69	(Badminov et al., 2013)
6	38	Dundu-Gol	140	–	–	12.5	75	(Badminov et al., 2013)
7	39	Rodnik, volcano	190	–	–	17	78	(Badminov et al., 2013)
Total Oka rift			126	–	–	9.7	74	–
Eastern Tuva lava plateau								
8	5	Choigan	420	43	422	38	84	(Rychkova et al., 2007)
			310	–	–	28	81	(Badminov et al., 2013)
9	6	Biche-Sorug	179*	1*	196	16	77	(Rychkova et al., 2007)
10	35	Sorug	280	–	–	25	81	(Badminov et al., 2013)
11	36	Torpa	370	–	–	33	83	(Badminov et al., 2013)
Total			345	–	–	31	82	–
Kandat springs								
12	40	Isven (Yi-Spen)	217	9.1	250	21	79	Sampling of 2016
13	30	Shandal-Oi (Sorug)	253	18.8	255	21	79	(Rychkova and Lebedev, 2013)
14	31	Aryskan (Dashtyg)	144	0.38	–	–	–	(Rychkova and Lebedev, 2013)
15	32	Lower Kadyr-Os	140	10	140	12	75	(Rychkova and Lebedev, 2013)
16	29	Ak-Sug BH 8	103	2.2	97	8	72	(Rychkova and Lebedev, 2013)
17	33	Kizhi-Khem (Chamdzhak)	122	0.36	–	–	–	(Rychkova and Lebedev, 2013)
18	BH I	Ak-Sug	–	–	–	–	$q_T = 75$	(Fotiadi, 1987)
19	BH II	Aryskan	–	–	–	–	$q_T = 77$	(Sokolova, 2008)
Total			–	–	185	16	76	–
Bilin–Busyin-Gol rift								
20	7	Tarys	41	–	41	3	65	(Rychkova et al., 2007)
21	9	Ush-Beldir	54	–	54	5	68	(Rychkova et al., 2007)
22	34	Shishkhid-Gol	80	–	54	5	–	(Rychkova et al., 2007)
23	10	Maimalysh	129	–	129	11	74	(Rychkova et al., 2007)
24	11	Saldam	44	–	43	4	66	(Rychkova et al., 2007)
25	13	Naryn	45	–	44	4	66	(Rychkova et al., 2007)
26	BH III	Ulug-Tanzek	–	–	–	–	$q_T = 60$	(Fotiadi, 1987)
Total			–	–	61	5	67	–

*Presence of air reduced true values of $R_{measured}$ and $^4He/^{20}Ne$ ratios.

The data were corrected (Table 1) for the share of atmospheric helium in the total He content of samples, in order to eliminate its contaminating effect at $R_{atm} = 1.4 \times 10^{-6}$ (Mamyrin et al., 1970) during mixing of ascending fluids with percolating waters. The correction was calculated as (Polyak, 2000):

$$R_{corrected} = (R_{measured}\ (^4He/^{20}Ne)_{measured} - R_{air} \cdot (^4He/^{20}Ne_{atm}) / ((^4He\ /\ ^{20}Ne)_{measured} - (^4He/^{20}Ne)_{air}). \quad (1)$$

In most of the samples we analyzed, $R_{corrected}$ approached $R_{measured}$, i.e., contamination with atmospheric helium was minor to absent. The obtained $R_{measured}$ and $(^4He/^{20}Ne)_{measured}$ values were compared with R_{air} and $(^4He/^{20}Ne)_{air} = 0.3$. In the $^3He/^4He$–$^4He/^{20}Ne$ diagram (Fig. 2), almost all samples fall within the domain of mixed crustal and mantle components thus contain different percentages of crustal and mantle helium, except for springs Nos. 31 and 33 that plot near the atmospheric composition (AIR). The share of mantle

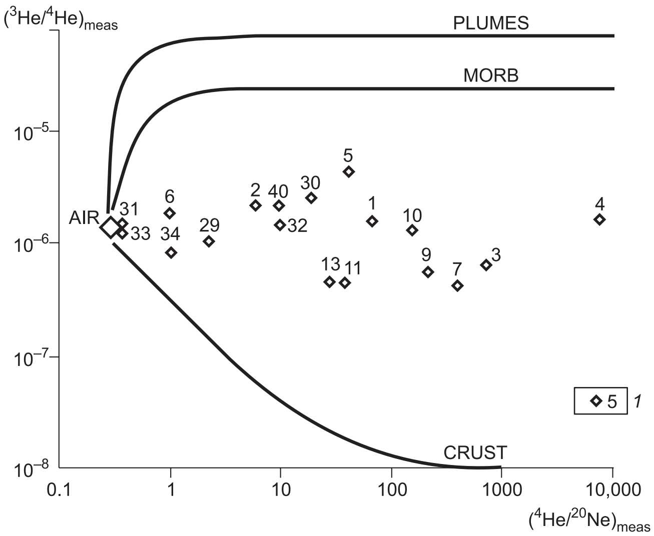

Fig. 2. Measured $^3He/^4He$ vs. $^4He/^{20}Ne$ ratios in spring water gases of the East Sayan area. Curves PLUMES and MORB correspond to $^3He/^4He$ and $^4He/^{20}Ne$ values in lower mantle and MORB reservoirs; curve CRUST corresponds to crustal values; AIR corresponds to atmospheric values. *1*, location of sampling site and sample number.

helium (He_m) relative to the total measured amount in a sample ($He_{measured}$) (Table 1) is from 3 to 38%, found as (Polyak, 2000):

$$He_{mantle} / He_{measured} = (R_{corrected} - R_{crust}) / (R_{mantle} - R_{crust}), \quad (2)$$

where $R_{crust} = 2 \times 10^{-8}$ and $R_{mantle} = 1200 \times 10^{-8}$.

Heat flux was estimated from helium isotope ratios using the relationship (Polyak, 1988)

$$q_R = 18.23 \cdot \lg R + 181.82. \quad (3)$$

The contents of major ions, gases, and minor elements in the water samples were determined at the Laboratory of Groundwater Chemistry in the *Water* Science and Education Center of the Tomsk Technological University.

The carbon isotope composition of carbon dioxide ($^{13}\delta C_{CO2}$) in six samples collected at three sites in the East Sayan Range (Table 2) was analyzed at the Laboratory of Isotope Methods of the Siberian Research Institute of Geology, Geophysics, and Mineral Resources, Tomsk Filial (Tomsk), on a Thermo Scientific *Delta V Advantage* isotope ratio mass spectrometer. The treatment of samples was chosen to provide $^{13}\delta C$ accuracy within 0.5‰ absolute error (at 95% confidence interval).

The locations of sampling sites are shown in Fig. 1.

GEOLOGICAL BACKGROUND

The study area belongs to the northwestern Tuva–Mongolia segment of the Central Asian Orogenic Belt at the junction of the stable Siberian craton and the mobile Mongolian and Amur plates (Zonenshain and Savostin, 1979). The regional tectonic framework formed by several events from the Precambrian through the Ordovician. The boundaries of Siberia with the two moving plates follow, respectively, the Main Sayan Fault and three rifts of the Baikal rift system (Fig. 1).

The basement consists of Mesoproterozoic (Riphean) and Late Neoproterozoic (Vendian) metamorphic complexes of the Baikalian orogeny which are erosively overlain by Early Cambrian rocks. The Baikalian orogenic complexes typically consist of widespread Precambrian carbonates separated by a sharp unconformity from the Lower Cambrian sequences (Sidorenko, 1966). They span almost the entire East Sayan Range in the northeast and the Sangilen Upland and the Hövsgöl system of basins in the south. Early Paleozoic orogenic complexes occupy the central part of the study territory and the Todzha intermontane basin filled with Precambrian and Early Cambrian volcanic-sedimentary rocks intruded by voluminous Early–Middle Paleozoic granitoids. The East Sayan fault zone is a tectonic suture between the older Baikalian orogenic complexes in the north and the younger Early Paleozoic ones in the south. The fault zone consisting of several NW faults connects with a regional-scale W–E Kandat fault. The junction between two fault zones is poorly pronounced in the east where they are separated by large granitic fields. The region is generally uplifted, and the uplift rates of ranges are faster than those for intermontane basins.

LATE CENOZOIC TECTONIC AND VOLCANIC ACTIVITY

Volcanic fields in the Central Asian orogenic belt are mainly localized within systems of rift basins along the

Table 2. $\delta^{13}C$ (CO_2) in springs of the East Sayan area

No.	Sampling site and sample number	Sampling date	Sample	$\delta^{13}C$, ‰ (CO_2)
1	*Lower Kara-Os, 3	17.07.13	Gas	–8.1
2	*Lower Kara-Os, 1	17.07.13	Gas	–6.4
3	Shandal-Oi (Sorug), 1	19.07.13	Gas	–7.3
4	Shandal-Oi (Sorug), 2	19.07.13	Gas	–7.5
5	Aryskan (Dashtyg), 1	23.07.13	Gas	–7.1
6	Aryskan (Dashtyg), 2	19.08.13	Gas	–7.6

*Sampling was from different issues of Kara-Os spring in the floodplain of Lower Kara-Os River.

Amur plate boundary. The volcanic fields among orogenic complexes consist of large (up to n·1000 km^3) lava plateaus, cones, and flows.

Cenozoic tectonic activity in the region has been associated with rifting in the Baikal rift system (BRS), but rift-related magmatism is restricted to several volcanic fields in its southwestern and northeastern flanks. The South Baikal volcanic province (SBVP) occupied by Late Cenozoic basalts covers an area of 350 × 450 km. It comprises the Tunka, Oka, and Hövsgöl sectors corresponding to the respective rift valleys that meet at Munku-Sardyk Mountain, the highest central point of the region (Fig. 1). Judging by the geochemical and isotope signatures of the SBVP lavas, their parental melts originated mainly from PREMA-type depleted mantle sources, with varying contributions of EM-II and EM-I components. On this basis, the origin of SBVP was attributed to the effect of a mantle plume of the Central Asian hot field (Yarmolyuk et al., 2003). The relation of the Late Cenozoic volcanism with a mantle hot field (Yarmolyuk et al., 2003) is in line with the presence of an asthenospheric upwarp beneath the Baikal rift (Zorin et al., 2006), local low-velocity zones in the asthenosphere (Kulakov, 2008), and a mantle plume beneath the Hangayn mountains traceable to 450–600 km depths (Mordvinova et al., 2007, 2015). Petrological and geochemical data coupled with seismic tomography, structural, and morphotectonic evidence support the mantle origin of the Hangayn Cenozoic volcanism and its relation to a mantle plume (Bushenkova et al., 2008).

The plume activity has continued since the Late Oligocene, with some lulls. In the Late Oligocene (>23 Ma), volcanic eruptions occurred almost all over the SBVP territory upon a generally flat terrain and produced lava plateaus (Yarmolyuk et al., 2003). The lava outpourings were especially voluminous reaching 9000 km^3 in the Early Miocene (23–17 Ma), within basins, mostly in the central SBVP part. The triple system of the Tunka, Hövsgöl, and Oka rifts accommodates Late Miocene (16–6 Ma) volcanic fields (Yarmolyuk et al., 2003). The volcanic activity began decaying at that time and became reduced to sporadic small fields within the Hövsgöl and Oka rifts in the Pliocene (6–3 Ma).

At the Early–Late Pliocene boundary, the tectonic stress field in the southwestern flank of the BRS changed dramatically from transtension that persisted from the Oligocene to transpression, with compression and shear in the NE direction (Parfeevets and Sankov, 2006). The stress change event induced the formation of the Azas and Bilin–Busiyn-Gol neotectonic basins.

After that event, <3 Ma, the Late Pliocene–Pleistocene–Holocene volcanism propagated to the northwest. The largest eruptions (~700 km^3) in the northwestern Oka rift formed the eastern Tuva lava plateau and numerous lava flows, which jointly make up the eastern Tuva lava field, one of largest latest Cenozoic volcanic fields in Central Asia (Sugorakova et al., 2003). The Late Pleistocene to Present history of volcanism in the area included at least eighteen mainly brief eruption events. The most intense fissure eruptions between 2.14 and 1.2 Ma (early stage) produced a lava plateau, while the later stage of 760 to 48 kyr BP shows up as remnant volcanic edifices looking like table mountains. The latest large eruption in the Zhombolok valley in the northeastern part of the plateau occurred 1000–2000 years ago, mainly from a few small fissure volcanoes of scoria type, and reached a volume of ~10 km^3. Repeated past volcanic activity in the area left traces as Middle Miocene volcanics under Quaternary lavas, both inside and outside the eastern Tuva lava field (Sugorakova et al., 2003).

A stress change in the Late Pliocene led to the formation of the Azas and Bilin–Busyin-Gol neotectonic graben-like basins. The Azas basin accommodated lavas while the N–S Bilin–Busyin-Gol graben, the westernmost in the system of Hövsgöl basins, is poor in volcanism: it is restricted to small occurrences in the center and almost lacks farther in the south.

WATER CHEMISTRY OF SAMPLED SPRINGS

The volcanism and tectonism induced hydrothermal activity in the area, with discharge of hot and cold groundwaters rich in nitrogen and carbon dioxide gases at numerous issues along deep faults. The study area comprises two hydrothermal provinces (Pinekker, 1968): (i) the East Sayan province of CO_2- and N-rich hot and cold springs in the north, which extends eastward within the East Sayan Range and encompasses the Tunka valley; and (ii) the Hövsgöl province of nitrogen- and silica-rich hot springs in the south, within the Hövsgöl system of rift basins (Fig. 1).

The discharged waters in the East Sayan province are hot and cold, above and below the mean annual climatic air temperature, respectively, and have N-, N-CO_2-, and CO_2-rich compositions of the gas phase. The springs issue at elevations from 1200 to 2000 m above sea level. We sampled N- and CO_2-rich hot and cold springs of Holon-Ugun, a spring at the foot of Peretolchin Volcano, as well as Dundu-Gol, Hoyt-Gol, Krasnye Kamni (Russian for *Red Stones*), Dargal, Shutkhulai, Choigan, Biche-Sorug, Sorug, and Torpa springs (Nos. 1–6, 35–39) along the Oka hydrothermal line following the valley of the Sentsa River, a tributary of the Oka. The water chemistry and gas composition of these springs were described in detail previously (Tkachuk and Tolstikhin, 1962; Pinekker, 1968; Badminov et al., 2001, 2013; Rychkova and Oyun, 2012).

The springs in the W–E East Sayan fault zone are mainly CO_2-rich hot and cold ones. We sampled several springs (Isven, Shandal-Oi (Sorug), Lower Kadyr-Os, Ak-Sug, Aryskan (Dashtyg), Kizhi-Khem (Chamdzhak), Nos. 29–33, 40, respectively) for water chemistry and gas composition (Fig. 1). The spring waters have mainly a moderately acidic pH and bicarbonate chemistry, with 32 to 36 mg/L Cl^-; the main cations are Na^+ and Ca^{2+} (46–63 wt.% Ca-equiv.), with a total salinity of 758 to 2169 mg/L at the Aryskan spring. The waters of the Lower Kadyr-Os and Aryskan springs contain much Li, Si, and Fe (from 0.67 to 5.54 mg/L) and lesser amounts of As, Mo, Se, and F. The Aryskan water is rich in uranium (>1 mg/L U). The Kizhi-Khem spring issues Mg–Ca-bicarbonate waters, with a total salinity of 434 mg/L and 0.34 mg/L Fe, of slightly alkaline pH.

CARBON ISOTOPE COMPOSITION

All spring water samples show uniform carbon isotope compositions (Table 2), with –7.1 to –7.6‰ $\delta^{13}C$ (CO_2), which are close to the values for deep-seated CO_2 carbon: $\delta^{13}C \cong -7‰$ (Hoefs, 2009), except for the Lower Kadyr-Os spring where $\delta^{13}C$ vary significantly ($\Delta = 1.7‰$). Therefore, the springs may be related to faults or fractures that act as conduits for deep fluids rich in isotopically heavy CO_2. This origin of the springs we sampled is consistent with the uniform $\delta^{13}C$ (CO_2) patterns.

Drilling at the Ak-Sug copper field tapped Ca-bicarbonate-sulfate waters with 333 to 917 mg/L SO_4^-, that have a neutral or moderately alkaline pH and a total salinity of 749 to 1451 mg/L. Note, however, that the samples were taken from an old borehole, where water may be stagnant. The water samples store relatively high concentrations of F, Sr, and Mo, sometimes Se, As, and Cd. The Isven spring waters have Mg–Ca-bicarbonate chemistry and a total salinity of 0.62 g/L (Orgiliyanov et al., 2017).

Numerous springs issue along the Bilin–Busiyn-Gol fault in the Hovsgol province of nitrogen- and silica-rich hot waters. Their major-ion chemistry and gas phase compositions were described by Pinekker (1968). We sampled the Ush-Beldir, Maimalysh, Tarys, Tere-Hol (Saldam), Shishkhid-Gol, and Naryn springs (Nos. 7, 9–11, 13, 34) for $^3He/^4He$ ratios. The names of the springs are according to (Pinneker, 1968), and local names are given in parentheses. For locations of the springs see Fig. 1.

DISCUSSION

Helium isotope composition of spring water gases. Almost all sampled spring waters show $^3He/^4He$ ratios much exceeding the background values for the Precambrian basement in the area (Table 1, Fig. 1).

Six springs were sampled in the Sentsa valley and within the East Sayan Range, in the western flank of the Oka rift along W–E and NE faults. The gas phase mainly consists of carbon dioxide and nitrogen (Nos. 1–4, 37–39, in Table 1 and Fig. 1). The samples from the Rodnik spring (No. 39), located at an elevation of 2000 m asl in the head of the Zhombolok lava river near Holocene Peretolchin Volcano, show a helium isotope ratio of $R = {}^3He/^4He = 190 \times 10^{-8}$, with 17% of mantle helium in the gas phase. The $^3He/^4He$ ratios are relatively low ($R = (60–64) \times 10^{-8}$) in two other springs (Hoyt-Gol and Dargal, Nos. 3 and 37, respectively) 12 km south of Rodnik, but higher than that (140–162) × 10^{-8} in the Holon-Ugun, Krasnye Kamni, and Dundu-Gol springs (Nos. 1, 4 and 38, respectively) 1.5–2.0 km farther to the south. The waters of three latter springs are currently about 3–5 ºC colder than they were previously (Tkachuk and Tolstikhina, 1962), and the lake they form has a lower level. A high $^3He/^4He$ ratio of 210 × 10^{-8} was measured in the Shutkhulai cold spring (No. 2) in the left side of the Sentsa valley 4 km south of the three springs. Thus, the measured $^3He/^4He$ ratios in the springs within the Oka rift are from 60 to 217 × 10^{-8} (141 × 10^{-8} on average), which is twice lower than in the Nilova Pustyn spring in the western flank of the Tunka basin (280 × 10^{-8}) (Polyak, 2000).

The gas phase of springs Nos. 5, 6, 35, and 36 that discharge along a large W–E fault in Cambrian metamorphic rocks within the eastern Tuva lava field, in the area of most voluminous Quaternary lava outpourings (about 650 km^3), contains a large percentage of mantle helium (31% on average) and has $^3He/^4He$ ratios reaching 196 × 10^{-8} to 422 × 10^{-8}, with an average of 316 × 10^{-8}. The highest value R = 422 × 10^{-8} corresponding to 38% of mantle helium was measured in the Choigan spring (No. 5). It exceeds the R value obtained in the western flank of the Tunka rift (280 × 10^{-8}) but is below the mantle values for the central part of the latter.

Three sites were sampled northwest of the eastern Tuva lava field where a group of springs occurs within the Kandat fault (Fig. 1): two carbonate springs (Shandal-Oi and Lower Kadyr-Os) and nitrogen-rich water from a blowing well at the Ak-Sug copper deposit (Nos. 30, 32 and 29, respectively). The analyses show lower R values from 97 to 255 × 10^{-8} (165 × 10^{-8} on average), at 98.0 and 96.5 vol.% CO_2 in the two carbonate springs, with–6.4 and –8.1 ‰ $\delta^{13}C_{CO_2}$ = (Table 2). These values approach those for mantle carbon according to (Chelnokov and Kharitonova, 2008), i.e., the springs within the Kandat fault may issue mantle CO_2.

Two springs sampled north of the Kandat fault show $^3He/^4He$ and $^4He/^{20}Ne$ ratios similar to the air gas composition (Fig. 2): the Aryskan cold spring (No. 31) with 99.3 vol.%, CO_2 and the Kizhi-Khem N-rich hot spring (No. 33). These ratios are common to fluids in the shallow subsurface zone of active groundwater exchange and would evidence for the lack of mantle helium in the gas phase. However, $\delta^{13}C_{CO_2}$ of –7.1‰ and –7.6‰ in the Aryskan spring fall within the same range as in the Shandal-Oi and Lower Kadyr-Os carbonate springs (Table 2), with a significant contribution of mantle helium. Note that the Aryskan water stores extremely high concentrations of U and Th which generate ^4He, while the high heat flow (75–77 mW/m^2) measured in a borehole within the Aryskan field may record a radiogenic heat anomaly. To clear up the controversy, more studies are required.

The Kizhi-Khem nitrogen-rich hot spring (No. 33) located 10 km north of Aryskan currently shows no gas emana-

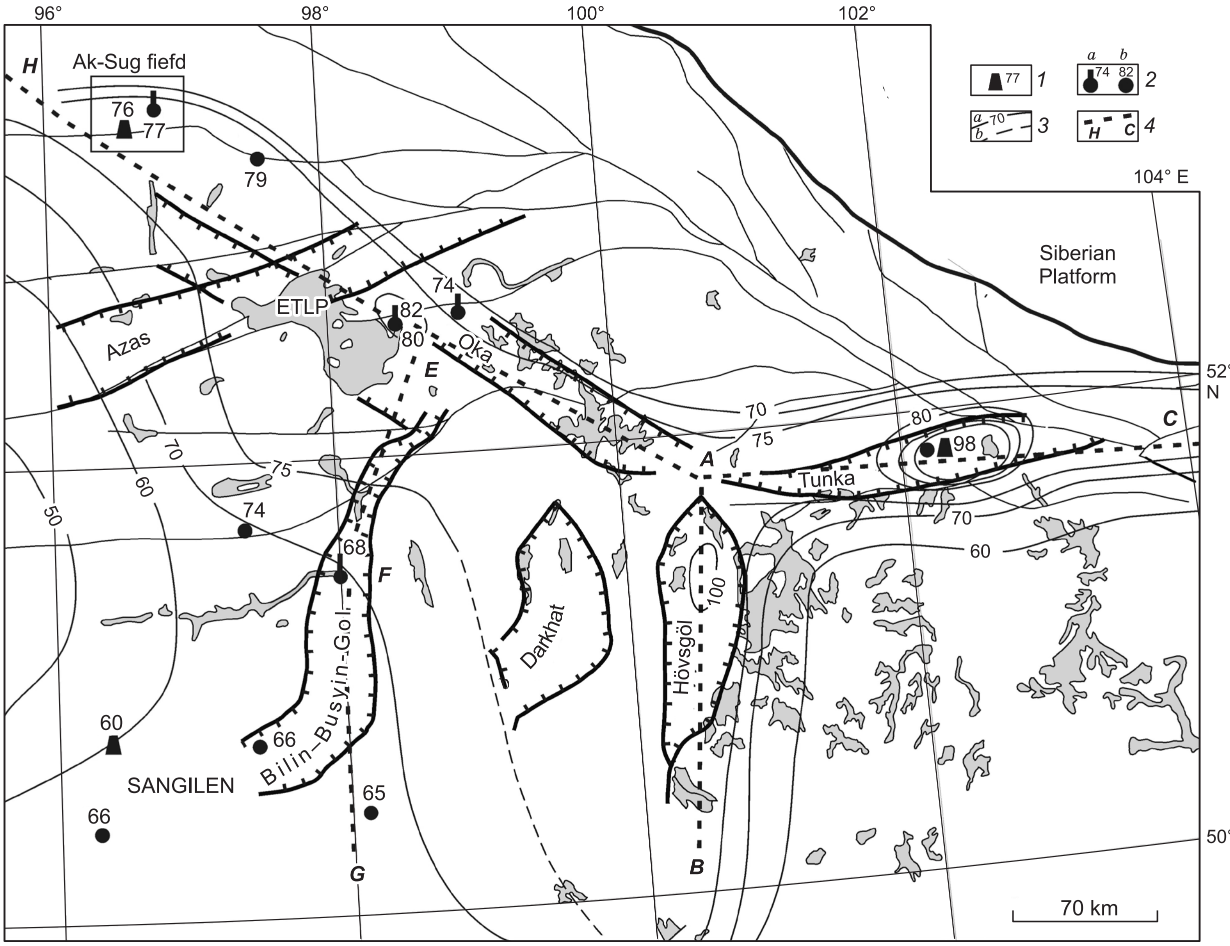

Fig. 3. Heat flow contour lines in the East Sayan and western BRS areas (Yarmolyuk et al., 2003), an atlas of GIS 1:500,000 geological maps of the Krasnoyarsk region, Khakassia Republic, Tyva Republic, and Evenki Autonomous District, http://atlaspacket.vsegei.ru. *1*, sites of direct measurements (mW/m^2); *2*, sites of heat flow (mW/m^2) determination from helium isotopes: average q_R over several springs (*a*), q_R for individual springs (*b*); *3*, heat flow contour lines (mW/m^2): field data (*a*) and prognostic values (*b*); *4*, axis of heat flow distribution along rift zones. Other symbols are as in Fig. 1.

tion and apparently underwent a fluid regime change, judging by the presence of a thick travertine cone downslope. However, the measured $^3He/^4He$ and $^4He/^{20}Ne$ ratios in its water correspond to atmospheric values and speak against magmatic activity across the Kandat fault zone.

The $^3He/^4He$ ratios of 250×10^{-8} measured in the Yi-Spen CO_2-rich spring (No. 40) in the axial part of the East Sayan Range, in the midway between the Kandat springs and the eastern Tuva lava field (Fig. 1), record a northwestward decrease of mantle helium in released gases.

Thus, the Oka–Sayan helium anomaly extends ~340 km northwestward from the western flank of the Tunka rift basin along the line *BEH* (Fig. 1) and follows faults in the Oka rift and the East Sayan fault zone. The helium isotope ratios decrease from 422×10^{-8} in the area of Quaternary volcanism to 141×10^{-8} and 165×10^{-8} in the eastern and western flanks of the rift. The northwestern extension of the anomaly falls within the low-velocity zone beneath the southwestern BRS that extends as far as the Siberian craton according to seismic tomography (Mordvinova et al., 2015). The mantle signal decays across the faults, faster northward (toward the craton) and more slowly in the southern direction.

The Bilin–Busyin-Gol rift lying south of the line *EFG* (Fig. 1) belongs to the Hövsgöl system of N–S basins. It is a classical rift with signatures of recent faulting and high seismicity. The rift is morphologically similar to the Hövsgöl basin but is notably smaller. The two basins appear to share a common history, which is confirmed by similarity of their $^3He/^4He$ patterns. The ratio decreases southward and westward along and across the strike of the basins: from the Tunka maximum to the background values typical of Precambrian crust along the Hövsgöl basin (Polyak et al., 1994) and from 422×10^{-8} to 36×10^{-8} (average $R = 61 \times 10^{-8}$) along the Bilin–Busyin-Gol basin (Rychkova et al., 2007). The latter pattern simulates the mantle signal variations along the whole Baikal rift system (Polyak, 2000).

These features are consistent with the regional tectonic setting: the Hövsgöl basin is the most developed one among parallel rifts and fits into the mantle hotspot projection, while the youngest Bilin–Busyin-Gol rift located 180–200 km in the west falls within the SBVP periphery, which may account for the lack of magmatism in its central and southern parts.

The revealed helium isotope anomalies in the Oka–Sayan–Bilin–Busyin-Gol fault zone extend the Tunka anomaly. The helium isotope ratios vary along the fault zone strike: two peaks of a similar magnitude in the center, within the fields of Quaternary volcanism, and lower R values on the flanks. This consistency prompts that the anomaly has been maintained by the same source all over the area, while the lateral R variations are due to variations in lithospheric deformation: the higher the deformation degree the higher the $^3He/^4He$ in the spring waters.

Heat flow. The $^3He/^4He$ ratios and heat flows demonstrate positive correlation throughout the Baikal rift system and, specifically, in the Tunka and Oka rifts in its southwestern flank. The perfect fit of heat flows determined by direct measurements (q_T) and retrieved from helium isotope ratios (q_R) at three sites (I, II, III in Figs. 1, 3) confirms the correlation of the two parameters and allows extrapolations over the whole Oka–Sayan zone (Table 1). The q_R heat flow is 74 mW/m^2 in the western Oka rift, increases to 82 mW/m^2 in the volcanic field of the East Tuva lava field, and the q_T value is 76 mW/m^2 in the extreme northwest; the anomaly decay is smoother in the western flank than in the east. The concerted variations in heat flow and helium isotope ratios all along the Tunka–Oka–Sayan rift zone (*HEBC* line in Fig. 1) appear as two double peaks corresponding to Quaternary volcanic centers and concordant decrease in both parameters away from the centers (Fig. 4).

Heat flows were not determined directly in the Bilin–Busyin-Gol rift, but the q_T and q_R values of 66–60 mW/m^2 at sites 13 and III correlate well with the He isotope composition in the area (Fig. 1). The measured and inferred heat flows in the rift and in the nearby Sangilen area form a large geothermal anomaly. The morphological and historic similarity of the Bilin–Busyin-Gol rift and the Hövsgöl basin, as well as the similarity in the helium isotope patterns, allows us to assume that the $^3He/^4He$ and heat flow values vary concordantly in the two basins and decrease toward the line *EFG*; the q_R values in the Bilin–Busyin-Gol rift decrease southward from 82 to 65 mW/m^2 (Table 1).

The $^3He/^4He$ vs. heat flow correlation all along the Oka–Sayan–Bilin–Busyin-Gol fault zone provides solid proof for

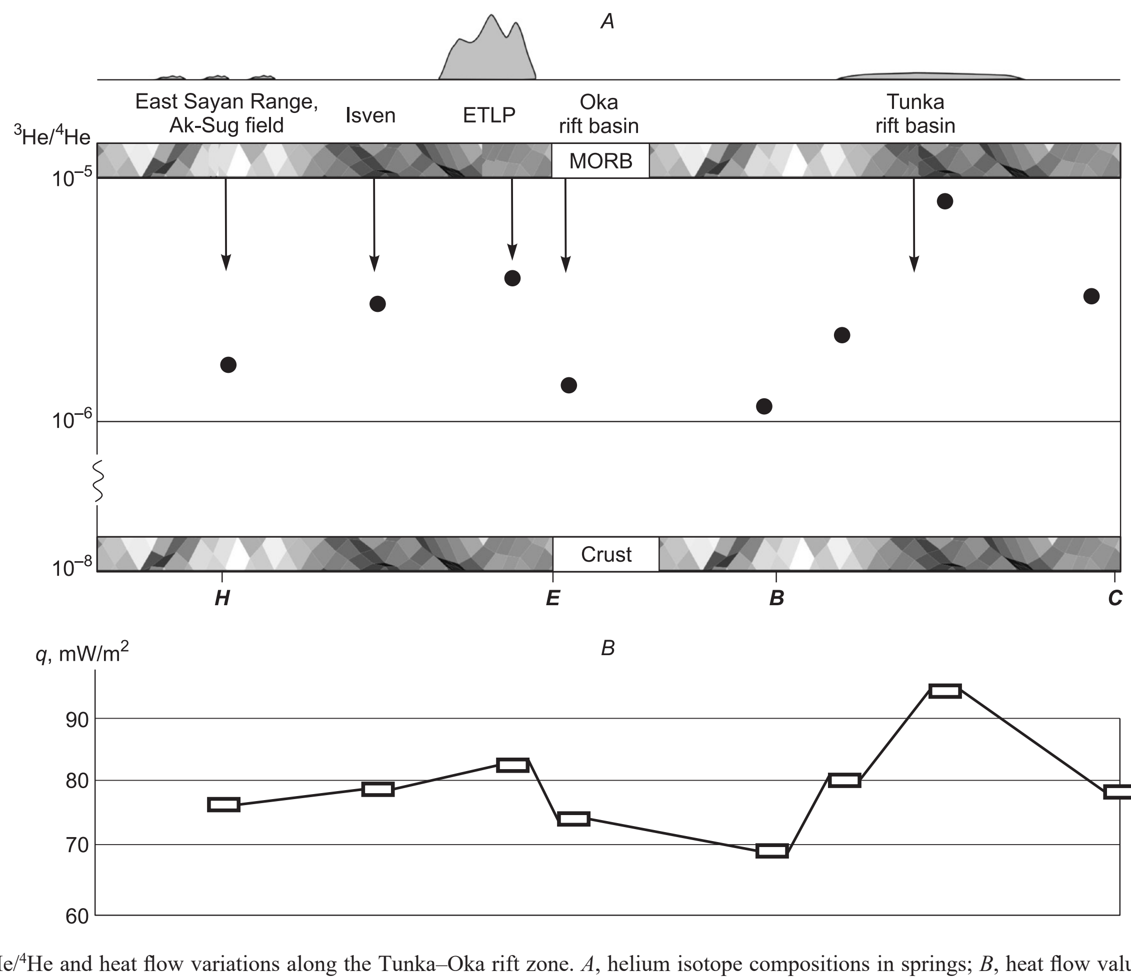

Fig. 4. $^3He/^4He$ and heat flow variations along the Tunka–Oka rift zone. *A*, helium isotope compositions in springs; *B*, heat flow values. Arrows point to central parts of tectonic units. *HEBC* is the axis of heat and mass fluxes along rift zones in the southwestern Baikal rift zone. Data along *BC* are from (Polyak, 2004).

the involvement of mantle heat and mass transfer (Fig. 4). The revealed concerted variations of the two parameters, with two peaks within Quaternary volcanic fields and lower values on the flanks (Fig. 4), are controlled by permeability of faulted crust, eruption volume, and crustal contamination of mantle melts. Correspondingly, the *R* and *q* values reduce to the background in the eastern flank of BRS, in the Chara basin (Lysak and Pisarsky, 1999), but spring water samples from the western end of the rift system contain large percentages of mantle helium, which is evidence of tectonic and magmatic activity propagation along the Oka–Sayan fault zone. The transport of mantle heat and helium agrees with the presence of low-velocity zones in the upper 200 km beneath the southwestern BRS that reach the Siberian craton. The velocity anomalies revealed by seismic tomography were attributed to heat transfer from beneath the craton (Kulakov, 2008; Mordvinova et al., 2015). According to our data, the discharge of heat and helium follows northward motion of mantle masses.

The tectonic and magmatic activity in the northwestern flank of the Baikal rift system became possible due to a change of tectonic setting in the Pliocene and to plume activity beneath SBVP.

CONCLUSIONS

The reported results reveal a helium isotope anomaly along the Oka–Sayan–Bilin–Busyin-Gol fault zone which extends the respective Tunka anomaly. The concerted variations in heat flow and $^3He/^4He$ ratios indicate that both geophysical and geochemical anomalies are maintained by the same mechanism of heat and mass transfer. Mantle helium is carried by a mantle plume beneath the South Baikal volcanic province. The $^3He/^4He$ patterns along fault zones with higher ratios in the center and lower values in the flanks are common to modern continental rifts and have been revealed also in the Baikal–Mongolia region (Polyak, 2004) and in the Oka–Sayan–Bilin–Busyin-Gol fault zone. This tendency indicates propagation of rifting and magmatism outside the Baikal rift system.

The neotectonic rifting processes in the BRS southwestern flank are most likely a far-field response of the lithosphere to the India–Eurasia collision (Parfeevets and Sankov, 2006), while flows of mantle material are driven by sublithospheric geodynamics (Yarmolyuk et al., 2003). Magmatic activity in the western end of BRS is maintained by lithospheric deformation (Polyak, 2004) coinciding with the projection of the SBVP mantle plume. The northwestward propagation of rifting and magmatism along the East Sayan faults inferred from helium isotope data fits the geothermal model for continental rifts (Khutorskoi and Polyak, 2014).

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REFERENCES

Badminov, P.S., Orgiliyanov, A.I., Pisarsky, B.I., 2001. Mineral waters in the western East Sayan: New data, in: Hydrothermal Resources of East Siberia [in Russian]. Irkutsk. Univ., Irkutsk, pp. 6–14.

Badminov, P.S., Ivanov, A.I., Pisarsky, B.I., Orgiliyanov, A.I., 2013. The Oka hydrothermal system (East Sayan). Vulkanologiya i Seismologiya, No. 4, 27–39.

Bushenkova, E.V., Deev, E.V., Dyagilev, G.S., Gibsher, A.A., 2008. The upper mantle structure and Cenozoic volcanism in Central Mongolia. Dokl. Earth Sci. 418 (1), 128–131.

Chelnokov, G.A., Kharitonova, N.A., 2008. Carbonate Spring Waters of the Southern Russian Far East [in Russian]. Dal'nauka, Vladivostok.

Du, J., 1992. $^3He/^4He$ ratios and heat flow in the continental rift-valley, in: Lanzhou, Y. Xu. (Ed.), Works of Gas Geochemistry. Gansu Sci. Technol. Press, pp. 165–171.

Duchkov, A.D., Rychkova, K.M., Lebedev, V.I. Kamensky, I.L., Sokolova, L.S., 2010. Estimation of heat flow in Tuva from data on helium isotopes in thermal mineral springs. Russian Geology and Geophysics (Geologiya i Geofizika) 51 (2), 209–219 (264–276).

Fotiadi, E.E. (Ed.), 1987. The Thermal Field of Siberia [in Russian]. Nauka, Novosibirsk.

Gordienko, V.V., Tarasov, V.N., 2001. Modern Activity and Helium Isotope Composition of Groundwaters in the Ukraine Territory [in Russian]. Znanie, Kiev.

Hoefs, J., 2009. Stable Isotope Geochemistry. Springer Verlag.

Italiano, F., Martelli, M., Martinelli, G., Nuccio, P.M., 2000. Geochemical evidence of melt intrusions along lithospheric faults of the Southern Apennines, Italy: geodynamic and seismogenic implications. J. Geophys. Res. 105 (B6), 13,569–13,578.

Khutorskoi, M.D., Polyak, B.G., 2014. Geothermal models of different geodynamic settings. Geotektonika, No. 1, 77–96.

Khutorskoi, M.D., Golubev, V.A., Kozlovtseva, S.V., Mitneyk, M.M., Yarmolyuk, V.V., 1991. The Subsurface Thermal Regime in Mongolia [in Russian]. Nauka, Moscow.

Kulakov, I.Yu., 2008. Upper mantle structure beneath southern Siberia and Mongolia, from regional seismic tomography. Russian Geology and Geophysics (Geologiya i Geofizika) 49 (3), 187–196 (248–261).

Lysak, S.V., Pisarsky, B.I., 1999. Estimation of heat flow from helium isotope ratios in the gas phase of spring waters from the Baikal rift zone and its surroundings. Vulkanologiya i Seismologiya, No. 3, 45–53.

Mamyrin, B.A., Anufriev, G.S., Kamensky, I.D., Tolstikhin, I.N., 1970. Estimation of helium isotope ratios in the atmosphere. Geokhimiya, No. 6, 721–730.

Mordvinova, V.V., Deschamps, A., Dugarmaa, T., Déverchère, J., Ulziybat, M., San'kov, V.A., Artemiev, A.A., Perrot, J., 2007. Velocity structure of the lithosphere on the 2003 Mongolian-Baikal transect from SV waves. Izvestiya Phys. Solid Earth 43 (2), 119–129.

Mordvinova, V.V., Treussov, A.V., Turutanov, E.Kh., 2015. Nature of the mantle plume under Hangai (Mongolia) based on seismic and gravimetric data. Dokl. Earth Sci. 460 (1), 92–95.

Orgiliyanov, A.I., Arakchaa, K.D., Kryukova, I.G., Badminov, P.S., Sodatova, E.S., Shestakova, A.V., Rychkova, K.M., 2017. Spring mineral waters of the Todzha area in the Tyva Republic, in: Health Resorts and Natural Health and Recreation Areas in Tuva and its Surroundings, Proc. 3rd Int. Conf., Book 3 [in Russian]. Anyyak, Kyzyl, pp. 1347–155.

Parfeevets, A.V., Sankov, V.A., 2006. Geodynamic setting of the Tunka branch of the Baikal Rift System. Geotektonika, No. 5, 61–84.

Pinekker, E.V., 1968. Mineral Waters of Tuva [in Russian]. Tuvinskoe Knizhnoe Izd., Kyzyl.

Polyak, B.G., 1988. Heat and Mass Fluxes from the Mantle in Main Tectonic Units of the Crust [in Russian]. Nauka, Moscow.

Polyak, B.G., 2000. Helium isotopes in groundwaters of the Baikal rift and its surroundings in the context of continental rifting. Rossiiskii Zhurnal Nauk o Zemle 2 (2), 1–21.

Polyak, B.G., 2004. Spreading and rifting: He–He isotope specificity. Geotektonika, No. 6, 19–32.

Polyak, B.G., Khutorskoi, M.D., Kamensky, I.L., Prasolov, E.M., 1994. Heat and mass transfer from the mantle beneath Mongolia. Geokhimiya, No. 12, 1693–1705.

Rasskazov, S.V., Demonterova, E.I., Ivanov, A.V., 2007. Late Cenozoic History of Magmatism at the Boundary of the Tuva-Mongolia Massif (East Tuva) [in Russian]. IZK, Irkutsk.

Rychkova, K.M., Lebedev, V.I., 2013. Isotope studies of springs in Tuva, in: Health Resorts and Natural Health and Recreation Areas in Tuva and its Surroundings, Proc. III Int. Conf., Book 3 [in Russian]. Anyyak, Kyzyl, pp. 162–166.

Rychkova, K.M., Oyun, L.A., 2012. Fluid and tectonic regimes of Tuva and its surroundings, in: Geological History of Water-Rock Interaction, Proc. Russian Conf. Int. Contrib. [in Russian]. NTL, Tomsk, p. 496.

Rychkova, K.M., Duchkov, A.D., Lebedev, V.I., Kamenskii, I.L., 2007. Helium isotopes in the underground springs of East Tuva. Dokl. Earth Sci. 417 (2), 1140–1143.

Sidorenko, A.V. (Ed.), 1966. Geology of the USSR, Vol. XXIX, Tuva ASSR [in Russian]. Nedra, Moscow.

Sokolova, L.S., Duchkov, A.D., 2008. Heat flow in the Altai–Sayan area: New data. Russian Geology and Geophysics (Geologiya i Geofizika) 49 (12), 940–950 (1248–1261).

Sugorakova, A.M., Yarmolyuk, V.V., Lebedev, V.I., 2003. Cenozoic Volcanism of Tuva [in Russian]. TuvIKOPR SO RAN, Kyzyl.

Tkachuk, V.G., Tolstikhin, N.I. (Eds.), 1962. Mineral Waters in Southern East Siberia, Vol. 1 [in Russian]. Izd. AN SSSR, Moscow.

Yarmolyuk, V.V., Ivanov, V.G., Kovalenko, V.I., Pokrovsky, B.G., 2003. Magmatism and geodynamics of the South Baikal volcanic province: geochronological, geochemical, and isotope (Sr, Nd, O) constraints. Petrologiya 11 (1), 3–33.

Zhao, D., 2009. Multiscale seismic tomography and mantle dynamics. Gondwana Res. 15 (3–4), 297–323.

Zonenshain, L.P., Savostin, L.A., 1979. Introduction into Geodynamics [in Russian]. Nedra, Moscow.

Zorin, Yu.A., Turutanov, E.Kh., Kozhevnikov, V.M., Rasskazov, S.V., Ivanov, A.V., 2006. The nature of Cenozoic upper mantle plumes in East Siberia (Russia) and Central Mongolia. Russian Geology and Geophysics (Geologiya i Geofizika) 47 (10), 1046–1059 (1060–1074).

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