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Helium isotopes in the ground fluids of the Baikal Rift and its surroundings: Contribution to continental rifting geodynamics

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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 in a wide range from $R = 0.01R_A$ (crustal radiogenic He) to $7.8R_A$ (close to the MORB He), where R_A is the atmospheric $^3He/^4He=1.4\times10^{-6}$. The lowest R values distinguish CH_4-rich gases. More diverse R values were measured in N_2- and CO_2-rich fluids, and the latter show the highest R. The N_2/Ar ratios for the N_2-rich gases are close to atmospheric values. 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 effects of solubility-controlled fractionation in gas-water system and gain/loss of chemically active gases within the crust. Gases of the pre-Riphean Siberian Platform have an average $R = 0.026R_A$ which is close to the "canonical" radiogenic crustal value. The distribution of the R values across the BRZ strike indicates a discharge of heat-mass flux from the mantle not only inside the BRZ as such, but much further to the east. The spectrum of R-values in the BRZ fluids is very wide: from $0.035R_A$ to $7.8R_A$, but there is a clear tendency to lowering of R-values at both sides with the distance from the Tunka depression considered as a "center of rifting". This trend correlates with both the heat flow density and the sizes of the rift depressions and demonstrates decreasing mantle-derived heat-mass flux to the margins of the rift zone. The comparison of BRZ data with those for other active continental rifts and mid-oceanic ridges suggests that the mechanisms of mantle-crust interaction during oceanic spreading and continental rifting are radically different.

1. Introduction

A relationship of continental rifting with the mantle activity is a generally accepted fact, yet the mechanism of this relationship still remains to be a matter of debate. The determination of the initial cause of the formation of continental rifts faces the same problem which was clearly formulated by V. E. Khain for the development of the Central Asia mountain belt: "collision or mantle diapirism?" [*Khain,* 1990]. A new light is thrown on this problem by the data available for helium isotope composition in deep freely circulating fluids.

It is known that the $^3He/^4He = R \sim 10^{-4}$ ratio in the primordial helium accounting for about 23% of the Universe mass and entrapped by the Earth during the accretion is four orders of magnitude higher than in the helium formed in ordinary terrestrial rocks during radioactive U and Th decay (the conventional radiogenic value for the ancient Earth crust being $R_{crust} \approx 2 \times 10^{-8}$), whereas in the atmosphere this ratio has an intermediate value, $R_a = 1.4 \times 10^{-6}$ (see a review in [*Mamyrin and Tolstikhin,* 1981]. At the same time, many active volcanoes, terrestrial hot springs, and sea-floor hydrothermal fluids flowing at mid-oceanic ridges and other

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objects show R values higher than in the atmosphere, namely $\sim 10^{-5}$, indicating that the mantle still contains primordial helium (see the reference mentioned above). Therefore, the isotope composition of helium is a highly sensitive indicator of the penetration of mantle derivatives into the upper layers of the lithosphere.

Mantle helium with R up to 1.2×10^{-5} was first discovered in the gases of the Kuril Island Arc [*Mamyrin et al.,* 1969]. Almost simultaneously, its traces were discovered in the oceanic crust in the area of the Kermadek Trench [*Clarke et al.,* 1969]. Thereafter, its searches began in tectonically active mobile structural features of other types, which resulted in finding R values as high as 3.5×10^{-5} in the hot springs of Iceland [*Kononov et al.,* 1974] and 2.1×10^{-5} in the gases of the Hawaiian Kilauea Volcano [*Craig and Lupton,* 1976]. Later, it was found that the ratios as high as that mark "hot spots" which were interpreted by *Morgan* [1972] as hot plumes rising from the lower undepleted mantle, whereas in the upper mantle, or in MORB reservoirs, they are known to have the average values of $(1.15\pm0.1)\times10^{-5}$ [*Marty and Tolstikhin,* 1998]. Of great interest were also specific mobile structures such as continental rifts, the Baikal rift being the first object of He isotope studies, where the R values as high as 0.89×10^{-5} were measured [*Lomonosov et al.,* 1976] in the gas from the thermomineral water flowing in the Tunka Basin, which after the correction for air contamination were found to be as high as 1.12×10^{-5}, these values being almost the same as those typical of the MORB reservoir.

These findings stimulated the further study of He isotopes in the gases of the Baikal Rift Zone (BRZ) itself and in the adjacent regions of Russia and Mongolia. Field fluid sampling operations were conducted there from 1975 to 1995, mainly by a team of researchers from the Geological Institute, Russian Academy of Sciences (Moscow), headed by the author of this paper and consisting of V. I. Kononov, S. V. Kozlovtseva, M. D. Khutorskoi, V. Yu. Lavrushin, and N. A. Lukina and by a team of researchers from the Institute of the Earth Crust, Siberian Division, Russian Academy of Sciences (Irkutsk), headed by E. V. Pinneker and consisting of B. I. Pisarskii, S. E. Pavlova, V. S. Lepin, and B. O. Shkandrii. Several samples were collected from thermal and minerals springs in the Trans-Baikal region (Zabaikalie) by N. E. Elmanova in the early 1970s. The mass-spectrometer determinations of the isotopic compositions of helium and other inert gases were carried out at the laboratories of the Ioffe Physicotechnical Institute, All-Union Petroleum Exploration Institute (both in St. Petersburg), and the Geological Institute, Kola Research Center, Russian Academy of Sciences (Apatity), with the participation of I. N. Tolstikhin, I. L. Kamenskii, E. M. Prasolov, B. A. Mamyrin, and L. V. Khabarin. Some results of these studies were published [*Khutorskoi et al.,* 1991; *Lavrushin et al.,* 1999; *Lysak and Pisarskii,* 1999; *Pinneker et al.,* 1995; *Polyak et al.,* 1992, 1994, 1998; *Prasolov et al.,* 1984].

The aim of this paper is to summarize these results for creating the general pattern of He isotope distribution in various ground fluids of the region, clarifying He association with the geochemical specifics of this regions's fluids, and finding regularities in the R variations along and across the strike of the continental rift discussed.

2. Description of the Data and Grounds for their Interpretation

2.1. Types and Number of Samples

The results of all R determinations in the freely circulating fluids of the Baikal Rift Zone and adjacent areas are summarized here in the Table 1 (see below). The fluids of this type are good objects for the regional study of terrestrial helium in contrast to rocks and minerals, where the isotope composition of helium is highly variable because of differences in their origin, composition, and structure, all controlling their ability to keep the helium entrapped. Yet, in the long run, as has been long known [*Gerling,* 1957], helium emanates from them, so that the rocks always contain lower amounts of helium than could be expected for their age and contents of the source elements, such as U and Th, as well as Li, the irradiation of which by thermal neutrons produces ^{3}He. In freely circulating fluids, to which helium passes from the rocks, its isotope composition is averaged in the natural way – in proportion with the contributions of all sources – and it becomes a quasiconstant regional characteristics of a given geological block in the hydraulically connected water-bearing systems. The conventional view of many researchers that helium is removed from the mantle by independent flows of volatile components is refuted by the correlation between the isotope compositions of atmophile helium and lithophile strontium, recorded in the products of recent volcanic and hydrothermal activity [*Polyak et al.,* 1979a].

The fluids used in this study were mineral waters and hydrocarbons (in the regions of the Siberian Craton). Based on their temperatures, the waters are classified into thermal water (with the outflow temperature higher than the average annual air temperature) and cold water, and, based on the main component of the gas phase, into nitric, carbonate, and methane water. Nitric water with the temperature as high as 84°C [*Lomonosov et al.,* 1977] occurs both in the platform area and in the Baikal Rift Zone, where it prevails, like in Mongolia. Yet, the Baikal Rift Zone also includes carbonic water in the Eastern part of the Tunka Basin, in the area of the manifestations of Quaternary volcanic activity. Here, the water flowing from the well-known Arshan Spring has a temperature of 8°C, whereas in the neighboring Well 39 its temperature is as high as 43°C at a depth of 750 m. Water of the same type prevails at the eastern flank of the zone (in Dauria and in the Khentey Kerulen Zone).

The temperature, flow rate, and composition of thermal mineral fluids vary in time in some springs. These changes seem to be provoked by geodynamic impulses. For instance, the temperature of water in the Zhemchug G-1 Well grew 5–10° higher after the earthquake of 30.06.95 in the Tunka Basin with M = 7 [*Lavrushin et al.,* 1999]. The 1995 testing of the East Baikalian Kopchagir Spring showed that the water flow had dropped compared with the period of 4–5 years before, the gas factor declined as well (the gas bubbling became sporadic compared to the previous steady and intensive flow). The chemical composition of emanating gas

Table 1. Inert gases from subsurface fluids of the Baikal-Mongolian region

Coordinates N latitude	Coordinates E longitude	LOCALITY	Sampling date	Sampling depth m	T °C	He (He+Ne) ppm	Ne ppm	Ar ppm	R_{corr} 10^{-8}	($^4He/^{20}Ne$) He/Ne	$^{40}Ar/^{36}Ar$	Major gas	Reference index
1	2	3	4	5	6	7	8	9	10	11	12	13	14
		SIBERIAN PLATFORM											
		Irkutsk Amphitheatre											
53°55′	104°33′	Christoforovskaya prosp.area, hole 12	<1976	1150		(480)		2000	4.2			CH_4	1
55°08′	105°13′	Gruznovskaya prosp. area, hole	<1976	2680		(2500)		440	1.0			CH_4	1
53°50′	103°50′	Shamanovskaya prosp. area, hole	<1976	2460		(2800)		460	1.8			CH_4	1
53°31′	103°39′	Bil'chirskaya prosp. area, hole	<1976	2280		(1920)		390	2.5			(CH_4)	1
53°40′	102°46′	Novo-Nukutskaya prosp. area, hole	<1976	450		(790)		1500	5.9			(CH_4)	1
53°43′	102°50′	Nukutskaya prosp. area, hole	<1976	430		(170)		11000	3.0			N_2	1
53°22′	103°59′	Osinskaya prosp. area, hole R-1	<1976	1650	13	(530)		990	3.5			(CH_4)	1
53°17′	104°06′	Parfenovskaya prosp. area, hole R-3	<1976	2400	35	(2460)		960	2.3			(CH_4)	1
52°18′	104°15′	Angara Sanatorium (Irkutsk), hole 223	1995		15	1975	19.8	13710	3.7	(110.5)	297.7	N_2	2
52°18′	104°15′	Angara Sanatorium (Irkutsk), hole 110	<1976	700	16	(990)		15800	4.0			N_2	1
52°37′	103°50′	Angarsk city, hole	<1976	400		(740)		12500	4.3			(N_2)	1
52°24′	104°09′	Batareynaya village, hole	<1976	400		(320)		10700	5.5			(N_2)	1
53°05′	105°30′	Bayanday village, hole	<1976	118		(770)		20800	10.0			(N_2)	1
53°05′	102°22′	Golumet' village, hole	<1976	60		(310)		20000	5.0			(N_2)	1
		Anzyr'–Beloyarsk profile, hole		370		25000			2.7				1
		Borovinok village, hole		152		440			2.0				1
		Bukhtumyr settlment, hole				350			2.0				1
		Nepa Arch											
56°33′	102°16′	Bratskoe prosp. area, hole		3020		2000			6.5			(CH_4)	3
57°13′	106°28′	Kosatkinskoe prosp. area, hole		2760		7500			1.2			(CH_4)	3
58°10′	106°14′	Nepskoe prosp. area, hole		2600		1960			1.6			(CH_4)	3
58°10′	105°53′	Verkhne-Nepskoe prosp. area, hole		1300		1550			1.6			(CH_4)	3
57°46′	107°04′	North-Markovskoe prosp. area, hole		2600		280			1.2			(CH_4)	3
57°46′	107°04′	North-Markovskoe prosp. area, hole		2200		3300			10.0			(CH_4)	3
57°55′	107°08′	Yaraktinskoe prosp. area, hole		2700		950		266	2.0		1673	(CH_4)	3
56°02′	103°17′	Yuzhnaya prosp. area, hole		3150		1540			2.2			(CH_4)	3
58°52′	102°39′	Endarma settlment				600			2.0				3
~58°30′	~107°00′	Isa river, spring, 2.5 from Nepa river mouth		0		350			2.5				3
54°02′	100°00′	Karasayskaya prosp. area, hole		1180		4250			12.0				3
58°03′	109°28′	Lena river, spring 4.5 km from Chay river mouth		0		310			2.5				3
~58°15′	~108°00′	Nepa river, spring 1		0		27000			10.0				3
~58°15′	~108°00′	Nepa river, spring 2		0		300			5.2				3
~58°15′	~107°00′	Zenan river, spring		0		2100			2.5				3

Table 1. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14
		BAIKAL-HOVSGOL RIFT ZONE											
		Verkhne-Chara Basin											
∼56°54′	∼118°15′	Verkhne-Charskiy Spr., spring # 2, bath	1984	0		(14200)		12000	9.8			N_2	1, 4
∼56°51′	∼118°12′	Luktur Spr.	1984	0	42	(22000)		16000	4.9			(N_2)	1, 4
		Udokan Range											
56°15′	116°53′	Plotinnyi Spr.		0					5.0			(N_2)	5, 6
56°15′	117°03′	Travertin Spr.		0					17.0			(N_2)	5, 6
		North-Muya Range											
56°16′	113°38′	Itykit Spr.		0					18.0			(N_2)	6
56°11′	113°35′	North Muya tunnel addit							18.0			(N_2)	5, 6
56°06′	113°41′	Okusikan Spr.		0					8.0			(N_2)	6
		Upper Angara Basin											
55°57′	110°33′	Dzhelinda Spr.		0					18.0			(N_2)	6
55°51′	111°12′	Irkana Spr.	1984	0		2450	9.66		50.0	(279)	301	(N_2)	7
		Northern Baikal Basin											
54°22′	109°31′	Davshinskiy Spr.	<1976	0	45	(190)		17000	45.0			N_2	1
55°30′	109°57′	Frolikhinskiy Spr.	1975	0	36	(780)		14200	15.0			N_2	1
55°24′	109°57′	Khakusskiy Spr.	1975	0	46	(720)		12000	19.0			N_2	1
55°24′	109°57′	Khakusskiy Spr.	1994	0	46				18	47.06		N_2	8
55°03′	109°04′	Kotel'nikovskiy Spr.	1975	0	64	(4100)		17800	5.0			N_2	1
53°40′	108°59′	Kulinnykh Bolot Spr.	1975	0	26	(100)		17600	18.0			N_2	1
53°45′	109°00′	Zmeinyy Spr.	1975	0	46	(500)		14000	40.0			N_2	1
53°37′	109°22′	Gniloi Spr.		0					72.0			(N_2)	6
55°42′	109°05′	Solnechniy Spr.		0					8.0			(N_2)	5
		Northern Basin of Lake Baikal, lake water	1982	920		(160)		8740	20.0				9
		Middle Baikal Basin											
52°58′	108°18′	Goryachinskiy Spr.	1972	0	54	(820)			41.0			(N_2)	1, 3
52°58′	108°18′	Goryachinskiy Spr.	1975	0	54	(750)			42.0			(N_2)	1
52°58′	108°18′	Goryachinskiy Spr.	1976	0		(629)			55.0			(N_2)	3
52°58′	108°18′	Goryachinskiy Spr.	1984	0	54	(1050)		10500	56.0			(N_2)	1, 10
52°31′	107°14′	Sykhaya Zagza th. area	1975		27	(290)			45.0			(N_2)	1
52°31′	107°14′	Sykhaya Zagza th. area	1984		27	(320)		1900	85.0			(N_2)	1
52°31′	107°14′	Sykhaya Zagza th. area, hole							100.0			(N_2)	6
		Middle Basin of Lake Baikal, lake water	1982	735		(80)		3580	22.0				9
		Middle Basin of Lake Baikal, lake water	1982	675		(80)		9500	24.0				9

Table 1. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14
		Southern Baikal Basin											
51°45′	105°50′	Sviatoi Kliuch Spr.		0					300.0			(N_2)	6
		Southern Basin of Lake Baikal, lake water	1982	1200		(50)		8980	102.0				9
		Southern Basin of Lake Baikal, lake water	1982	1260		(50)		9340	115.0				9
		Tunka Basin											
51°37′	102°23′	Zhemchug prosp.area, hole R-1	1973		38	2420		3108	890.0		410	CH_4	11
51°37′	102°23′	Zhemchug prosp.area, hole R-1	1985		38	2600		2400	850.0			CH_4	1
51°37′	102°23′	Zhemchug prosp.area, hole G1	1995		54	430	0.64	809	800.0	(742)	322.5	CO_2	2
51°37′	102°23′	Zhemchug prosp.area, hole 2							620.0				6
51°37′	102°23′	Zhemchug prosp.area, hole1							825.0				6
51°54′	102°28′	Arshan Resort, Glaznoy Spr.	1995	0	9.5	1176	4.1	4010	994.0	(315)	307.5	CO_2	1
51°54′	102°28′	Arshan Resort, Glaznoy Spr.	1983	0	8	506	3.43		860.0	(162)	303	CO_2	2, 7
51°54′	102°28′	Arshan Resort, Glaznoy Spr.	1975	0	8	(210)		2300	1100.0			CO_2	2
51°54′	102°28′	Arshan Resort, hole 26	1973		21	50		4213	800.0		315	CO_2	11
51°54′	102°28′	Arshan Resort, hole 28	1985		43	(14)		770	1000.0			CO_2	1
51°54′	102°28′	Arshan Resort, hole 39	1995		43	83	0.15	180	983.5	(614.5)	315.6	CO_2	2
51°41′	101°41′	Nilova Pustyn’ Resort, hole							214.0			N_2	5
51°41′	101°41′	Nilova Pustyn’ Resort, hole 1	1973		41	30		10033	280.0		300	N_2	11
		Hovsgol Basin											
50°46.5′	100°48.2′	Bulnay Spr.	1982	0	47	5740			46.0			N_2	12
50°46.5′	100°48.2′	Bulnay Spr.		0					46.0			(N_2)	13
51°20′	100°59.8′	Chzhilge Spr.	1982	0	6	23	19.4		30.0	(1.27)	296	N_2	1
51°32.7′	100°25.2′	Delger-Bulag Spr.	1982	0	4	90	19.3		56.0	(5.04)	296	N_2	1
49°25.5′	100°17.5′	Naran-Bulag Spr.	1988	0	0.2	9	19.2		50.0	(0.5)	300	N_2	1
51°33′	100°48′	Oboni Spr.	1982	0	3	9	18.9		142.0	(0.496)	296	N_2	1
51°36.8′	100°36′	Bilyutyyn Spr.	1982	0	5	180	23		74.0	[7.8]		(N_2)	1
50°4.2′	100°2.9′	Ulkhan Spr.	07.1973	0	7	140			290.0				13
50°4.2′	100°2.9′	Ulkhan Spr.	1982	0	2.8		22		296.0	[6.4]			1
		Barguzin Basin											
54°42′	110°42′	Allinskiy Spr.		0					81.0			N_2	6
53°26′	109°25′	Gusikhinskiy Spr.	<1976	0	55	(1500)		15600	61.0			N_2	1
54°59′	111°07′	Umkheyskiy Spr.	<1976	0	46	(1200)		12000	30.0			N_2	1
		Baunt Basin											
55°07′	112°59′	Bauntovskiy Spr.	<1976	0	48			15000	34.0			N_2	1
55°07′	112°59′	Bauntovskiy Spr.		0					25.0			N_2	5
55°22′	113°30′	Busanskiy Spr.	<1976	0	53	(4300)		14000	16.0			N_2	1
55°31′	113°50′	Frantsevo Spr.		0					34.0			(N_2)	5
55°25′	113°35′	Mogoi Spr.		0					25.0			(N_2)	6

Table 1. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14
		TRANSBAIKALIA (DAURIYA)											
50°19′	110°58′	Angi-Arshan Spr.	1995	0	3	3720	9.9	6970	4.4	(412)	298.3	CH_4	2
51°11′	113°48′	Darasun Resort, hole 6/56	1984		2.4	320		500	79.0			CO_2	2, 14
50°42′	110°58′	Kapchagir Spr.	1995	0	3.5	47	1.7	2.28	206.0	(31)	299.5	CO_2	2
51°45′	112°58′	Kuka Resort, hole 41	1972		0.2	190			185.0			CO_2	2, 14
50°39′	110°04′	Moduy Spr.	1995	0	4	21	0.33	461	187.0	(69)	303.5	CO_2	2
50°38′	110°29′	Poperechny Spr.	1995	0	4	22	0.2	334	214.0	(119)	305.4	CO_2	2
51°50′	116°40′	Urguchan Resort	1970		2				110.0			CO_2	2, 14
50°38′	110°15′	Yamarovka Resort	1972			(180)			50.0			CO_2	2, 14
50°38′	110°15′	Yamarovka Resort, hole 15	1995		4	45	0.2	195	95.0	(244)	305.7	CO_2	2
50°34′	110°54′	Mergitayka Spr.	1995	0	5	0.3	0.1	111	141.0	(3)	296.5	(CO_2)	2
50°15′	110°04′	Kunaley Spr.	1995	0	19.5	1029	21	11200	7.4	(54)	295.7	N_2	2
51°30′	118°28′	Yamkun Resort, spring	1984	0	17.5	(1400)		600	47.0			N_2	2, 14
		HENTIYN NURUU RANGE											
47°20′	110°04′	Dashi-Chingiyn Spr.	1983	0	10	230	2.56		120.0	(98)	292	CO_2	12
47°54.1′	100°55.5′	Orgil Spr.	1982	0	2-5	<20			110.0			CO_2	12
47°54.1′	100°55.5′	Orgil Spr.	06.04.1989	0	3.5				110.0			CO_2	13
47°33.5′	109°24.3′	Urta Spr.	1982	0	4	<30			190.0			CO_2	12
47°33.5′	109°24.3′	Urta Spr.	21.08.1989	0	1.5				190.0			CO_2	13
46°11.5′	109°21′	Dundyn-Amralt Spr.	1982	0	10	2370			13.0			N_2	12
48°45′	115°10′	Minzhur Spr.	1988	0	60	7	19.2		58.0	(0.41)	296	N_2	12, 15
47°49.9′	110°6.2′	Yargach Spr.	1982	0	1	240	24		27.0	[10.0]		N_2	12
47°06′	109°06′	Avrag Spr.	24.06.1990	0	8				65.0				13
47°03′	112°44′	Tal-Bulag Spr.	22.06.1990	0	3.4				130.0				13
		HANGAYN NURUU RANGE											
47°48′	97°34′	Bogdo-Ula Spr.	1988	0	41–54	1200	13.3		6.0	(98)	299	N_2	12
46°45′	100°26′	Bor-Tal Spr.	14.07.1990	0	46.5				18.0			(N_2)	13
47°45.3′	100°14.7′	Chulutu Spr.	1982	0	44	9700			12.0			N_2	12
47°45.3′	100°14.7′	Chulutu Spr.	16.07.1989	0	45				12.0			N_2	13
47°05′	101°00′	Gialgar Spr	15.07.1090	0	52				21.0			(N_2)	13
47°24′	101°36′	Khalun-Us Spr.	1982	0	86	5490			26.0			N_2	12
47°24′	101°36′	Khalun-Us Spr.	11.08.1978	0	35				26.0			N_2	13
48°20′	98°22.2′	Khodzhulin Spr.	1982	0	35	2400			11.0			N_2	12
48°20′	98°22.2′	Khodzhulin Spr.	13.08.1978	0	45				11.0			N_2	13
46°53.8′	102°46′	Khudzhirte Spr.	1982	0	44	7220			13.0			N_2	12
46°53.8′	102°46′	Khudzhirte Spr.	16.04.1990	0	55				11.0			N_2	13
48°15′	102°59′	Khul'dzhi Spr.	1983	0	51	3800	12.5		34.0	(333)	299	N_2	12
48°39′	102°37′	Khul'dzhi Spr. (Saikhan-Khul'dzh)	23.06.1990	0	51–56				30.0			N_2	13

Table 1. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14
		HANGAYN NURUU RANGE											
46°20′	101°13′	Shargalzhut Spr.	1983	0	90	1740	14.5		36.0	(131)	294	N_2	12
47°39′	101°32′	Shibertu Spr.	1982	0	60	3740	14.2		9.7	(290)	301	N_2	12
47°39′	101°32′	Shibertu Spr.	16.07.1990	0	59				8.4			N_2	13
49°15′	98°19′	Toshint Spr.		0					42.0			(N_2)	5, 6
47°02′	102°02′	Tsagan-Sumeit Spr.	12.07.1990	0	69				14.0			(N_2)	13
		Tsankhar	14.07.1990		85.5				15.0			(N_2)	13
47°13′	99°36′	Tsokhot Spr.	1988	0	20.5	3170	15.3		12.4	(227)	298	N_2	12
48°21.1′	98°47′	Zartyn-Chalun Spr.	1982	0	38	1010	7.05		4.9	(158)	297	N_2	12
		MONGOLIAN ALTAY RANGE											
		Chikhirt Spr.	1988	0	26	800	17.5		10.1	(50.2)	305	N_2	12
		GOBI DESERT											
45°44′	106°43′	Ara-Shantu Spr.	1983	0	10	252	6.6		46.0	(42.2)	293	CO_2	12

References: 1 – *Polyak et al.*, 1992; 2 – *Lavrushin et al.*, 1999; 3 – E. M. Prasolov's collection; 4 – collected by E. V. Pinneker and B. O. Shkandrii; 5 – *Pinneker et al.*, 1995a; 6 – *Lysak and Pisarskii*, 1999; 7 – collected by N. V. Lukina; 8 – *Kipfer et al.*, 1996; 9 – *Grachev et al.*, 1982; 10 – collected by G. N. Flerov; 11 – *Lomonossov et al.*, 1976; 12 – *Polyak et al.*, 1994; 13 – *Pinneker et al.*, 1995b; 14 – collected by N. M. Elmanova; 15 – collected by A. A. Rasskazov.

changed too. A sample collected in 1995 showed the concentrations of CO_2, N_2, and Ar to be 74.5, 25.3, and 2.3 tot.%, respectively [*Lavrushin et al.,* 1999], compared to the respective estimates of 1947 reported by *Karaseva* [1980]: 91.4, 6.9, and 1.3 tot.%. It appears that the growth of N_2 and Ar concentrations in the gas phase reflects a decline of their contents in the total mass of the fluid, rather than their growth in the total fluid and also in the spontaneously emanating carbon dioxide.

Most of the studied samples were free gases emanating from the fluids as they were discharged onto the ground surface by way of natural springs and boreholes. Researchers from the Institute of the Earth Crust, Russian Academy of Sciences, also collected samples of gases dissolved in water [*Pinneker et al.,* 1995b]. Some of the samples collected from the Siberian Craton sites adjacent to the Baikal Rift Zone were gasses dissolved in oil. The sampling procedures were described in the papers cited above. The technique of the mass spectrometer analysis was described in the above and other publications [*Kamenskii et al.,* 1976, 1990; *Tolstikhin et al.,* 1991]. For this reason we omit their description here. The total number of the samples analyzed was 139, collected in 104 different sites of the study region.

2.2. Introduction of Corrections into the Results of Measurements

The samples collected by the workers of the Geological Institute (Moscow) were used to determine R values, He, Ne, and Ar concentrations, the isotope compositions of the latter, and the $^4He/^{20}Ne$ ratios. This allowed them to take into account the contamination of deep gases by the air, that is, to determine the content of atmospheric helium in the sample and introduce a respective correction into the results of the measurements (denoted below by the index "meas"). The true R value in the deep gases, R_{cor}, was found from the relationship:

$$R_{cor} = \{R_{meas}(^4He/^{20}Ne)_{meas} - R_{atm}(^4He/^{20}Ne)_{atm}\}/\{(^4He/^{20}Ne)_{meas} - (^4He/^{20}Ne)_{atm}\}$$

on the assumption that all neon in the sample is atmospheric. This is the most accurate correction, because the similarity of He and Ne solubility precludes their substantial fractionation during the separation of fluid as a free gas phase. Where the $^4He/^{20}Ne$ was not measured in the sample, yet the concentration and isotope composition of argon were determined, Ar_{sam} and $(^{40}Ar/^{36}Ar)_{meas}$, respectively, then, following *Prasolov* [1990], and using the well known atmospheric value of the ratio $(^{40}Ar/^{36}Ar)_{atm} = 295.6$, the content of ^{40}Ar in the air was computed:

$$Ar_{atm} \approx \{(^{40}Ar/^{36}Ar)_{atm}/(^{40}Ar/^{36}Ar)_{meas}\} \times Ar_{sam},$$

this allowed the analysts to find the content of the air helium and introduce a respective correction which was less reliable because of different solubilities of Ar and He.

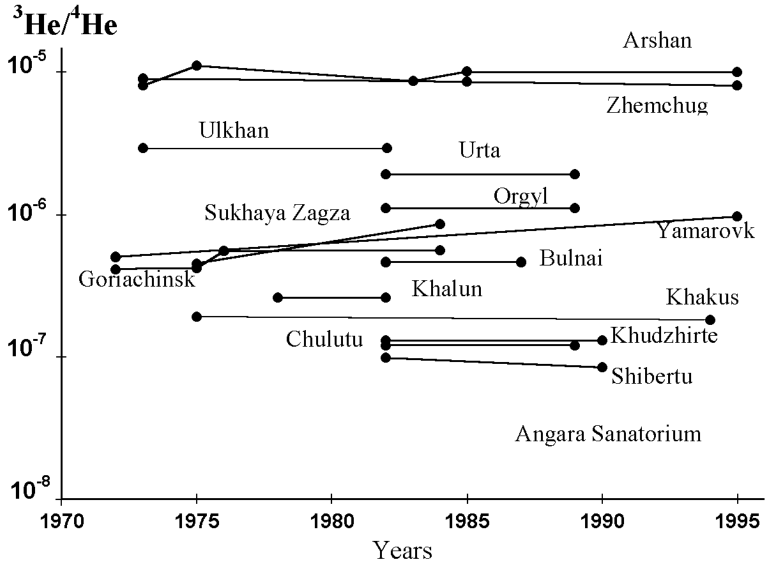

Figure 1. Variations of the $^3He/^4He$ ration in the ground fluids with time. Sampling sites: (1) Angara Health Resort area, hole (Irkutsk amphitheater); (2) Shibertu Spring (Khangai), (3) Chulutu Spring (Khangai); (4) Khudzhirte Spring (Khangai); (5) Khakusskii Spring (North Baikal Basin); (6) Khalun-Us Spring (Khangai); (7) Khuldzhi Spring (Khangai); (8) Bulnai Spring (Khubsugul Basin); (9) Goryachinskii Spring (Middle Baikal Basin); (10) Sukhaya Zagza area, hole (Middle Baikal Basin): Khudzhirte Spring (Khangai); (11) Yamarovka Health Resort area, Hole 110 (Trans Baikal area); (12) Orgyl Spring (Khentei Kerulen Zone); (13) Urta Spring (Khentei Kerulen Zone); (14) Ulkhen Spring (Khubsugul Basin), (15) Zhemchug area, Holes R-1 and G-1 (Tunka Basin); (16) Arshan Resort Area, Holes 26, 28, 39, and Glaznoi Spring (Tunka Basin).

In the general case, the value of the correction depends on the purity of the sample, because its contamination by the atmospheric component may result not only from the natural mixing of the abyssal fluid with air-saturated meteoric water, and from the carelessness of the person who collected the sample, but also from the content of helium in the sample, which can be significant even where its content is low. In most of the samples used to determine the parameters necessary for the introduction of a correction its value was low. Having determined the R value in the deep gas, R_{cor}, and using its values prescribed to the crust and mantle (R_{crust} and R_{mantle}, respectively), one can estimate the contribution of the mantle component, $\mathrm{He_m}$ in the total amount of helium in the sample, and $\mathrm{He_{sam}}$, using the relationship:

$$\mathrm{He_m}/\mathrm{He_{sam}} = (R_{\mathrm{cor}} - R_{\mathrm{crust}})/$$

$$(R_{\mathrm{man}} - R_{\mathrm{crust}}) \approx (R_{\mathrm{cor}} - R_{\mathrm{crust}})/R_{\mathrm{man}}.$$

The comparison of the He isotope data with the other compositional features of the fluids under study opens up new possibilities for specifying their genesis. This approach, which in its strict form consists in normalizing the contents of a given component in terms of ^3He concentration, was offered by I. N. Tolstikhin at the early stage of this research [see *Polyak et al.,* 1976] and is now rather popular, see, for example, [*Jenden et al.,* 1988; *Prasolov and Tolstikhin,* 1987]. For this reason, in order to use these data in the geochemical aspect, the Table 1 presented here lists the predominant components of the gas phase from the fluid sites investigated, which had been reported earlier [*Balabanov and Disler,* 1968; *Ivanov,* 1969, 1974; *Karaseva,* 1980; *Lomonosov,* 1974; *Lomonosov et al.,* 1977; *Tkachuk and Tolstikhin,* 1962; *Tkachuk et al.,* 1957], as well as our data. Yet, in order to find any patterns in the lateral variations of He isotope composition, in addition to introducing corrections for the air contamination in the resulting measurements, two more conditions should be fulfilled.

2.3. Interpretation Premises

First, we have to clarify what is the range of the R value variation in time. In the case of its substantial variations in time, as can be expected in the dynamic systems such as ground fluids (see above), regional differences may happen to be illusory. It is natural that observations cannot be made at all sites. Yet, as follows from the data given in the table, the repeated measurements carried out at some sampling sites during more than 20 years showed a kind of stability, that is, the absence of any pulsation of the He isotope ratios

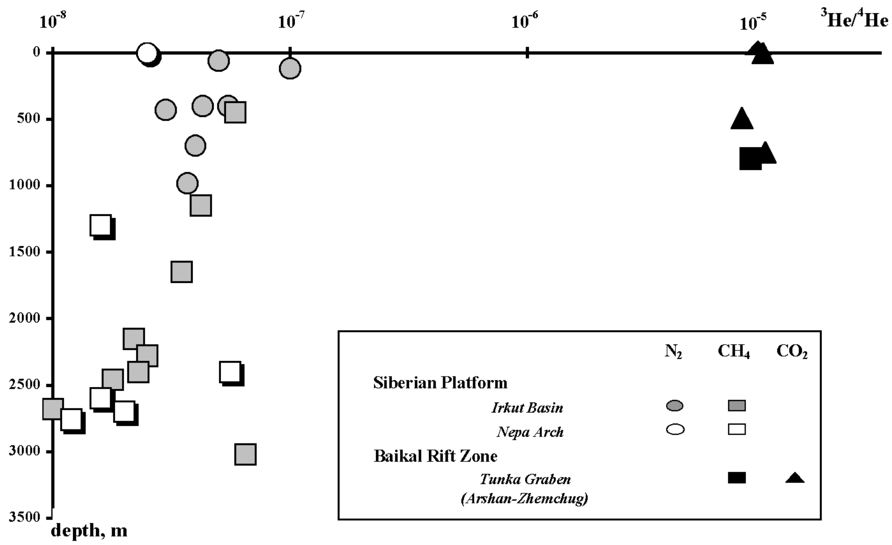

Figure 2. ^{3}He/^{4}He variations in ground fluids as a function of depth. One can see the structural and tectonic affiliation of the sampling sites and the predominant gas phase (see the legend in the figure).

almost everywhere for any R values (Figure 1). It is worth noting that at most of these sites samples were collected by different people and were analyzed in different laboratories. Therefore the data available support the idea that the results obtained at different sites during different periods of time can be compared to get the idea of the real regional patterns in the R value distribution.

Secondly, we have to clarify for the same purpose the variation range of the He isotope ratio in the fluids distributed in the vertical sections of the study areas. This is the general condition of the objective analysis of the lateral variations of any geochemical or geophysical parameter, assigned to particular geographical sites. This condition is especially important in heat flow mapping. Naturally, in our case this condition was satisfied only in areas where holes had been drilled. As regards the region of the Baikal Rift Zone, these areas include the Tunka Basin and the surrounding areas of the Siberian Craton. As follows from the data available (see the Table 1), in the craton areas the R value is equally low in the gases of the surface springs and in various intervals of a 3-km section, irrespective of a component prevailing in the gas composition. In the east of the Tunka Basin of the Baikal Rift Zone, this ratio is also identical in the springs and subsurface water-bearing layers, being independent of the total gas composition, yet being three orders of magnitude higher than in the cratonic regions (Figure 2). It can be stated, therefore, that the areas where wells have been drilled do not show any systematic vertical differences in the He isotope ratio, so that the combined analysis of the R data obtained for the samples from different wells and springs (the latter accounting for the bulk of the data) looks justified.

Figure 3 shows the distribution of the sites where ground fluids were collected for helium isotope studies in South Siberia and in the adjacent areas of Mongolia.

3. Helium Isotopes and the Specifics of Underground Gases

3.1. Relationship Between the Isotope Composition and the Concentration of Helium

Both the isotope composition of He and its concentration were found to be highly variable in the fluids examined in this study. As far as the gases of the Siberian Craton are concerned, almost all R values fit in the very narrow range of $(1.0–6.5)\times10^{-8}$, almost coinciding with the standard radiogenic value of 2×10^{-8}. It has been found by some special studies [*Loosli et al.,* 1995; *Tolstikhin et al.,* 1996, 1999] that slightly higher R values may be caused by the higher Li concentrations in the rocks or by the long preservation of ^{3}He in some chemical precipitates. The R values vary wider from 4.4×10^{-8} to 2.14×10^{-6} at the eastern flank of the Baikal Rift Zone, namely in the Khentei Kerulen zone of Mongolia, reactivated in the Mesozoic Cenozoic period of time, and in its continuation in the East Baikal region. At the same time the gases of the rift zone show a highly wide R variation range, embracing three orders of magnitude: 4.9×10^{-8} to 1.1×10^{-5}.

Also highly variable is the concentration of helium in the gases of the study area: in most cases it varies from 7 to 9700 ppm. It amounts to 22000–27000 ppm in the gases of the Upper Chara Basin and in two areas of the Siberian Craton, being as low as 0.28 ppm in the Mergitaika Spring in the East Baikal area. All of these data are plotted in Figure 4.

The data points plotted in this figure show a negative correlation between the R value and the helium concentration in the gas phase of the fluids. This correlation is statistically

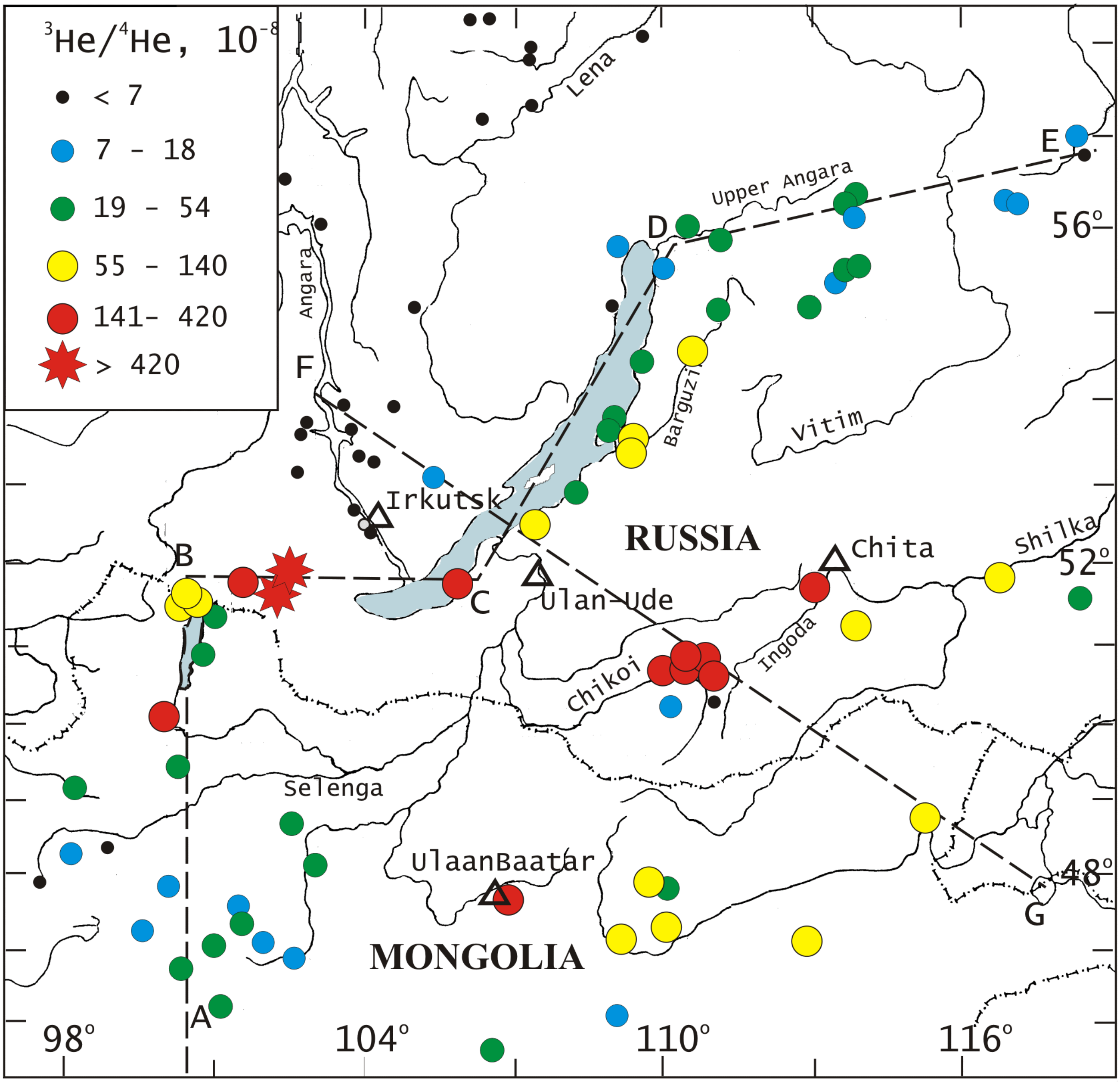

Figure 3. Results of the study of He isotope composition in the ground fluids of the Baikal-Mongolian region. The sites where the $^3He/^4He$ ratio was measured repeatedly or in different objects, coinciding spatially in terms of the map scale, show the average values of the ratio depicted using respective symbols (see the legend in the figure). F–G and A–E are the lines of the profiles (see Figures 7 and 8, respectively).

true both in terms of the whole data set, irrespective of the seemingly anomalous data from the Mergitaika Spring (the extreme left data point in Figure 4), and in the smaller data sample including the data for the Baikal Rift Zone (including those for the Tunka Basin) and for its eastern flank. The correlation of this kind has been reported from many areas of young volcanism, for example, in the Trans-Mexican volcanic belt [*Polyak et al.,* 1982], in the Rhine Graben [*Griesshaber et al.,* 1989], and in the North Caucasus region [*Polyak et al.,* 1998]. This trend suggests the idea of the mixing of two end members: the mantle material with high R and low He concentration and the crustal material enriched in He with low R. However, the real situation in much more complex, because the He concentration in the mantle gas is not a vanishingly small value, being estimated in MORB reservoirs as 97±30 ppm with $R_{\rm man} = 1.15 \times 10^{-5}$ and $CO_2/^3He = (0.9\pm0.2)\times10^9$ [*Marty and Tolstikhin,* 1998]. This is why the curve, plotted for the mixing of two reservoirs (inclined

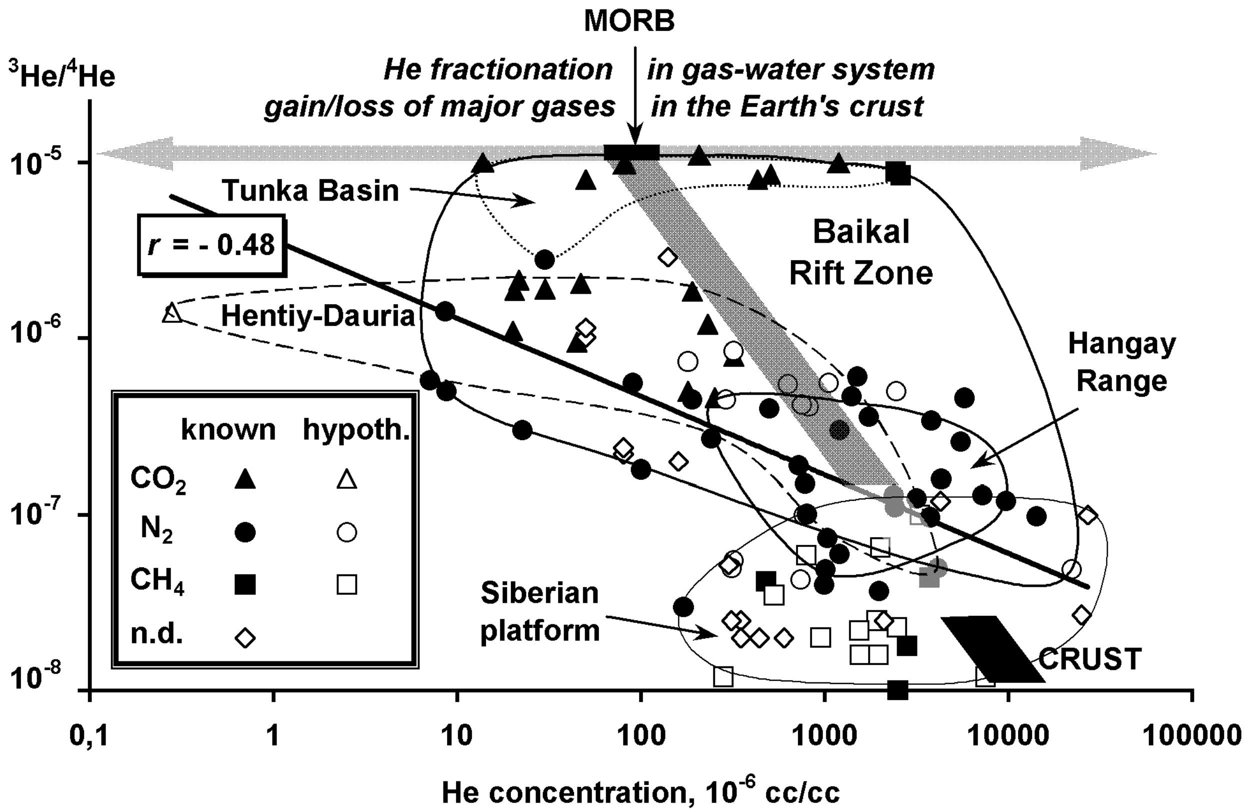

Figure 4. A relationship between of isotope compositions a concentrations of helium in the gas phases of the fluids. The predominant component of the gas phase is shown using a special symbol (see the legend in the figure). Where direct data were not available, the gases of the hydrocarbon pools of the Siberian Craton were ranked as methanic, and the waters of the West Baikal region, and nitric. The figure shows the fields characterizing the compared parameters in the ancient continental crust ("CRUST") and in the basalts of mid-oceanic ridges ("MORB") and the lines of the mixing of the gases from these reservoirs (inclined shaded band). The gently dipping black line crossing this band shows the statistically true relationship trend between the parameters compared in the combined data sample characterizing the Baikal Rift Zone and its eastern flank ($|r| = 0.376 > 0.26 = r_{0.05}^{\text{sign}}$ for $n = 57$). The exclusion of the data for the eastern part of the Tunka Basin and for the Mergitaika Spring (extreme left point in the plot) yielded $|r| = 0.648 \gg 0.29 = r_{0.05}^{\text{sign}}$ for $n = 46$. The total data set ($n = 101$) also showed significant correlation ($|r| = 0.476 \gg 0.196 = r_{0.05}^{\text{sign}}$). The horizontal arrows in the upper part of the plot characterize variations in He concentration under the effect of intracrustal processes (see the text for the explanation).

band in Figure 4) on the assumption that the crustal end member is represented by helium with the canonical radiogenic $R_{\text{crust}} = 2 \times 10^{-8}$ without any admixture of other gases passes to the left from the line of the statistical trend. It is evident that the vertical scatter of the data points in Figure 4 reflects the mixing of the mantle and crust helium. As regards the horizontal scatter (deviations from the mixing line of two final members), it may be caused by two factors.

One of them is the fractionation of helium and other gases in the gas water system because of their different solubilities. The shift of the data points to the left from the mixing line suggests the enrichment of the gas phase in poorly soluble helium. This process takes place as a result of both fluid degassing and the incomplete dissolution of gases generated in the crust (or rising from the mantle) in the fluids. The shifting of the data points to the left stems from the fact that the fluids under study had experienced partial degassing earlier and lost some amounts of helium.

This seems to account for the scatter of the data characterizing the eastern part of the Tunka Basin. The R values in these samples are almost equally close to the mantle level, whereas the He concentrations in them vary over the range of two orders of magnitude. Earlier (see Figure 1 in [*Kononov et al.,* 1974]), a very similar subhorizontal trend, though with a higher level of the R values, reflecting the addition of helium by a plume from the undepleted mantle, was reported from Iceland (see Figure 1 in [*Kononov et al.,* 1974]).

Another possible factor responsible for the horizontal dispersion of data points is the variation of the concentration of the major chemically active components of the gas phase, generated or expended in the crust (in particular, as a result of carbonate formation/decomposition). In the former case, where these components are added to the fluid composition (with the absolute content of helium in the fluid remaining the same), the respective data points lie to the left of the mixing line, in the latter, to the right.

The general scatter of the data points in Figure 4 reflects the diverse contributions of the phenomena discussed into the formation of underground gases.

3.2. Helium Isotopes and the Formation of Underground Fluids

The comparison of the isotope characteristics of helium with its concentrations in the fluids of different geochemical types helps to specify the conditions of their formation. Figure 4 shows that a certain relationship exists between the He isotope characteristics of fluids and the composition of the main components of their gas phases.

Nitric gases are seen to be grouped in the lower half of the plot. Their values vary from 3×10^{-8} to 2.8×10^{-6}. The lowest values, close to the conventional radiogenic one, preclude the participation of any mantle derivatives in the formation of fluids with this He type. Yet, the maximum values show that the nitric fluids of this geochemical type contain a distinct admixture of mantle helium. This, however, does not mean that the nitrogen itself, the predominant gas in the fluids of the Baikal Rift Zone, is of mantle origin. Earlier, *Prasolov* [1990] got an estimate of $N_2/He\approx4$ for the mantle proceeding from the model of nondissipating atmosphere. At the same time, the samples from the Baikal Rift Zone examined later showed this ratio to be much higher (10^2 to 10^4) without any notable contribution of mantle nitrogen [*Polyak et al.,* 1992]. The N_2 origin helps to specify the data available on the content and composition Ar. E. M. Prosolov found the N_2/Ar_{atm} ratio in the gas samples investigated in the Baikal Rift Zone and the Siberian Craton vary between 47 and 85, corresponding the range expected for the air gases (37–84) and, hence, support the conventional views of the atmospheric origin of nitrogen. It is only in the Tunka Basin, where this ratio is higher than 80–94, about third of nitrogen can be of crustal ratler than of atmosphere origin (see [*Polyak et al.,* 1992]).

The methane gases from the Siberian Craton (except for the gas from the Zhemchug R-1 well drilled in the Tunka Basin) occupy the lowermost part of the plot. Their predominant values of R=(1–6.5)$\times10^{-8}$ suggest the obviously crustal origin of these gases. As regards the high values of R=(0.85–0.89)$\times10^{-5}$ in the gas of the Zhemchug R-1 Well, they cannot be used as the basis for assigning this methane a mantle origin. The $CH_4/^3He$ ratio in the mantle was reported to be equal roughly to 10^6 [*Poreda et al.,* 1988; *Prasolov and Tolstikhin,* 1987]. The gas from the Zhemchug R-1 Well showed this ratio to be 100 times higher. Moreover, as follows from the measurements of E. M. Prasolov, the value of $\delta^{13}C = -66.9^o/_{oo}$ suggests the primarily biochemical origin of this methane (see [*Polyak et al.,* 1992]).

Carbonic gases tend to be located in the upper half of the plot shown in Figure 4: the R values in these gases do not show the values lower than 5×10^{-7} (one sample from the area of the Yamarovka Helth Resort) and are similar to those typical of the MORB reservoir. This proves the presence of mantle helium in the carbonic gases. Yet, most of these gases show a $CO_2/^3He$ value different from that of MORB, though the simple dilution of the mantle helium by the crustal one could not change it. This ratio is notably higher than in MORB in the carbonic gases of the Russian Trans-Baikal region and in two wells drilled in the Tunka Basin, whereas the other samples from this basin showed its notably lower value. In the case of the previous analysis these deviations of the $CO_2/^3He$ value from the “mantle standard” show that the formation of carbonic gases was accompanied by the fractionation of the components in the gas water system. It cannot be excluded however that the formation of these gases was affected by CO_2 consumption and generation in the crust. The former (in the form of dissolved carbonate) seems to be likely in the case of the “He-rich” gas of the Tunka Basin. The latter (as a consequence of deep metamorphic activity) explains the pattern observed in the Trans-Baikal region. This conclusion is supported by the results of studying other gases, such as Ar, Ne, and N_2, using the samples collected in the Trans-Baikal region.

The direct correlation of the Ar_{atm} and Ne confirms the purely atmospheric origin of neon (inferred after the introduction of a respective correction into the results of the R measurements, see above). This allows one to infer the origin of the nitrogen. Figure 5 plotted in the coordinates of the nitrogen and neon contents normalized using argon of the air (so-called fN_2 and fNe) shows that the data points of the two nitric gases from the Trans-Baikal region reside near the lines marking the degassing of the air dissolved in water, indicating the purely atmospheric origin of the nitrogen. Yet, five out of six carbonic gases reside above these lines, suggesting the presence of excessive nonatmospheric nitrogen, especially significant in three springs from the Trans-Baikal region. The excess of nitrogene in carbonic gases is not accidental suggesting the combined generation of N_2 and CO_2 by the metamorphism of the crustal rocks under the effect of the mantle heat and mass flow traced by the isotope composition of helium.

The association of the He isotope anomalies with the geothermal ones is ascertained by one more characteristics of the fluids, namely, by the value of their ratio between radiogenic helium and argon, $^4He/^{40}Ar_{rad}$. Non-atmospheric ^{40}Ar was found only in carbonic gases, mainly in small amounts in the fluids of the Tunka Basin showing a submantle He composition. The data obtained in this study yielded $^4He/^{40}Ar_{rad} \sim 7$. The same value was obtained for the gases from the Trans-Baikal Yamarovka Helth Resort area, which, as follows from [*Prasolov,* 1990], corresponds to the gas generation temperature of about 260°C. As to the two other investigated carbonic springs from the Trans-Baikal area, Modui and Poperechnyi, this value is as low as $\sim$2 which suggests even higher temperatures.

Summing up, it should be concluded that there is no strict universal relationship between the isotope composition of helium and the total composition of the gas phase of the fluids. This is proved by the fact that the fields of the data points for the fluids of different geochemical types overlap in Figure 4. The same conclusion stems from Figure 2. Other arguments in its support will be given below.

4. Lateral Variation of the Helium Isotope Composition as the Image of the Tectonic Structure and Evolution of the Region

As mentioned above, the R value distribution at the fluid sampling sites in the study area shows a highly variegated pattern. This can be seen in Figure 3. However, this pattern shows some principal tectonic regularities. For this purpose we will discuss, in the section that follow, the specific features of the He isotope composition in the major structural elements of the region, and also in their smaller subdivisions, for example, in the rift zones and in their individual segments. These differences exist in the specifics of the geological structure and history, in the geophysical (primarily, geothermal) characteristics, morphology, and other features in accordance with the known reviews [*Duchkov et al.,* 1987; *Khutorskoi,* 1996; *Lysak,* 1988] and regional studies [*Devyatkin et al.,* 1987; *Genshaft and Saltykovskii,* 1979; *Grachev et al.,* 1982; *Tectonics...,* 1966, 1974, 1980; *Zorin et al.,* 1982, 1986, 1988], to cite but a few.

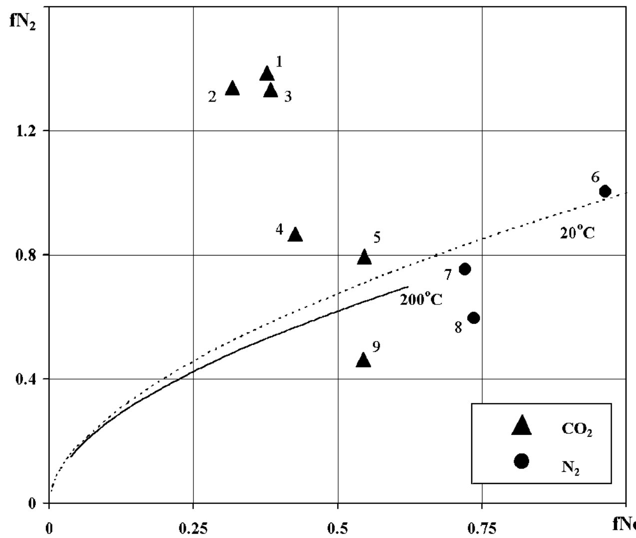

Figure 5. The relations between the N_2 and Ne concentrations, normalized twice using the content of atmospheric argon: $f_i = \{[i]/[Ar_{atm}]\}_{sample}/\{[i]/[Ar]\}_{atm}$, where $\{[i]/[Ar_{atm}]\}_{sample}$ is the ratio between the concentrations of these gases in the air. The solid and dash lines show the degassing of the atmospheric gases dissolved at temperatures of 200°C and 20°C, respectively. The numbers in the figure denote the test sites: (1) Modui Spring, (2) Poperechnyi Spring, (3) Kopchagir Spring, (4) Arshan Resort (Hole 39), (5) Arshan Resort (Glaznoi Spring), (6) Kunalei Spring, (7) Angi-Arshan Spring, (8) Angara Resort (Hole 223), (9) Yamarovka Resort (Hole 15).

4.1. Helium Isotope Specifics of the Structural and Tectonic Elements of the Region

The structural and tectonic elements of the region, such as the Siberian Craton (including its Irkutsk Amphitheater and Nepa Dome), the Khangai Block, the Khentei Kerulen and Dauria blocks, forming the eastern flank of the rift zone, and, finally, this zone itself, differ in terms of their R values (Figure 6). In the areas around the rift the helium isotope composition changes notably in accordance with the general dependence of the composition of helium on the age of the crust reflecting the general obliteration of the initial mantle imprints in the rocks composing the crust and the generation of radiogenic ^{4}He [*Polyak,* 1988; *Polyak et al.,* 1979b].

As to the gases of the pre-Riphean platform, the R values, both in the Irkutsk Amphitheater and in the Nepa Dome, the R values fit in the narrow range of $(1.0–6.5)\times10^{-8}$ being as high as 10×10^{-8} only in two cases (possibly, because of the contamination by atmospheric air and the lack of data for introducing corrections). The average value of $\overline{R} = (3.5\pm0.8)\times10^{-8}$ is very close to the conventional radiogenic one, this fact being typical of old platforms (here and below, the accuracy of an average estimate is $1.96 \times s/n^{0.5}$, where s is standard deviation and n is the number of R determinations). The heat flow in the platform is also low being equal to that of the continental background [*Duchkov et al.,* 1987].

The Khangai Uplift in Mongolia ia composed of late Paleozoic crustal rocks [*Tektonics...,* 1974; *Zorin et al.,* 1982], enclosing the Late Paleozoic block of Western Khangai. The fourteen sites of study showed an elevated He isotope ratio, notably higher than those from the platform: $(4.9–36)\times10^{-8}$, the average values being $(16.3\pm4.9)\times10^{-8}$. This value is slightly higher than the value typical of the Hercynean structures. It is possible, however, that the values shown by three springs in Central Khangai, namely, by Khuldzhi (Saikhan-Khuldzhi), Khalun-Us, and Shargalzhut, as high as $(26–36)\times10^{-8}$, are anomalous R values (see the extreme left column in the histogram of Figure 6), which trace some submeridional extension zone of no morphological expression (see below). After the elimination of these data from the total data sample, the average R value declined to $(12.3\pm2.9)\times10^{-8}$, which corresponds to the Paleozoic crust where the heat flow is also somewhat higher than the continental background [*Khutorskoi,* 1996].

The Khentei Kerulen Zone of Mongolia includes widely developed volcano-plutonic rocks of Mesozoic age, reflecting the tectonic and igneous reactivation in the Late Triassic Early Jurassic time and in the time between the end of the Jurassic and the beginning of the Cretaceous [*Nagibina,* 1967]. In seven sites from this zone, the R values vary greatly, amounting to 1.9×10^{-6} and averaging 0.94×10^{-6}. These values are too high even for the Late Mesozoic crust (see [*Polyak,* 1988]). The Mesozoic and some later reactivation embraced also the Trans-Baikal region (Dauriya), where the He isotope composition in gases from eleven springs was

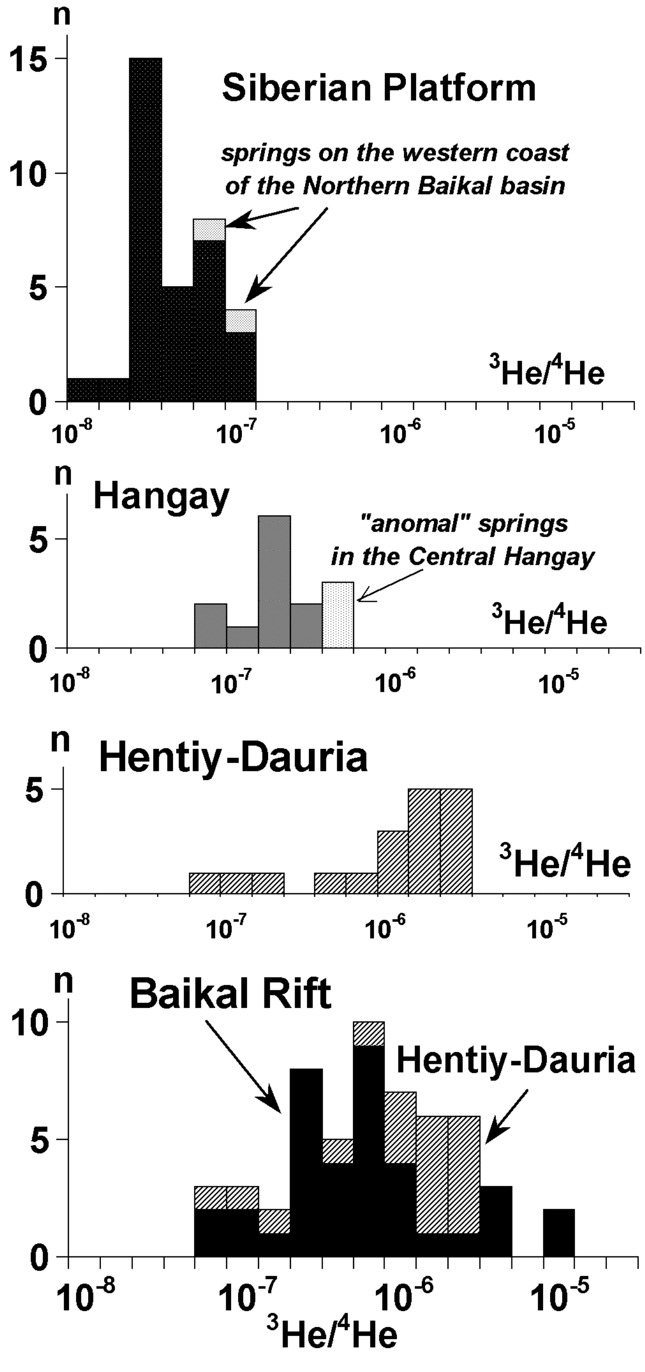

Figure 6. Distribution of the $^3He/^4He = R$ values in the ground fluids of different structural elements of the Baikal-Mongolian Region. The histograms were plotted using one R value for each site (in the case of several measurements the average value was used, like in the case of Figure 3).

found to be also highly variegated, its average value being 1.14×10^{-6}. The combined data set showed the $\overline{R}$ value to be $(1.06\pm0.33)\times10^{-6}$. This value can be taken as typical of the eastern flank of the rift zone, where the heat flow is also slightly elevated [*Lysak,* 1988; *Lysak and Pisarskii,* 1999]. At the same time the high asymmetry of the histogram (see Figure 6) suggests the heterogeneity of the data sample.

The regional variations of the He isotope composition in underground fluids are clearly seen in the profile plotted across the strike of the Baikal Rift Zone (Figure 7). This profile clearly shows a high contrast between the pre-Riphean Siberian Craton and the Baikal Rift. Note that in this segment of the profile the R values are lower than those of MORB, but clearly suggest the contribution of mantle helium into the fluid. At the edge of the craton (Bayandai Hole) the R value of 1×10^{-7} is slightly higher than the conventional radiogenic value, which can be expected here proceeding from the age of the crust. This can be the consequence of both the local specifics of the radiogenic helium composition (see Section 3.1), and the Late Paleozoic tectonomagmatic reactivation of the southeastern margin of the craton [*Ryazanov,* 1979], or some echo of the recent rifting activity.

The pattern east of the Baikal Lake is absolutely different from that in the west: the values of the He isotope ratio in the gases investigated in the Dauriya and Khentey-Kerulen blocks resemble those in the rift zone, obviously suggesting some repeated tectonic and magmatic reactivation of these structural elements, as has been mentioned above.

This pattern agrees well with the specifics of the crustal structure of the region recorded by geophysical measurements. As follows from seismological data, under the rift zone the P wave velocities at the M discontinuity are as low as 7.7–7.8 km/s compared to 8.1–8.2 km/s under the Siberian Craton [*Florensov,* 1977]. *Zorin et al.* [1990] showed that the relative decline of V_p values under the Baikal Rift Zone perseveres to a depth of some 200 km (base of the lithosphere under the craton, and that the overlying volume (anomalous or low-velocity mantle) is the protrusion of the asthenosphere, where the material is partially molten, as indicated by the high attenuation of S waves. As follows from the gravity data, the top of this protrusion coincides with the crustal base throughout the rift zone from Southern Yakutia to Northern Mongolia at a depth level of less than 50 km (see Figure 2 in [*Zorin et al.,* 1988]. This contour line outlines, with some overlap, the region of high R values in the fluids of the rift zone, compared to the normal values of the crust dissected by this zone.

Geothermal modeling suggested that the top of the asthenosphere rose to depths levels as high as <50 km not only under the Baikal Rift Zone but also east of it over a distance of 150 km, where an intracrustal layer with temperature above the Curie point was inferred (see Figure 5 in [*Zorin and Lepina,* 1985]). As follows from gravity data, the top of the asthenosphere was supposed to be as deep as 150 km below the ground surface and rose eastward again to depths of about 75 km (see the above-mentioned Figure 2 in [*Zorin et al.,* 1988].

The crustal structure of the Trans-Baikal region looked different in the light of seismological and DSS data. These data [*Berdichevskii et al.,* 1999] suggest that a low-velocity layer (anomalous mantle) branches off from the subvertical channel ("big dike" of Yu. A. Zorin) rising from the asthenosphere to a depth of less than 40 km. This low-velocity zone (anomalous mantle) extends to the southeast for a dis-

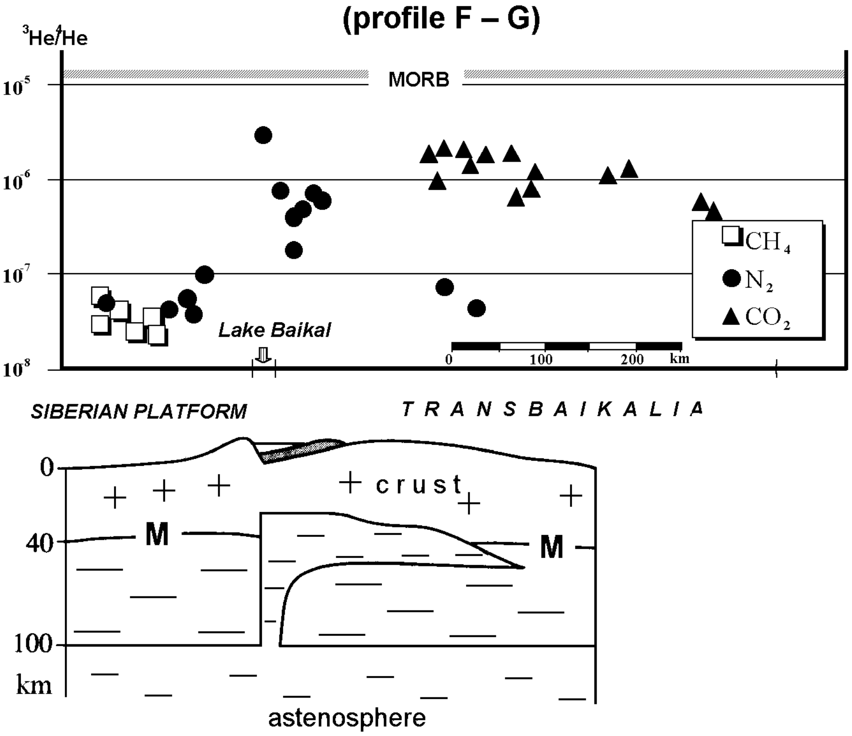

Figure 7. Variations of the $^3He/^4He$ ratio in the ground fluids across the strike of the Baikal Rift.

tance of roughly 300 km from Lake Baikal and to the northeast for a distance of >1500 km. This view on the crustal structure of the region was supported by A. F. Grachev who emphasized the asymmetry of the Baikal Rift [*Grachev,* 1996]. This view was later supported by the recent analysis of the magnetotelluric data accumulated for this region [*Berdichevskii et al.,* 1999]. This analysis revealed the configuration of the crustal high conductivity zones, which suggests the high temperature of the crustal rocks. The best convergence of the magnetotelluric data was obtained for a model with vertical conductive channels in the upper and intermediate crust with conductivity of 5–10 Ω·m under the Baikal Rift and 20–50 Ω·m under the Trans Baikal region. These channels have been interpreted as fluid-saturated fault zones. Yet, they can be magma feeders. Although recent volcanic activity is very scarce in the Trans-Baikal region, one of its manifestations is a small melanephelinite plateau in the upper reaches of the Chikoi R. [*Aschepkov et al.,* 1996]. It is in its vicinity that the R values are as high as 2.14×10^{-6} in the samples from the carbon dioxide springs we studied [*Lavrushin et al.,* 1999; *Polyak et al.,* 1998]. The $^4He/^{40}Ar_{rad}$ values in these gases, discussed in Section 3.2, suggest the significant heating of rocks in this area of the Trans Baikal region.

The obvious admixture of mantle He in the springs from the eastern flank of the rift zone, which declines only at distances of a few hundred kilometers from this zone, proves the latent heat and mass flow from the mantle operating over a much larger area compared to the open flow. A similar situation has been reported from many other regions, for example, from the North Caucasus [*Polyak et al.,* 1998, 2000]. The distribution pattern of R values in the fluids of the Trans-Baikal region suggests that the sheet intrusion of the anomalous mantle, containing, as follows from seismological and electromagnetic data, a few per cent of melt [*Berdichevskii et al.,* 1999], and possibly having served as a source of hypabyssal igneous rock bodies, extends farther to the southeast, as compared to the extent suggested thus far by geophysical data.

The data presented in the profile discussed (Figure 7) support the conclusion offered in Section 3.2 about the absence of an unambiguous relationship between the isotope composition of He and the total composition of the fluid gases. For instance, the CO_2 fluids of the Trans Baikal region differ greatly in terms of the R value from the nitric fluids of the same region, but are almost identical to the nitric springs flowing in the Lake Baikal basin. The latter, in turn, differ in this respect from their analogs in the Trans-Baikal region and in the Siberian Craton. The nitric gases from the latter are indistinguishable in terms of the He composition, characteristic of ancient crust, from methane gases. At the same time, as demonstrated in Figure 2, the methane gases from the Tunka Basin of the Baikal Rift Zone are similar in terms of the submantle isotope composition of helium to the CO_2 gases.

As to the rift zone itself and its nearest surroundings, the isotope composition of He in its fluids is distinguished by the broadest range of the R values varying from the minimum value of 4.9×10^{-8} in the sample, collected by E. V. Pinneker from the Luktur Spring in the Upper Chara Basin,

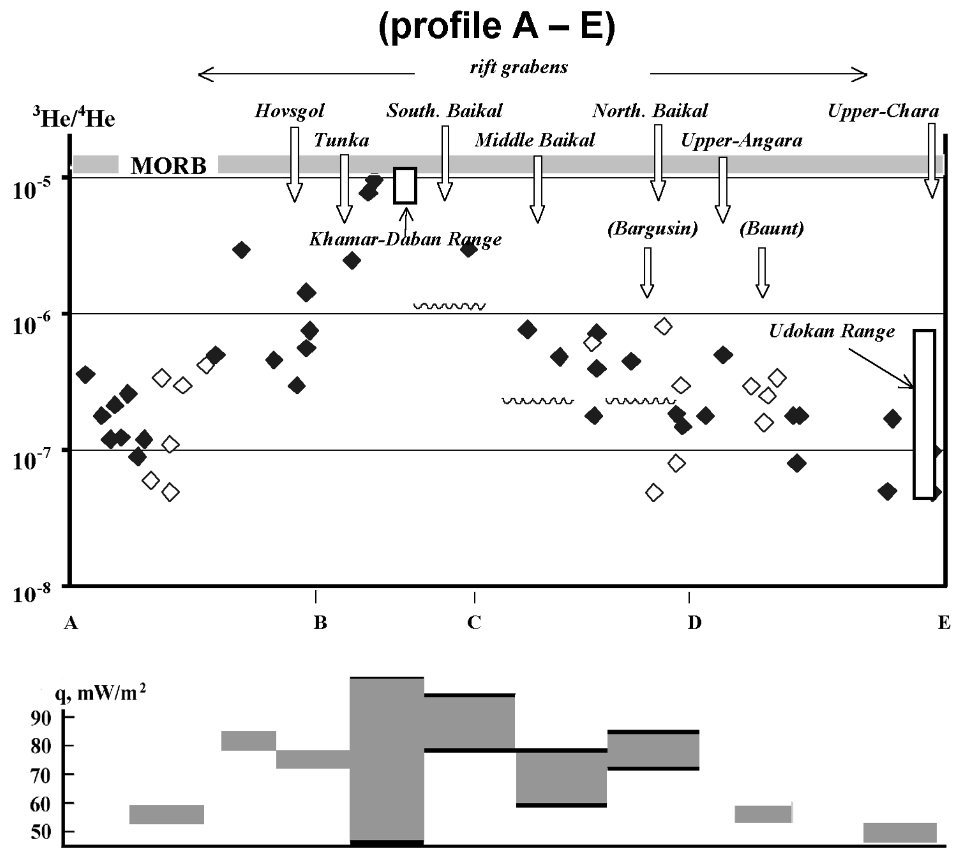

Figure 8. Variations of He isotope composition in fluids and rocks (top) and of the heat flow (bottom, after [*Lysak,* 1988]) along the strike of the Baikal (Baikal Khubsugul) rift zone. The black rhombs show the R values at sites inside the rift zone, open rhombs, the values for the Adjacent areas (for example, in the Bargusin and Bauntovo basins). The data for the rocks are shown by shaded rectangles in accordance with the range of the R values reported in [*Drubetskoi and Grachev,* 1987] (see the text for the explanation). The wavy lines show the R values in the gases dissolved in the water of lake baikal. For comparison, the horizontal line shows the R values for a MORB reservoir.

to the maximum value of 1.1×10^{-5} measured in one of the samples collected in the Arshan Resort area in the Tunka Basin. As has been clarified using the Wilcockson criterion (see [*Mineev,* 1973]), this data sample is statistically indistinguishable, in terms of its average value, from the former data sample characterizing the Khentey Kerulen Zone of Mongolia and the Russian Trans-Baikal region, both reactivated during the Meso-Cenozoic time. This allowed us to include both data samples into one general data sample (see the lower curve in Figure 6). This affinity of the data samples can be taken as the confirmation of the above mentioned views of geophysicists on the crustal structure of the region and as the evidence in favor of the similar conditions of shaping the isotope composition of helium in underground fluids inside the rift zone and at its eastern flank, the fact proved by the distribution of the R values across the strike of the Baikal Rift Zone (see Figure 7).

With the great dispersion of the R particular values observed in the rift zone the formal determination of the R mean value does not have any exact geological sense. Yet, the variations of the R values along the strike of the rift zone are obviously of great importance.

4.2. Variations of the He Isotope Composition of Fluids Along the Strike of the Rift Zone

We succeeded to trace the distribution of the R values along the strike of the rift zone over a distance of >2000 km (Figure 8) between the Upper Chara and Khubsugul rift-related basins and farther roughly along the 100°E longitude as far as the Bolnai Fault. This fault appears to be a transform fault, along which the rifting axis was displaced eastward [*Khutorskoi,* 1996; *Polyak et al.,* 1992]. Although there are no basins of rift origin south of this fault, this view is supported by the sporadic occurrences of Neogene Quaternary volcanism in the North Khangai area along 102°E in the form of small monogenic volcanoes and the thin fields of alkalic basalt in the northern Khangai area [*Devyatkin et al.,* 1987; *Genshaft and Saltykovskii,* 1979], and also by the above cited data on the elevated He isotope ratio in gases from three springs of the Central Khangai region.

Our analysis of the He isotope composition variations along the strike of the rift zone revealed an obvious regular pattern in the distribution of the R values.

The maximum, submantle R values, as high as 1.1×10^{-5}, responsible for almost 96% of the mantle helium in the helium of the fluids (with $R_{\text{mantle}} = 1.15 \times 10^{-5}$), which had been discovered in the eastern part of the Tunka Basin by the first investigators [*Lomonosov et al.,* 1976] and confirmed later by all subsequent investigations, turned out to be characteristic only of this segment of the Baikal Rift Zone. As close as in the west of the basin they decline to 2.8×10^{-6} (Nilova Pustun Health Resort), so that the average $\overline{R}$ value, based on all data available, is 0.65×10^{-5}. This basin is known to be different from all other graben-shaped depressions of the rift zone in terms of its highest volcanic activity: the products of this activity, which lasted from the Early Miocene to Holocene, inclusive, compose the bulk of its nearly 3 km thick sedimentary cover [*Logachev et al.,* 1983] and form four groups of small monogenic cones sitting on its surface [*Kiselev et al.,* 1979].

A twice as low value of R (0.3×10^{-5}) was measured in a sample from the Svyatoi Klyuch Spring flowing at the eastern flank of the neighboring South Baikal Basin [*Pinneker et al.,* 1995b]. Deep fluids flow at the floor of this basin, as has been proved by geothermal measurements [*Golubev,* 1982] and by the He isotope composition in the lake water: the R values in the samples from the depths of 1260 and 1200 m were 115×10^{-8} and 102×10^{-8}, respectively [*Grachev et al.,* 1982]. The analysis of these samples excludes the possibility of explaining these values by the simple mixing of radiogenic He with the helium contained in the air dissolved in water, or as the entrapment of technogenic tritium from the atmosphere, transformed to ^{3}He by way of β-decay [*Polyak et al.,* 1992]. These values are lower, $(24\text{–}20)\times10^{-8}$, in the Middle and North basins of the Baikal Lake. However, the isotope composition of helium is different in the springs flowing on the banks of these basins, especially on the eastern one.

Six different samples collected from two sites of the North Baikal Basin (Goryachinskii Spring and Sukhaya Zagza Hole) showed the R values ranging from 4.1×10^{-7} to 1×10^{-6} with the formal average value of 6.26×10^{-7}. This value is five times lower than that from the South Baikal Basin, yet is higher than in the lake water.

A still lower R value was found in the springs flowing at the eastern shore of the North Basin: the samples taken from five springs showed the values varying over a range of $(1.85\text{–}4.5)\times10^{-7}$ and being as high as 7.2×10^{-7} in one spring (Gniloi Spring in the south of the basin [*Lysak and Pisarskii,* 1999; *Pinneker et al.,* 1995a], averaging 3.48×10^{-7}. It is remarkable that the isotope composition of helium in the gas emanating from the Khakusskii Spring is absolutely invariable: the results of its sampling by V. I. Kononov in 1975 are absolutely identical to those obtained by an international crew 20 years later [*Kipfer et al.,* 1996]. On the contrary, at the western bank of this basin the R values decline to the common radiogenic level, amounting to $(5\text{–}8)\times10^{-8}$ in two springs. This suggests that in the antirift direction the mantle signal declines more rapidly to the west than to the east.

Similar to the North Baikal Basin, the average R value remains in the next northward depression of rift origin, namely, in the Upper Angara depression, where two springs were tested. Yet, in the more northwestern segments of the rift zone, namely, in the North Muya Range, Udokan Range, and the Upper Chara depression, the R value declines to 1.47×10^{-7}, 1.1×10^{-7}, and 7.4×10^{-8}, respectively, approaching the value characteristic of the old crust dissected by the rift. The crustal origin of helium in the Upper Chara depression is validated by its extremely high concentration (2.2 vol.%).

A similar trend was observed in the He isotope composition in the fluids from the flank graben-shaped basins of rift origin, parallel to the strike of the rift: the Barguzin and Bauntov basins (see Figure 8). The average R value is 5.73×10^{-7} in the former, and 2.61×10^{-7} in the latter. The same trend is typical of the periphery of a rift zone from Mongolia (see Figure 8).

South of the Tunka maximum, the He isotope ratio in ground water declines, similar to the trend observed in the NE direction. In the Khubsugul Depression it has a value similar to those observed in the west of the Tunka Basin only in one, southernmost, Ulkhen Arshan Spring, averaging 0.9×10^{-6}. At the Khangai foothills, as far as the Bolnai fault, it declines twofold again (in the Naran-Bulag Spring flowing at the continuation of the rift zone and in the Toshint Spring, flowing somewhat more to the west [*Pinneker et al.,* 1995b]). In the area of the Khangai Range itself, the He isotope ratio corresponds to the Paleozoic age of the tectonomagmatic activity and suggests some small (~2.5%) admixture of mantle helium only in three East Khangai springs mentioned above.

4.3. A Relationship Between the He Isotope Composition and the Geological and Geophysical Characteristics of the Baikal Rift Zone: The Problem of Continental Rifting

A decline in the He isotope ratio in ground fluids, observed along the strike of the Baikal Khubsugul Rift, is accompanied by a decline in the lengths of the rift basins [*Lysak,* 1988; *Sherman,* 1977; *Zorin,* 1971], in the their widths [*Florensov,* 1977; *Lukina,* 1988], and in their depths. For instance, the top of the crystalline basement (the surface of the Cretaceous Paleogene prerifting levelling) lies 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 [*Florensov,* 1977]. These depths agree with the gravity data (same references and [*Zorin et al.,* 1986]) suggesting the higher densities of the crustal rocks under some basins because of the emplacement of basic and ultrabasic intrusions, the latter contributing to the extensions of the basins by way of isostatic compensation.

The source of these intrusions, namely, a deep-seated melt reservoir, can be identified using their He isotope characteristics. Yet, the rocks of this region have been studied in this respect to a lesser extent compared with the ground fluids which, as mentioned in Section 2.1, are more preferable for the aim of elucidating the lateral variations of the He isotope composition. The possibility of studying these He composition variations in the young igneous rocks of the region is limited also by their sporadic occurrences (in contrast to the almost ubiquitous fluid occurrences). The Cenozoic basaltoids tend to occur in several volcanic areas (see Figure 1 in [*Ashchepkov et al.,* 1996]), of which only one area has been studied in detail, namely, the Khamar-Daban volcanic center, located slightly south of the Tunka Basin [*Drubetskoi and Grachev,* 1987; *Grachev,* 1998] and, partially, the Udokan area adjoining the extreme NE segment of the rift zone [*Drubetskoi and Grachev,* 1987].

Reported in the last of the cited references are the results of determining He isotope composition in mantle xenoliths (spinel lherzolites) and in the olivine from the Khamar-Daban and Udokan volcanics, which preserves well the mantle He. They were compared with the data on the He composition in the fluids of the Baikal Rift Zone (see Figure 8). It was found that the data obtained for the rocks repeated the trend observed in the fluids: the R values found for the Khamar-Daban area were found to be much higher, up to 1.2×10^{-5} (and even higher as reported in [*Grachev,* 1998]), than in the Udokan area ($<0.8\times10^{-6}$ [*Drubetskoi and Grachev,* 1987]). This situation seems to be fairly strange. If the xenoliths had been entrapped from the same mantle reservoir and had not been contaminated by crustal helium, this means that the mantle is not homogeneous in He isotope terms along the rift strike. It was namely this conclusion which was made by *Grachev* [1998]. But then, this contradicts the pattern observed in the fluids, which can be more naturally explained by the contamination of the mantle fluids by crustal He derivates, which grows more active away from the Tunka Basin. In this case, the helium contained in the Udokan rock samples must have been entrapped not from the mantle. This problem calls for a further study which should include necessarily geothermal data.

As basic magma is intruded in the crust, it introduces into it not only some respective silicate material with its volatiles but also the heat accumulated in it. In the areas of open discharge, like in the Tunka Basin with its surface flows of recent volcanism, the mantle material is removed to the surface of the crust. Indirect evidence in favor of this process is provided by magnetic, magnetotelluric, and deep seismic sounding data [*Berdichevskii et al.,* 1999; *Florensov,* 1977; *Lysak,* 1988]. As follows from these data, the thickness of the crustal magnetically active layer, correlating with the depth of the Curie point of titanomagnetite, the predominant ferromagnetic material ($\sim$440°C), is as small as 18.5–19.5 km as compared to 32.5 km under the Siberian Craton. The lowermost part of the layer includes a seismic waveguide, this layer being underlain by a layer of high electric conductivity which is accounted for by the heating of the rocks and by the content of high-T solutions in this depth interval.

It is significant in this respect that the natural variations of the He isotope composition discovered along and across the strike of the rift repeats the well-known heat flow distribution pattern there [*Duchkov et al.,* 1987; *Lysak,* 1988; *Lysak and Zorin,* 1976]. In her book, *Lysak* [1988] proved that the average conductive heat flow density varies in different segments of the rift, decreasing in both directions away from the South Baikal Basin, which was called by her as a "rifting center". Taking into account her accuracy of deriving the mean value, it can be supposed that this heat flow density is comparable with that in the Tunka Basin. The positive correlation between the He isotope ratio and the heat flow density observed in the Baikal Rift is a particular case of the general regularity observed for the entire continental block of North Eurasia [*Polyak,* 1988; *Polyak et al.,* 1979b]. This is a natural paragenetic correlation of two parameters reflecting the effect of the same cause, namely, the heat and mass flow from the mantle. This correlation is found not only where different regions are compared but also at a regional and even at a local scale [*Polyak et al.,* 1985]. This correlation was confirmed by the investigations carried out in Japan [*Sano et al.,* 1982], in China [*Du,* 1992], in the Eastern Carpathian region [*Polyak et al.,* 1999], and in the North Caucasus [*Polyak et al.,* 1998b, 2000]. This correlation was also discovered in the area of this study [*Polyak et al.,* 1992], where the correlation of these parameters was used successfully to estimate heat flow values using the composition of helium in the fluids in the areas lacking deep drill holes in Mongolia [*Khutorskoi et al.,* 1991] and in Russia [*Lysak and Pisarskii,* 1999].

The regular variation of the mantle component in the fluid helium and in the heat flow background density along the strike of the Baikal Rift Zone suggests differences in the intensity of heat and mass flow from the mantle in different fragments of this zone. The conjugation of the geochemical and geothermal traces of this discharge with the high scatter of R values was observed in the similar structural features of Western and Central Europe: in the system of grabens from the upper and lower Rhine North Sea region [*Griesshaber et al.,* 1989, 1992; *Hooker et al.,* 1985], in the Okhrge (Eger) rift [*O'Nions et al.,* 1989] and in East Asia [*Du,* 1992]. A similar pattern exists in the distribution of the He isotope ratio in the ground fluids and in the tectonic type of continental rifts, such as the Afriacan Arabian rift belt [*Craig and Lupton,* 1978; *Craig and Rison,* 1982; *Lupton et al.,* 1977]; see also a review in [*Scarsi and Craig,* 1996]. It can be concluded that the broad variation of the He isotope composition in ground fluids is the common universal feature of continental rift zones.

An absolutely different pattern is observed in the global system of mid-oceanic ridges which had been referred to as oceanic rifts in the early studies. It was found later that the sizes of their axial rift valleys were inversely proportional to their spreading rates and in the rapidly spreading East Pacific Rise had been incomparably lower than in the first studied Mid-Atlantic Ridge, so that their formal similarity with continental rifts is highly relative. The isotope composition of helium in the products of submarine volcanic and hydrothermal activity is highly uniform in the products of submarine volcanic and hydrothermal activity throughout mid-oceanic ridges, except for the hot spots (see, for example, [*Kurz et al.,* 1982]). The particular results of measuring R values in mid-oceanic ridges deviate little from their average value, characteristic of average MORB, that is a depleted mantle: $(1.15\pm0.1)\times10^{-5}$ [*Marty and Tolstikhin,* 1998].

The data available enable one to verify the specifics of the processes responsible for the formation of continental rifts. The great variation of the He isotope composition in ground fluids, which is associated with heat flow variations in the geothermally investigated segments of rift zones (and in some regions, as, for example, in the Baikal Rift Zone, showing an ordered pattern, being accompanied by changes in the morphology of the rift zones and in the geophysical characteristics of the rocks), suggests variations in the intensity of mantle diapirism in their segments, distinguishing greatly continental rifting from oceanic spreading. This seems to reflect differences in the extent of continental rift opening and, consequently, a peculiar mechanism of crust and mantle interaction, different from that od mid-oceanic ridges. The process of oceanic spreading is the response of the lithosphere to the rise of the mantle material along the axis of the mid-oceanic ridge, operating throughout its length with invariable intensity (this being reflected in subparallel narrow magnetic anomalies), meaning that in this case the lithosphere extension is caused by the mantle activity. This process is usually referred to as active or axial spreading. In contrast, continents are formed by the crowding ("conglomeration") of individual blocks and exist in the environment of compression (collision) resulting, in the long run, in shear deformations breaking the crust (lithosphere). These breaks facilitate the autonomous movements of the new plates (microplates), producing pull-apart structures as the "embryos" of continental rifts. It is worth while reminding here that the term "collision rifting" was proposed long ago [*Sengör,* 1976; *Sengör et al.,* 1978], and that the idea of "passive spreading" is still popular (see, for example, [*Bott,* 1990; *Khain,* 1990]). These environments involve the possibility of mantle diapirism, that is, the rise of mantle material, decompression melting at its front, and volcanic activity. It follows that during continental rifting activity (and, possibly, during back-arc spreading) the mantle activity is not the cause but the consequence of deformation in the overlying lithosphere. Deformation of this kind can be intensified by the wedging effects of mantle plumes rising from the undepleted mantle where their projections to the Earth surface coincide with rift zones. Judging by the He isotope composition in the fluids of the African Arabian rift belt, this process operates in the Afar region [*Craig and Lupton,* 1978; *Craig and Rison,* 1982; *Scarsi and Craig,* 1996]. Yet, in the area of the other, Yellowstone, hot spot [*Craig and Lupton,* 1978], no opening of a continental rift took place. Some researchers [*Grachev,* 1996; and others] believe that plumes rising from the undepleted mantle can be interpreted as the primary cause responsible for continental rifting creating prerifting conditions in areas of future rifting. Yet, in this case, too, the breaking of the continental lithosphere will not develop simultaneously throughout the extension of the arising rift zones (as is the case in oceanic spreading), but successively, by the mechanism of a "propagating fracture" [*Shaw et al.,* 1980], from the "rifting center" to the peripheral segments of these zones, so that the conclusion of the specific process of continental rifting, compared to the formation of mid-oceanic ridges, remains to be valid.

In the critical case, this development of events can lead to the complete destruction of continental crust (Red Sea), the opening of new oceans (Atlantica), and, obviously, to the rearrangement of the system of convection cells in the mantle. This suggests the conclusion of a "feedback" between continental rifting and oceanic spreading.

5. Conclusion

The analysis of the results of studying helium and other gases in the ground fluids of the Baikal Rift Zone and adjacent areas suggested the following conclusions.

1. The value of the ratio of He isotopes, $^3He/^4He = R$, derived at different sites of the region, varies greatly from 1×10^{-8} to 1.1×10^{-5}. The minimal R values correspond to crustal radiogenic helium, and the maximal values, observed locally inside the Baikal Rift Zone, are similar to those characteristic of the modern mantle (MORB reservoir).

2. The repeated sampling of some sites during 20 years showed stability, that is the absence of any pulsation of the He isotope ratio almost at each of them for all R values.

3. The areas of the region where deep holes had been drilled did not show any systematic vertical differences of the He ratio, this justifying the joint analysis of the results of determining R values in the samples from different holes and springs.

4. The comparison of the isotope composition of helium with its concentration and with the composition of the main gases in the fluid shows that the composition of the gas phase of the fluids is formed under the effect of the fractionation of the differently soluble components in the gas water system and the generation and consumption of chemically active components in the crust.

5. There is no strict universal relationship between the He isotope composition and the general composition of the fluid gases, although some relationship does exist. The methane gases of the hydrocarbon deposits show the minimum crustal R values. Much more diverse is the composition of He in nitric and carbonic gases, the latter showing the maximum R values.

The nitric gases of the Baikal Rift Zone are of atmospheric origin, as follows from the N_2/Ar_{atm}. Their N_2/He ratio ranging between 10^2 and 10^4 is much higher than that inferred in the mantle ($\approx$4 [*Prasolov,* 1990]), excluding the notable addition of mantle N_2. The fN_2/fNe ratio in the nitric gases suggests the presence of excessive (not atmospheric) nitrogen, this being a seeming consequence of the common generation of N_2 and CO_2 by metamorphic processes operating in the crustal rocks under the effect of mantle mass and heat transfer traced by the He isotope composition. In the carbonic gases the $CO_2/^3He$ ratio is different from that in MORB $(0.9\pm0.2)\times10^9$ [*Marty and Tolstikhin,* 1998], apriori precluding to consider these gases to be of mantle origin.

6. The structural elements of the region also differ in the R values. The gases of the pre-Riphean Siberian Craton showed the R value to be $(3.6\pm0.9)\times10^{-8}$, which almost coincides with the cannonic radiogenic value. The heat flow of the craton is also low, close to the continental background [*Duchkov et al.,* 1987].

The Khangai dome-shaped uplift of Mongolia showed the average $R = (16.3\pm4.6)\times10^{-8}$, the most probable estimate being $(12.3\pm2.9)\times10^{-8}$, which corresponds to the Paleozoic crust where the heat flow is somewhat higher than the continental background [*Khutorskoi,* 1996].

The Khentei Kerulen zone of Mongolia with its abundant volcano-plutonic rocks of Mesozoic age showed highly variable R values amounting to 1.9×10^{-6} and averaging 0.94×10^{-6}. The Mesozoic and later tectonic reactivation embraced also the Russian Trans-Baikal region, where the He isotope composition is also highly variable with the average $R = 1.14\times10^{-6}$. The combined data sample showed $R = (1.06\pm0.33)\times10^{-6}$ which can be taken as atypical value for the eastern flank of the rift zone. where the heat flow is also notably higher [*Lysak,* 1988; *Lysak and Pisarskii,* 1999]. For this reason the distribution of the values of the He isotope ratio across the rift zone is highly asymmetric suggesting the heat flow from the mantle not only in the rift zone, but also in the region much more eastward.

The fluids of the rift zone showed that the He isotope composition there was distinguished by the widest spectrum of the R values: 4.9×10^{-8} to 1.1×10^{-5}. The determination of the average R value has no geological sense, yet the variation of the R values along the strike of the rift zone shows a definite pattern.

7. The value of the He isotope ratio in ground fluids decreases along the strike of the rift zone from Southern Yakutia to Northern Mongolia in both directions away from the Tunka Basin where it attains a mantle value. This trend is accompanied by a conductive heat flow decline and by the sizes of the rift basins becoming smaller [*Lysak,* 1988]. This correlation indicates a decline in the heat and mass flow from the mantle in the distant segments of the rift zone.

8. The wide variation of the He isotope composition in the fluids is the general universal property of continental rift zones, proved by numerous studies in Africa, West and Central Europe, and East Asia [*Craig and Lupton,* 1978; *Craig and Rison,* 1982; *Du,* 1992; *Griesshaber et al.,* 1989, 1992; *Hooker et al.,* 1985; *Lupton et al.,* 1977; *O'Nions et al.,* 1989], and also by our previous study of the Baikal Rift [*Polyak et al.,* 1992]. This variation distinguishes them from the zones of oceanic spreading in mid-oceanic ridges, throwing light on the principle difference between the crust and mantle interaction in these environments.

Oceanic crust spreading is the reaction of the lithosphere to the rise of mantle material along the axis of a spreading ridge throughout its extension with the same intensity, that is. in this case the extension of the lithosphere is caused by mantle activity. In the case of continental rifting the mantle activity is not the cause but the consequence of shear deformation in the overlying lithosphere. This deformation is obviously provoked by collision which breaks the crust (lithosphere) and creates conditions favorable for the autonomous movements of the arising plates (microplates) and for origin of pull-apart structures favoring the formation of mantle diapirs.

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