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GEOGRAPHY

Hydrothermal Activity in the Baikal Rift Zone: Recent Hot Springs and Deposits of Paleothermal Waters

Corresponding Member of the RAS **E. V. Sklyarov**[a], **V. S. Fedorovskii**[b], **O. A. Sklyarova**[c], **T. M. Skovitina**[a], **Yu. V. Danilova**[a], **L. A. Orlova**[d], **and N. N. Ukhova**[a]

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Thermal springs, which are widely developed within the Baikal rift zone (BRZ), form a NE-trending zone extending from the upper course of the Olekma River in the northeast to the Selenga River mouth in the southwest (Fig. 1). Thermal springs are rare west of Lake Baikal. Springs, mainly represented by nitric thermal waters of variable composition, mark recent hydrothermal activity in the BRZ [1, 2]. This zone also contains deposits of paleothermal water represented by travertines and geyserites [2, 3]. Travertines can be deposited within a wide range of temperatures, from cold water inclusive. However, they are mostly deposited from thermal water [2], the temperature of which in the study region can vary from 20 to 70°C [4]. As to geyserites, the minimal temperatures of their formation do not fall below 70°C [2]. We found geyserites on the western coast of Lake Baikal [5] at the southwestern extension of the above-mentioned zone of hydrothermal activity. The amount of siliceous deposits in the Ol'khon region is much higher as compared to previously described geyserite occurrences on the eastern coast of Lake Baikal, where only thin crusts of opal-like chalcedony were found in fragments of bedrocks with silica as cement [1]. Recently, travertines have been found in association with geyserites and as independent veins in the Ol'khon region.

In most cases, geyserites are dense opal-like rocks composed of brown chalcedony of different tints. They are represented by eluvial coarse-block debris confined to an area of tens of meters (more rarely, 100–150 m). Blocks, from tens of centimeters to several meters in size are usually unrounded. However, their microsurface gives the impression of fusion due to processes of surface dissolution. They are characterized by a spongy structure related to the leaching of silicate and carbonate fragments in the chalcedony matrix. Rocks primarily composed of iron hydroxides and travertines are encountered along with geyserites in some coarse-block debris. At some bedrock exposures, geyserites overlap ultrabasites, marbles, gneisses with granite veins, and geyserite cut in marbles. Table 1 demonstrates that the composition of enclosing rocks governs the geochemistry of geyserites. For instance, geyserites overlapping ultrabasites are characterized by higher contents of Ni and Co. The contents of virtually all rare and rare-earth elements in the marble-hosted geyserites are considerably lower than in other hydrothermal siliceous deposits. Concentrations of Pb, Zn, Cu, Ag, Sb, Th, Y, As, and REE are very high in geyserites in the suture zone between the Siberian Craton and the Ol'khon Terrane (Table 1, analysis 2). The contents of the major components in geyserites are as follows (%): SiO_2 82–99.7, ($FeO + Fe_2O_3$) 0.7–10, and ($CaO + MgO$) 0.04–2.96. The contents of other major components are negligibly small (Table 1).

Bedrock and eluvial exposures of geyserites make up extended narrow zones (Fig. 2), which clearly exhibit correlation with the Early Paleozoic and Cenozoic tectonics. These zones are conformal with the principal suture of the region (Primorsky fault) and numerous linear NNE-trending blastomylonite sutures, which mark the final stages of the Early Paleozoic collisional

[a] *Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences, ul. Lermontova 128, Irkutsk, 664033 Russia*

[b] *Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119119 Russia; e-mail: west45@migmail.ru*

[c] *Vernadsky Institute of Geochemistry, Siberian Division, Russian Academy of Sciences, ul. Favorskogo 2, Irkutsk, 664033*

[d] *Institute of Geology and Mineralogy, Siberian Division, Russian Academy of Sciences, Universitetskii pr. 3, Novosibirsk, 630090 Russia*

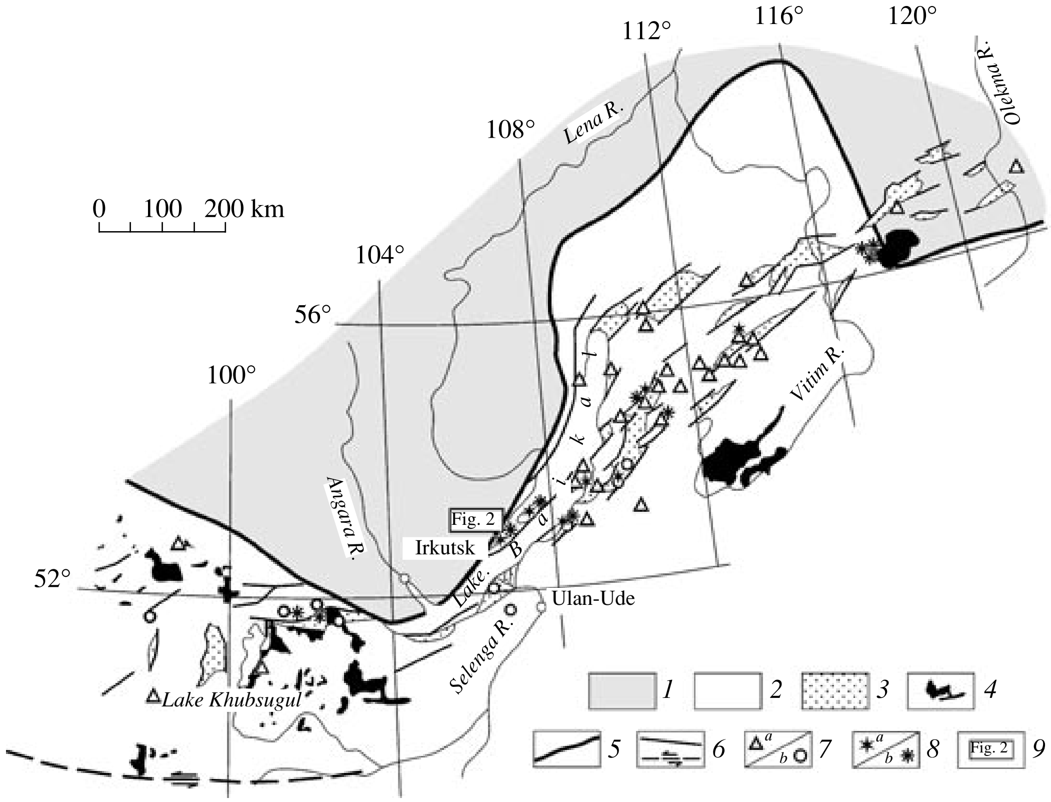

Fig. 1. Recent thermal manifestations and mineral formation in the Baikal rift zone (tectonic pattern modified after [9]). (*1*) Siberian Craton; (*2*) Sayan–Baikal folded region; (*3*) rift troughs; (*4*) volcanic fields; (*5*) boundary between craton and fold zone; (*6*) faults of different kinematics; (*7*) springs (*a*) and wells (*b*) with water temperature exceeding 42°C (after [2]); (*8*) (*a*) geyserites and (*b*) travertines; (*9*) position of Fig. 2.

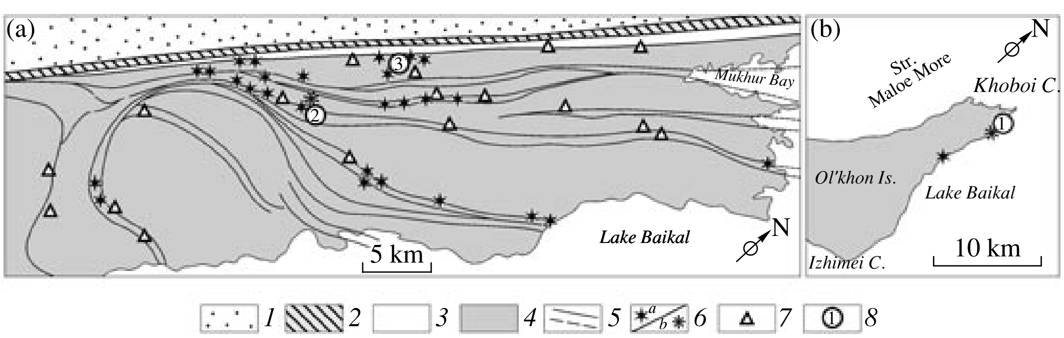

Fig. 2. Distribution of geyserites, travertines, and springs (a) in the Ol'khon region and (b) on Ol'khon Island. (*1*) Siberian Craton; (*2*) escarpment of the Primorsky fault; (*3*) collisional suture; (*4*) Ol'khon Terrane (early Paleozoic collision complex); (*5*) Cenozoic inherited faults; (*6*) (*a*) geyserites and (*b*) travertines; (*7*) springs; (*8*) dated objects. Numbers in the figure correspond to sample numbers in Table 2.

orogen and mainly correspond to dextral faults [6]. Inherited strike-slip and normal faults appeared in these sutures in the course of the formation and evolution of the BRZ [7, 8]. Hydrothermal water discharges were controlled by inherited NNE-trending faults related to the Baikal rift evolution.

Travertines are much less common than geyserites in the region, probably because it is rather difficult to identify the travertines among the widespread marbles of the crystalline basement and, therefore, their quantity is likely to be underestimated. Two travertine occurrences have been reliably established.

Table 1. Representative analyses of geyserites and travertines in the Ol'khon region

Component	1	2	3	4	5	6	7	8	9
SiO_2	94.30	84.53	95.45	93.42	58.16	8.94	3.44	1.91	0.23
TiO_2	0.003	0.031	0.003	0.02	0.02	0.02	0.08	0.06	0.05
Al_2O_3	0.06	0.69	0.10	0.43	0.53	0.43	0.46	<0.04	<0.04
Fe_2O_3	2.66	10.15	2.16	1.62	2.75	2.31	12.09	2.75	0.26
FeO	n.d.	n.d.	n.d.	0.84	0.38	0.55	0.92	0.26	n.d.
MnO	0.02	0.03	0.02	0.13	0.06	0.05	0.04	0.11	0.003
MgO	0.05	0.02	0.05	0.56	1.40	1.92	1.62	1.50	1.92
CaO	0.07	0.17	0.04	0.34	19.60	46.48	43.72	50.65	53.99
Na_2O	0.02	0.05	0.01	0.01	0.01	0.01	0.05	0.04	0.04
K_2O	0.03	0.14	0.03	0.01	0.01	0.01	0.13	0.08	0.10
P_2O_5	0.017	0.100	0.024	0.040	0.030	0.030	0.004	0.002	0.002
CO_2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	35.18	40.56	40.70
H_2O	″	″	″	″	″	″	0.21	0.18	0.05
L.O.I.	1.31	2.59	0.94	1.97	16.71	38.64	2.551	1.712	3.119
Total	98.55	98.50	98.83	99.39	99.66	99.39	100.50	99.81	100.47
As	2.38	45.8	1.51	1.72	1.43	1.22	3.96	5.68	6.73
V	19.3	131.5	64.7	10.5	19.1	46.0	37.3	11.2	0.2
Co	1.56	4.61	0.83	13.45	69.81	73.77	2.04	2.27	0.93
Ni	7.58	28.99	11.34	167	1055	973	19.33	22.32	7.56
Cu	8.9	60.1	16.7	9.9	2.1	1.4	7.8	2.8	2.4
Zn	6.4	349	16.5	17.1	7.5	5.4	11.6	10.9	10.2
Rb	0.3	3.5	0.5	0.9	0.4	0.3	6.7	1.0	0.1
Sr	4	11	3	16	119	132	176	105	234
Y	0.82	10.01	9.70	0.95	0.05	0.06	1.45	2.51	2.28
Ag	0.19	21.9	0.13	0.02	0.04	0.04	2.24	0.45	1.86
Sb	0.11	32.7	0.14	0.12	0.10	0.07	0.10	0.02	<0.02
Ba	19.1	142	7.9	146	13.7	8.8	49.3	44.4	8.5
La	0.597	3.712	0.635	0.275	0.061	0.059	1.102	0.731	0.457
Ce	0.802	3.821	1.085	0.371	0.079	0.066	2.026	0.455	0.228
Pr	0.131	0.880	0.152	0.091	0.012	0.013	0.254	0.125	0.118
Nd	0.521	3.821	0.635	0.389	0.042	0.039	0.966	0.512	0.539
Sm	0.107	0.876	0.166	0.105	0.008	0.008	0.211	0.125	0.137
Eu	0.040	0.244	0.059	0.053	0.002	0.002	0.062	0.039	0.020
Gd	0.111	0.954	0.214	0.136	0.006	0.006	0.216	0.178	0.184
Tb	0.024	0.212	0.067	0.025	0.001	0.001	0.032	0.029	0.030
Dy	0.129	1.351	0.700	0.181	0.006	0.006	0.203	0.184	0.197
Er	0.074	0.928	0.645	0.123	0.004	0.005	0.113	0.111	0.121
Tm	0.011	0.135	0.105	0.022	0.001	0.002	0.015	0.015	0.016
Yb	0.077	0.884	0.027	0.162	0.021	0.021	0.093	0.094	0.105
Lu	0.013	0.142	0.118	0.031	0.006	0.006	0.014	0.014	0.016
W	0.26	1.02	0.14	0.46	0.66	0.44	0.19	0.07	0.03
Pb	0.57	5.45	0.97	0.10	0.28	0.02	0.98	0.30	0.07
Th	0.039	0.212	0.034	0.097	0.027	0.024	0.44	0.07	0.01
U	1.48	1.89	0.76	3.65	1.31	2.55	7.22	1.42	1.18

Note: Geyserites (1–4) and travertines (5–9) in different enclosing rocks: (1) marbles, (2) blastomylonites, (3) amphibolites, (4–6) ultrabasites, (7–9) gneisses. Analyses of the major components (wt %) were carried out at the Analytical Center of the Institute of the Earth's Crust, Irkutsk. Concentrations of trace elements (ppm) were determined using an ELEMENT-2 ICP-MS in the Vernadsky Institute of Geochemistry, Irkutsk. (n.d) Not detected; (n.a) not analyzed.

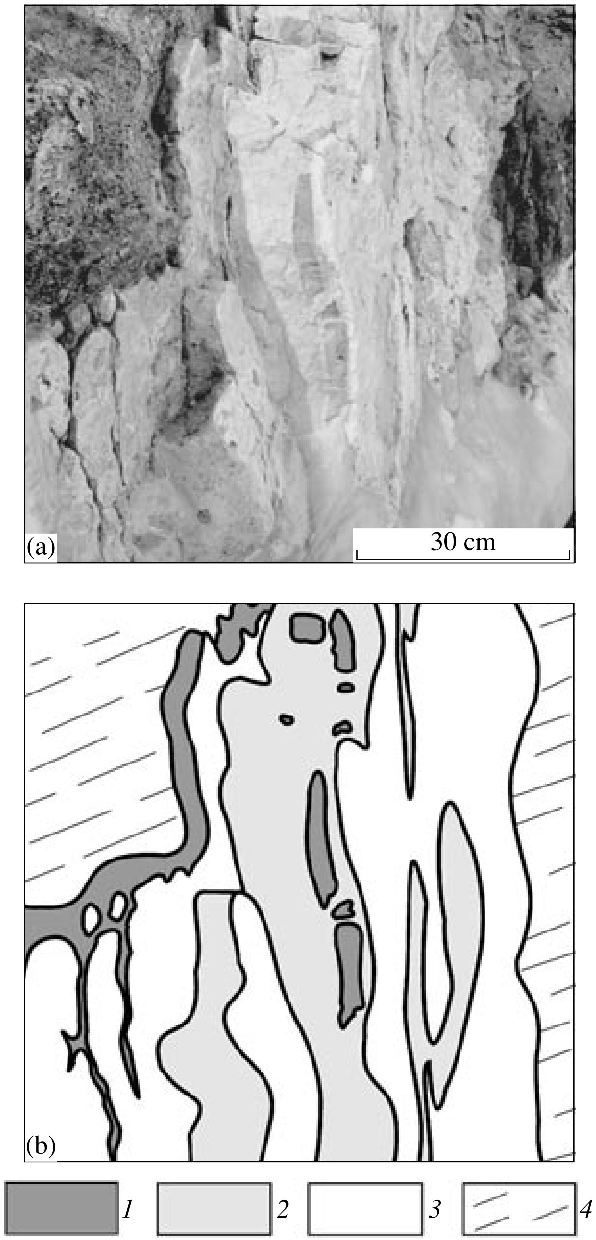

Fig. 3. (a) Photograph and (b) photograph-based drawing of a travertine vein fragment. (*1–3*) Travertines of the (*1*) first, (*2*) second, and (*3*) third phases; (*4*) enclosing gneiss. See text for explanations.

(1) Small bodies of an indefinite form among geyserites in Krasnaya Gorka ("Red Hill") made up of fine-crystalline light gray to white (often with a yellowish tint) calcite (Fig. 2). Their relationships with geyserites in bedrock exposures have not been established. Altered ultrabasites of the crystalline basement stripped by a bulldozer include numerous veinlets of acicular and columnar calcite. The zone can be regarded as a conduit of thermal solutions. The thickness of calcite veins and veinlets varies from 1 mm to 3 cm.

(2) A nearly vertical vein up to 30 cm thick among gneisses at the northern edge of Ol'khon Island (strike azimuth 340°). The vein has a zonal structure reflecting three phases of carbonate deposition (Fig. 3). The first phase is represented by Fe_2O_3-rich cryptocrystalline brown carbonates that occur as small fragments at the margin of a vein (up to 5 cm thick), as well as rectangular fragments (2 × 5 × 6 cm in size) among brownish yellow fine-crystalline carbonates of the second phase. The third phase is represented by light gray to white semitransparent sintered (agathic) calcite in marginal parts of the vein. Calcite of the third phase includes numerous acute-angled fragments of nearly isometric to lamellar carbonates of the second phase. Fragments vary in size from a few millimeters to a few centimeters. Thus, we can confidently distinguish three consecutive phases in the deposition of carbonate material with different chemical compositions (Table 1). The first phase is enriched in Fe (up to 10% Fe_2O_3), whereas the third phase is represented by virtually pure calcite with an insignificant dolomitic admixture. Based on the XSA data, the carbonate is represented by calcite rather than aragonite. Compositional differences of the three phases are reflected in contents of rare and rare-earth elements as well (Table 1). Their concentrations decrease from the first phase to the third phase. The first phase is enriched in LREEs (La–Gd), whereas the second and third phases exhibit clear Ce- and Eu-negative anomalies.

Palynological data suggest a late Quaternary age of geyserites [5]. Travertine samples were taken from two sites to carry out more exact dating. In addition, graphite uniformly distributed in rock was separated from geyserites in a vein ~5 m thick. The results of the dating (Table 2) demonstrate within the measurement error limit that travertines of Krasnaya Gorka and geyserites of the Tonta zone were deposited nearly synchronously (~23 500 yr), whereas travertines from the vein on Ol'khon Island are younger (19 500 yr). Ages of travertines from the Ol'khon region match the age interval of travertines from the Garginskii hot spring in the Barguzin Depression (19 245–25 725 yr) [3].

Finds of geyserites and travertines allow us to ascertain confidently the discharge of paleothermal waters in the Ol'khon region, whereas present-day springs are characterized only by cold water [7]. The wide development of deposits of thermal waters (Fig. 2) justifies the apparently exotic comparison of the Ol'khon region with the Geysers Valley in the first publication devoted to geyserites [5]. Judging from the available data, the maximum hydrothermal activity in the BRZ took place 20–24 ka ago. Indications of the later existence of thermal springs in the Ol'khon region are absent. However, deposition of silicates and carbonates is still in progress east of Lake Baikal (e.g., present-day silica deposits in Kulinii swamps, Svyatoi Nos Isthmus; carbonate deposits at the Allinskii and Garginskii hot springs, among others). Maximal development of deposits of thermal waters on the southwestern flank of the hydrothermal zone at early stages (late Neopleistocene) and

Table 2. Ages of travertines and geyserites in the Ol'khon region

Ord. no.	Sample no.	Dated material	Coordinates	Age, yr
1	SE142	Travertine from a vein in metamorphic rocks, Ol'khon Island	53°23′48″ N, 107°47′21″ E	19550 ± 300
2	SK41	Travertine from debris on a hill in association with geyserites, Ol'khon region	52°50′18″ N, 106°30′51″ E	23420 ± 425
3	SE246	Graphite from a geyserite vein in marbles, Ol'khon region	52°54′32″ N, 106°32′84″ E	23720 ± 210

Note: Datings were carried out in the Laboratory of Cenozoic Geology and Paleoclimatology, Institute of Geology, Siberian Division, Russian Academy of Sciences. Carbon residual activity was determined with QUANTULUS-1220 (Liquid Scintillation Counters). The dating was based on CO_2. The ^{14}C half-life equal to 5570 yr was used for dating. The age was calculated as of 1950.

the absence of present-day thermal springs suggest a decrease in the heat flow and northeastward migration of the hydrothermal activity in the study region.

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