Microbiology, Vol. 73, No. 2, 2004, pp. 202–210. Translated from Mikrobiologiya, Vol. 73, No. 2, 2004, pp. 248–257.

EXPERIMENTAL ARTICLES

Bacterial Processes of the Methane Cycle in Bottom Sediments of Lake Baikal

O. P. Dagurova*,[1], B. B. Namsaraev*, L. P. Kozyreva*, T. I. Zemskaya, and L. E. Dulov*****

** Institute of General and Experimental Biology, Siberian Division, Russian Academy of Sciences, ul. Sakh'yanovoi 6, Ulan-Ude, 670047 Buryat Republic, Russia*

*** Limnological Institute, Siberian Division, Russian Academy of Sciences, ul. Ulan-Batorskaya 3, Irkutsk, 664033 Russia*

**** Institute of Microbiology, Russian Academy of Sciences, pr. 60-letiya Oktyabrya 7, k. 2, Moscow, 117312 Russia*

Received November 26, 2002; in final form, March 24, 2003

Abstract—The activity of methanogenic and methanotrophic bacteria was evaluated in bottom sediments of Lake Baikal. Methane concentration in Baikal bottom sediments varied from 0.0053 to 81.7 ml/dm^3. Bacterial methane was produced at rates of 0.0004–534.7 μl CH_4/(dm^3 day) and oxidized at rates of 0.005–1180 μl CH_4/(dm^3 day). Peak methane production and oxidation were observed in Frolikha Bay near a methane vent. Methane was emitted into water at rates of 49.2–4340 μl CH_4/(m^2 day). Rates of bacterial methane oxidation in near-bottom water layers ranged from 0.002 to 1.78 μl/(l day). Methanogens and methanotrophs were found to play an important role in the carbon cycle through all layers of sediments, particularly in the areas of methane vent and gas-hydrate occurrence.

Key words: methane production, methane oxidation, methane emission, Lake Baikal.

The methane cycle is comprised of the processes of methane production and oxidation, which are driven by specialized bacterial groups [1]. The ratio of these processes in aquatic ecosystems determines the methane emission into the atmosphere from the water surface. Previous studies indicate that methanogens and methanotrophs play an important role in the biogeochemical cycle of carbon and strongly influence the composition of environmental gases [1–9].

Methanogenesis is the main terminal process during the anaerobic degradation of organic matter (OM) in bottom sediments of Lake Baikal, the deepest lake of our planet [10, 11]. The processes of methane oxidation in bottom sediments and water column of Lake Baikal have not been studied. Of particular interest is the activity of bacteria involved in the methane cycle in those parts of the lake where sediments are characterized by peculiar physicochemical conditions. Among such areas are the hydrothermal vents of Frolikha Bay and the places of discovery of methane hydrates in southern Baikal [12, 13].

The aim of our study was to evaluate the rates of bacterial processes of methane production and oxidation in bottom sediments of different parts of Lake Baikal.

[1] Corresponding author. E-mail: dagurova@biol.bsc.buryatia.ru

MATERIALS AND METHODS

Microbiological studies were carried out during expeditions on board the *Vereshchagin* research vessel in August through September 1991, June 1992, September 1997, and March 2000.

Sediment samples were collected using a clamshell, a geological tube, and a dredger. The pH and redox potentials were measured potentiometrically with an SC-82 portable ionometer (Japan). The carbonate content was determined by liquid chromatography on an EnviroChrom chromatograph (Japan). Methane was quantified using a desorption method [14]. Sediment samples were collected in Balch glass tubes 30 cm^3 in volume containing 5 g of NaCl. The tubes were closed with gas-impermeable rubber stoppers so that the volume of the gas phase was 2 cm^3. Methane concentration was determined on a M-3700 gas chromatograph (AO Khromatograf, Russia) equipped with a flame-ionization detector [10, 14].

The rates of bacterial methane production and oxidation were determined by the radioisotope method [4, 14] in the surface and subsurface layers of sediment and in core samples (to a depth of 87 cm) from the southern basin of the lake. Samples (1–2 cm^3) were collected in penicillin vials, incubated with $NaH^{14}CO_3$ (0.25 MBq, 0.8 GBq/mmol) or $^{14}CH_4$ (0.08 MBq, 1.2 GBq/mmol) for 18–24 h at an in situ temperature and fixed with 2 ml of a 1 N KOH solution. Radioactivity was measured on

0026-2617/04/7302-0202 © 2004 MAIK "Nauka/Interperiodica"

a RackBeta scintillation counter (LKB, Sweden). The rates of methane production and oxidation were calculated by using common equations [4, 14].

The methanotrophic bacteria *Methylosinus trichosporium, Methylobacter capsulatus, Methylosinus echinoides, Methylomonas methanica*, and *Methylobacter bovis* were detected and enumerated by the immunofluorescence method [6, 14] using species-specific sera obtained from L.V. Bezrukova.

RESULTS

Physicochemical characteristics of bottom sediments. Sediment samples were collected from depths of 4 to 1530 m in the northern, central, and southern basins of Lake Baikal. Deep-water sediments were represented by silts; in gas-hydrate areas of the southern basin, gray clay and pebbles also occurred [12]. In shallow waters of Bugul'dei neck, Selenga River, Frolikha Bay, Khakusy Bay, Sosnovka Bay, and near Baikal'sk and Bol'shie Koty, sediments were represented by fine-grained sand and black and brown silts.

The values of the redox potential in bottom sediments ranged from +225 to –140 mV, pH values were 6.3–7.2, and temperature varied from 3.2 to 8.0°C (Table 1).

Methane content in bottom sediments. Methane concentration in bottom sediments of the lake ranged from 0.0053 to 81.7 ml/dm^3 of wet silt (Table 2). The peak concentration of 81.7 ml/dm^3 was observed in Frolikha Bay at a depth of 415 m (station 2-97). A high methane concentration (45 ml/dm^3) was observed in the sediments of Frolikha Bay at a depth of 405 m (station 3-97). Minimal methane concentrations ranging from 0.0053 to 0.0065 ml/dm^3 were recorded in the northern basin at a depth of 820 m and in Frolikha Bay at a depth of 105 m. Methane concentration in the near-bottom water of the gas-hydrate area was 0.0059 ml/l (G.V. Kalmychkov, personal communication).

Bacterial methane production in bottom sediments. The process of methanogenesis was studied in the bottom sediments of the southern basin in areas of gas hydrates and Ivanovskii Cape (Table 3). Methane production rates ranged from 4.4 to 341.6 μl/dm^3 of bottom sediments. The maximum rate of methane formation was registered in samples from the surface horizon of the sediments from station 5-00 (Novyi Crater). A high methanogenesis rate (up to 301.2 μl) was registered in sediment samples obtained from a depth of 25–30 cm at station 3-00. The rate of methanogenesis in sediments collected near Ivanovskii Cape ranged from 4.43 to 18.9 μl/(dm^3 day) and increased down the profile to the depth of 87 cm. The same pattern was observed at station 1-00, whereas at stations 3-00, 4-00, 5-00 and 6-00 the highest rates of methanogenesis were observed in surface horizons. The consumption of organic matter for the production of methane by the microbial community was evaluated as 9.6–734.7 μg C per day in 1 dm^3 of wet silt. The rates of bacterial methane production and the results of methanogen enumeration in bottom sediments of Frolikha Bay, Khakusy Bay, Selenga River shoal, Bugul'dei neck, the southern and central basins, Akademicheskii Ridge, and littoral areas near Baikal'sk and Bol'shie Koty were reported earlier [10, 11].

Bacterial methane oxidation in bottom sediments. The rate of bacterial methane oxidation was evaluated in shallow-water and deep-water sediments, in bay waters, and in shallow waters of the Selenga River (Table 3). In Frolikha Bay, where a great number of measurements were taken, the highest rate of methane oxidation (up to 1180.4 μl CH_4 per dm^3 of wet silt per day) was registered in the area of a methane vent at station 3-97. High rates of methane oxidation (438.4–1083 μl CH_4/(dm^3 day)) were registered in Frolikha Bay at depths of 400–415 m. In sediments near gas hydrates, the rate of methane oxidation ranged from 35 to 273.2 μl CH_4/(dm^3 day). The minimal methane oxidation rate (0.004 μl/(dm^3 day)) was recorded in sediments of the northern basin at a depth of 820 m.

In the process of methane oxidation in Lake Baikal, the bulk of carbon is converted to CO_2 (up to 100% in some samples). However, in gas-hydrate areas, a considerable proportion of carbon is found in bacterial exometabolites and biomass (17–95% in sediments and 29–82% in water).

The population densities of five species of methane-oxidizing bacteria were evaluated in bottom sediments of Frolikha Bay (station 2-97) and Sosnovka Bay (station 21-97). The highest rate of methane oxidation was registered in sediments of Frolikha Bay. It was almost 10 000 times lower in sediments of Sosnovka Bay (Table 4). In the area of a methane vent in Frolikha Bay, the total number of methanotrophs was 17360 cells per 1 cm^3, almost two times higher than in Sosnovka Bay (8470 cells per 1 cm^3). However, in Sosnovka Bay, all five methanotrophic species were found, whereas in Frolikha Bay only three species were revealed. The maximal number of cells of the same species was registered in a surface layer of sediments at station 2-97 (up to 13200 cells per 1 cm^3), whereas the minimal value was recorded at station 21-97 (220 cells per 1 cm^3).

Bacterial methane oxidation in water. From the calculations of methane production and oxidation, it was deduced that 49.2–4340 μl CH_4/m^2 of methane was emitted into the water column per day (Table 5). The methane arriving from the bottom sediments was oxidized by bacteria in water. The rates of methane oxidation in the near-bottom water of Frolikha Bay ranged from 0.15 to 0.83 μl CH_4/(l day) (Table 6).

At station 1-97 (Zavorotnyi Cape), methane oxidation was not registered in the near-bottom and surface water layers and was minor in horizons at depths of 50–775 m (to 0.014 μl CH_4/(l day)). A considerable portion of methane (up to 98%) was oxidized to organic matter.

Table 1. Physicochemical characteristics of bottom sediments of Lake Baikal

Sampling site	Station	Depth, m	Horizon, cm	Type of sediment	*t*, °C	pH	Eh, mV
Frolikha Bay	2-97	415	0–3	Dark gray silt	6.1	7.0	+10
	3-97	405	0–0.5	Gray silt	4.8	7.3	–35
			1–5	Dark gray silt			
	6-97	400	0–1	Gray silt	5.0	6.9	+33
	7-97	215	0–1	Dark gray silt	6.2	6.9	+5
	8-97	105	0–1	Dark gray silt	6.0	7.3	+6
	9-97	685	0–1	Dark gray fluid silt	5.9	7.0	–
	11-97	22.5	0–5	Dark brown silt, plant debris	8.0	7.2	–
	12-97	42	0–3	Dark brown silt, plant debris	7.6	7.2	–
	13-97	31.8	0–1	Gray fine-grained sand	7.8	6.7	–
	16-97	690	0–1	Brown silt	5.3	7.1	–
	20-97	690	0–1	Brown silt	5.4	6.3	–
Zavorotnyi Cape	1-97	825	0–1	Brown silt	5.8	7.5	+78
			1–5	Diatomaceous silt	–	–	–
			5–12	Diatomaceous silt	–	–	–
			13–20	Yellowish brown clay	–	–	–
Sosnovka Bay	21-97	300	0–0.5	Brown silt	5.5	7.1	–
Southern basin							
Bol'shoi Crater	1-00	1400	0–1	Gray diatomaceous silt	5.6	7.2	+185
			1–7	″	5.6	–	–
			15–18	″	5.6	7.1	–140
			23–28	″	5.5	–	–
			32–36	″	5.9	–	–
			38–40	″	4.5	7.0	–50
Malen'kii Crater	2-00	1380	0–1	Silty pebbles	–	7.2	–55
			1–3.5	Brownish black clay	4.0	–	–
			3.5–13	Gray clay	3.8	6.9	–80
			13–25	Black clay	3.5	–	–
			30–36	Gray clay	3.4	6.9	+70
Malen'kii Crater	3-00	1400	0–24	Pebbles with sand	4.4	6.1	+225
			25–30	Water-bearing clay	4.2	–	–
			30–35	Dense gray clay	4.1	–	–
			35–45	″	3.6	–	–
			52–57	″	3.2	6.2	+5
Malen'kii Crater	4-00	1380	0–2	Aleurite silt	3.4	–	–
			21–23	Aleurite silt, gassing	3.0	6.8	+150
Novyi Crater	5-00	1080	0–1	Gray diatomaceous silt	2.9	7.2	–
			7–10	″	3.2	–	–
			29–31	″	3.2	–	–
			49–50	″	3.2	6.7	+15
Malen'kii Crater	6-00	1400	0–5	Oxidized layer	4.2	7.1	+80
			5–11	Gray silt	3.9	–	–
			14–17	Sand band	3.8	–	–
			20–24	Dark gray silt	3.8	–	–
			45–50	Dark gray silt	3.8	6.8	+60
Ivanovskii Cape	7-00	1400	0–5	Pelitic diatomaceous silt	5.1	–	–
			20–25	″	4.6	–	–
			40–45	″	4.0	–	–
			60–65	″	4.0	–	–
			82–87	″	4.5	–	–

Note: "–" stands for "not determined."

* In this and the other tables, in the column "station," the figures after the hyphen signify the year of sampling.

Table 2. Methane concentration in bottom sediments of Lake Baikal

Sampling region, station	Horizon, cm	CH_4 concentration, ml/l	Sampling region, station	Horizon, cm	CH_4 concentration, ml/l
Frolikha Bay			Zavorotnyi Cape		
2-97	0–1	81.7	1-97	0–1	1.0
3-97	0–1	45.0		1–5	0.01
	1–5	27.0		5–12	0.008
6-97	0–1	0.4	Northern basin		
7-97	0–1	0.01	20-97	0–1	0.005
	5–10	0.2	Sosnovka Bay		
8-97	0–1	0.006	21-97	0–1	0.005
	10–15	0.22			
9-97	0–1	0.027			
11-97	0–1	0.013			
12-97	0–1	0.014			
13-97	0–1	0.042			
16-97	0–1	0.024			

The rates of methane oxidation in the near-bottom water of gas-hydrate areas were higher than in Frolikha Bay and ranged from 0.59 to 1.78 μl CH_4/(l day). The highest rate was registered in the near–bottom water at station 1-00; the lowest rate was recorded at station 5-00. At a depth of 1380 m (station 2-00), methane oxidation was registered along the entire water column. The rate of oxidation ranged from 0.88 to 0.53 μl CH_4/(l day), decreasing insignificantly toward the surface. From 29 to 82% of methane was oxidized to organic matter.

DISCUSSION

Methane is the basic terminal product of anaerobic decomposition of organic matter in bottom sediments of the oligotrophic Lake Baikal [10, 11]. The highest methane concentration (81.7 ml/dm^3) was registered in sediments of the thermal area of Frolikha Bay. This could be due to the arrival of methane with hydrothermal emanations and to active metabolism of methanogens. The methane concentrations in sediments of southern Baikal and near the Baikal'sk pulp and paper mill were evaluated earlier; they amounted to 1.8 [15] and 1.46 ml/kg of wet silt [16], respectively. The methane content in gas hydrates was 98–99% [17]. According to isotopic data, methane in bottom sediments of the lake, including gas hydrates, was of biogenic origin [10, 18].

The rate of bacterial methane production in bottom sediments ranged from 0.01 to 534.70 μl CH_4/(dm^3 day) [10, 11]. This process was registered in all horizons of bottom sediments studied, including oxidized layers, which suggests active metabolism of methanogens inhabiting anaerobic microzones of the upper layers of sediments.

High rates of methanogenesis were recorded in areas of gas-hydrate occurrence in the southern basin (to 341.6 μl/dm^3 per day). Up to 734.7 μg of organic carbon was used for methane synthesis in these sediments.

Bacterial methane oxidation was registered in both bottom sediments and water. In the areas studied, the rate of methane oxidation in water was 3–4 orders of magnitude lower than in sediments. Methane oxidation was most intense in surface layers of sediments, which confirms the regularities revealed for deep oligotrophic lakes [19].

In bottom sediments of Lake Baikal, methanotrophic bacteria oxidize from 0.004 to 1180.4 μl CH_4/dm^3 per day. High rates of bacterial methane oxidation were observed in sediments of littoral regions and bays, where high rates of bacterial methane production were registered. The highest methanotrophic activity was observed in sediments of Frolikha Bay near methane vents, characterized by a high methane content. This is in agreement with the positive correlation between the concentration of methane and the rate of its oxidation ($r = 0.96$; $n = 18$). Bacterial methane oxidation was also observed through the full length of cores studied, which indicates that anaerobic bacteria may contribute to methane consumption.

Thus, in the areas of fluxes of thermal waters and gases in Baikal, the rate of methane oxidation reached 1180.4 μl CH_4/(dm^3 day), whereas in background areas the maximal rate registered was 180.2 μl CH_4/(dm^3 day).

Table 3. Rates of bacterial methane production and oxidation in bottom sediments of Lake Baikal

Sampling site	Station	Depth, m	Horizon, cm	CH_4 production, µl/(dm^3 day)	CH_4 oxidation, µl/(dm^3 day)	Label transition into CO_2, %
Southern basin	1-91	1503	0–1	2.78	180.2	80
Ol'khon Island	2-91	1530	0–1	7.6	31.0	46
Bugul'dei neck	3-91	390	0–1	0.43	144.9	58
Frolikha Bay	4-91	430	0–1	26.28	355.9	62
	5-91	430	0–1	95.65	707.6	64
			2–4	534.6	124.0	75
	8-91	430	0–0.2	241.23	235.8	66
Khakusy Bay	7-91	420	0–1	73.97	121.3	40
Baikal'sk	1-92	15	0–1	0.39	1.8	–
Area of BPPM*	2-92	18	0–1	0.36	22.36	–
Bol'shie Koty	4-92	5	0–1	0.20	7.33	–
Shallow water of the Selenga River	7-92	30	0–1	0.34	16.38	–
	8-92	189	0–1.5	0.44	57.94	–
Akademicheskii Ridge	9-92	267	0–1	2.53	9.36	–
	10-92	922	0–1	0.34	9.9	–
Frolikha Bay	2-97	415	0–3	140.5	1083.0	42
	3-97	405	0–0.5	120.0	1180.4	56
			1–5	450.0	438.4	55
	6-97	400	0–0.1	24.2	7.2	50
	7-97	215	0–1	–	0.07	51
			1–5	–	0.13	100
	8-97	105	0–1	–	0.005	96
			5–10	–	0.12	100
	9-97	685	0–1	–	0.045	70
	11-97	22.5	0–5	–	0.37	64
	12-97	42	0–3	–	0.43	71
	13-97	31.8	0–1	0.28	13.0	74
	16-97	690	0–1	–	0.33	47
Zavorotnyi Cape	1-97	825	0–1	0.36	3.4	77
			1–5	1.5	0.007	81
			5–12	–	0	0
Northern basin	20-97	820	0–1	–	0.004	100
Sosnovka Bay	21-97	310	0–0.5	65.8	0.46	66
Bol'shoi Crater	1-00	1400	0–1	5.00	141.78	5
			1–7	–	118.89	31
			15–18	9.77	105.54	26
			23–28	–	148.59	41
			32–36	13.49	166.21	55
			38–40	17.74	97.64	25
Malen'kii Crater	2-00	1380	0–1	79.74	121.85	59
			1–3.5	57.08	76.40	29
			3.5–13	138.59	130.70	71
			13–25	24.78	124.24	9
			30–36	40.47	125.70	39

Table 3. (Contd.)

Sampling site	Station	Depth, m	Horizon, cm	CH_4 production, µl/(dm^3 day)	CH_4 oxidation, µl/(dm^3 day)	Label transition into CO_2, %
Malen'kii Crater	3-00	1400	0–24	210.27	112.18	54
			25–30	301.15	64.95	61
			30–35	158.73	35.64	51
			35–45	154.38	68.71	39
			52–57	77.17	40.02	6
Malen'kii Crater	4-00	1380	0–2	146.44	37.86	16
			21–23	74.33	59.02	56
Novyi Crater	5-00	1080	0–1	341.64	273.16	13
			7–10	339.25	130.22	60
			29–31	78.38	121.40	45
			49–50	92.59	243.78	83
Malen'kii Crater	6-00	1400	0–5	24.72	59.69	41
			5–11	8.30	–	–
			14–17	8.91	35.00	25
			20–24	18.73	70.81	54
			45–50	13.32	45.74	23
Ivanovskii Cape	7-00	1400	0–5	4.43	92.21	49
			20–25	7.01	54.03	–
			40–45	13.93	–	–
			60–65	13.70	46.01	19
			82–87	18.90	35.58	19

* The Baikal'sk pulp and paper mill.

A similar pattern is characteristic of sediments near hydrothermal vents in the ocean rift zones, where the intensity of microbial processes is 2–4 times higher than in background areas [2]. A considerable increase in the rate of methane oxidation was registered in the regions of hydrothermal vents in the Pacific Ocean compared to other parts of the ocean [3]. In the regions of methane seeps in the Atlantic Ocean, the rate of methane oxidation in sediments reached 1570 µl CH_4/(l day) [5].

In such ecosystems, organic matter is synthesized by chemosynthesizing and/or methane-oxidizing bacteria, which act as primary producers for the benthic communities developing around the hydrothermal vents [2, 3, 5]. In the zone of a methane vent in Frolikha Bay, the biomass of benthic animals (sponges and planarians) is characterized by a light isotopic composition (the values of $\delta^{13}C$ reach –66.0‰) [10, 12].

The measurements of methane production and oxidation allowed us to evaluate the methane flow into the Lake Baikal water column (Table 5). In different types of sediments of the lake, from 2.45 to 8200 µl of methane was produced and from 4.6 to 11804 µl of methane was oxidized under 1 m^2 per day. The processes of bacterial methane production and oxidation were most intense in the areas of methane vent and gas hydrate occurrence. Methane oxidation prevailed over methane production in most of the samples studied.

Table 4. Density and composition of the methanotrophic population in bottom sediments of Lake Baikal

Sampling site, station	Horizon, cm	Species	Density, cell/ml
Frolikha Bay, 2-97	0–2	*Methylosinus trichosporium*	13200
		Methylomonas methanica	3500
		Methylobacter bovis	660
Sosnovka Bay, 21-97	0–1	*Methylobacter bovis*	2400
		Methylosinus trichosporium	850
		Methylomonas methanica	3500
		Methylocystis echinoides	1500
		Methylobacter capsulatus	220

Table 5. Balance of the methane cycle in bottom sediments of Lake Baikal

Sampling site	Station no.	Horizon, cm	CH_4 production, μl/(m^2 day)	CH_4 oxidation, μl/(m^2 day)	Methane emission into water column, μl/(m^2 day)
Baikal'sk	1-92	0–6	68	18.8	49.2
	2-92	0–10	789	223.6	565.4
Bol'shie Koty	4-92	0–1	2.45	73.3	–70.9
Shallow water of the Selenga River	7-92	0–10	32.7	163.8	–131.1
	8-92	0–22	10.24	579.4	–569.16
Akademicheskii Ridge	9-92	0–354	258.24	93.6	164.64
Tatarnikov Waterway	10-92	0–18	14.03	99.13	–85.1
Southern basin	1-91	0–70	44.42	182	–137.58
Ol'khon Island	2-91	0–100	401.4	310	91.4
Bugul'dei neck	3-91	0–205	204.9	1449	–1244.10
Frolikha Bay	4-91	0–23	728.5	3559	–2830.5
	5-91	0–14	2500	7076	–4576
Khakusy Bay	7-91	0–16	442.85	1213	–770.15
Frolikha Bay	1-97	0–1	3.6	34	–30.4
	3-97	0–1	1200	11804	–10604
	6-97	0–1	242	72	170
	13-97	0–1	2.8	13	–10.2
Sosnovka Bay	21-97	0–1	658	4.6	653.4
Bol'shoi Crater	1-00	0–40	460	5060	–4600
Malen'kii Crater	2-00	0–36	2260	3970	–1710
Malen'kii Crater	3-00	0–57	8200	3860	4340
Malen'kii Crater	4-00	0–23	2340	1060	1280
Novyi Crater	5-00	0–50	5710	8300	–2590
Malen'kii Crater	6-00	0–50	660	2310	–1650
Ivanovskii Cape	7-00	0–5	890	4630	–3740

For example, in samples taken at station 3-97 in the area of the hydrothermal field of Frolikha Bay, methane was oxidized almost ten times faster than it was produced. Such an imbalance either means that the high potential activity of methane-oxidizing bacteria in the areas studied is not fully realized or that intense methane production occurs in the sediment lower layers, which were not investigated in this work. In gas hydrate areas of Frolikha Bay, seepage of geologically buried methane is also possible.

In some of the sediments, the rate of methanogenesis was higher than the rate of methane oxidation, and a portion of biogenic methane (49.2–4340 μl/(m^2 day)) was emitted into water and oxidized in the near-bottom water layers.

The quantitative evaluation of the activity of methanogenic and methanotrophic bacteria showed that these bacteria take an active part in the biogeochemical filtration of flows of juvenile gases (hydrogen, carbon dioxide, methane) to bottom sediments and the water column and play a crucial role in the cycles of biogenic elements and in the regulation of the gas regime of Lake Baikal.

ACKNOWLEDGMENTS

We are grateful to the crew of the R/V *Vereshchagin* (captain O.A. Kalinin[†]) and to O.M. Khlystov for collecting samples of deep-sea sediments.

[†] Deceased.

Table 6. Methane oxidation in waters of Lake Baikal

Sampling site	Station	Depth, m	CH_4 content, µl/l	Methane oxidation		
				µl CH_4/(l day)	to biomass and exometabolites, %	to CO_2, %
Frolikha Bay	6-97 near-bottom	400	4.0	0.83	50	50
	7-97 near-bottom	215	0.26	0.31	62	38
	8-97 near-bottom	105	41.0	0.15	2	98
Zavorotnyi Cape	1-97 near-bottom	825	0	0	0	0
		775	3.0	0.006	95	5
		400	2.0	0.014	98	2
		200	1.5	0.005	98	2
		50	1.0	0.002	92	8
		25	0	0	0	0
		0	0	0	0	0
Southern Baikal	1-00 near-bottom	1400	5.94	1.78	41	59
	2-00 near-bottom	1380	–	1.57	43	57
	3-00 near-bottom	1350	–	0.88	49	51
	4-00 near-bottom	300	–	0.72	51	49
	5-00 near-bottom	0	–	0.53	55	45
	6-00 near-bottom	1400	–	0.91	42	58
	7-00 near-bottom	1380	–	1.49	29	71
		1080	–	1.14	82	18
		1400	–	0.59	47	53
		1400	–	0.95	55	45

This work was supported by the Russian Foundation for Basic Research (project no. 01-05-97256) and by the federal program "The World Ocean" (project no. 16.7).

REFERENCES

1. Kuznetsov, S.I., Saralov, A.I., and Nazina, T.I., *Mikrobiologicheskie protsessy krugovorota ugleroda v ozerakh* (Microbial Processes of the Carbon Cycle in Lakes), Moscow: Nauka, 1985.
2. Gal'chenko, V.F., Ivanov, M.V., and Lein, A.Yu., Microbiological and Biogeochemical Processes in the Water Column of the Ocean as Indicators of the Activity of Submarine Hydrothermal Vents, *Geokhimiya*, 1989, no. 8, pp. 1075–1087.
3. Namsaraev, B.B., Kachalkin, V.I., Dulov, L.E., and Obzhirov, A.I., Bacterial Methane Oxidation in the Region of Shallow-Water Gas Hydrotherms of the Western Part of the Pacific Ocean, *Mikrobiologiya*, 1995, vol. 64, no. 1, pp. 125–132.
4. Belyaev, S.S., Laurinavichus, K.S., and Ivanov, M.V., Determination of the Intensity of Microbial Oxidation of Methane with the Use of $^{14}CH_4$ *Mikrobiologiya*, 1975, vol. 44, no. 3, pp. 542–545.
5. Pimenov, N.V., Savvichev, A.S., Rusanov, I.I., Lein, A.Yu., and Ivanov, M.V., Microbiological Processes of Carbon and Sulfur Cycles at Cold Methane Seeps of the North Atlantic, *Mikrobiologiya*, 2000, vol. 69, no. 6, pp. 831–843.
6. Gal'chenko, V.F., Abramochkina, F.N., Bezrukova, L.V., Sokolova, E.N., and Ivanov, M.V., Species Composition of Aerobic Methanotrophic Microflora of the Black Sea, *Mikrobiologiya*, 1988, vol. 57, no. 2, pp. 305–311.
7. Gal'chenko, V.F., Dulov, L.E., Kramer, B., Konova, N.I., and Barysheva, S.V., Biogeochemical Processes of Methane Cycle in the Soils, Bogs, and Lakes of Western Siberia, *Mikrobiologiya*, 2001, vol. 70, no. 2, pp. 215–225.
8. Kosolapov, D.V., The Processes of Methane Production and Consumption at the Littoral of the Rybinsk Reservoir, *Vodnye Resursy*, 2002, vol. 29, no. 2, pp. 193–199.
9. Dzyuban, A.N., Intensity of the Microbiological Processes of the Methane Cycle in Different Types of Baltic Lakes, *Mikrobiologiya*, 2002, vol. 71, no. 1, pp. 111–118.
10. Namsaraev, B.B. and Zemskaya, T.I., *Mikrobiologicheskie protsessy krugovorota ugleroda v donnykh osadkakh ozera Baikal* (Microbial Processes of the Carbon Cycle in Bottom Sediments of Lake Baikal), Novosibirsk: SO Ross. Akad. Nauk, filial "Geo," 2000.
11. Namsaraev, B.B., Dulov, L.E, Sokolova, E.N., and Zemskaya, T.I., Bacterial Methane Production in the Bottom Sediments of Lake Baikal, *Mikrobiologiya*, 1995, vol. 64, no. 3, pp. 411–417.
12. Khlystov, O.M., Klerx, J., and De Batist, M., Bottom Sediments Containing Near-Surface Gas Hydrates in

Lake Baikal, *Tez. 3-i Vereshchaginskoi Baikal'skoi konferentsii*, (Abstr. 3rd Vereshchagin Baikal Conf.), Irkutsk, 2000, p. 258.

13. Granina, L.Z., Kallender, E., Klerx, J., Golobokova, L.P., and Gorbunova, L.A., Peculiarities of the Biogeochemistry of Bottom Sediments in the Zone of Hydrothermal Activity at Baikal, *Tez. mezhd. simp. "Geokhimiya landshaftov, paleoekologiya cheloveka i etnogenez"* (Abstr. Int. Symp. "Geochemistry of Landscapes, Paleoecology of Man, and Ethnogeny"), Ulan-Ude, 1999, pp. 297–301.
14. Kuznetsov, S.I. and Dubinina, G.A., *Metody izucheniya vodnykh mikroorganizmov* (Methods for Studying Aquatic Microorganisms), Moscow: Nauka, 1989.
15. Fedorov, Yu.A., Nikanorov, A.M., and Tambieva, N.S., First Data on the Distribution of Biogenic Methane in the Water Column and Bottom Sediments of Lake Baikal *Dokl. Akad. Nauk*, 1997, vol. 353, no. 3, pp. 394–397.
16. Geodekyan, A.A., Avilov, V.I., and Avilova, S.D., Geoecological Studies of Lake Baikal, *Dokl. Akad. Nauk SSSR*, 1990, vol. 310, no. 6, pp. 1442–1446.
17. Matveeva, T.V., Kaulio, V.V., Mazurenko, L.L., Klerx, J., Soloviev, V.A., Khlystov, O.M., and Kalmychkov, G.V., Geological and Geochemical Characteristic of Near-Bottom Gas Hydrate Occurrence in the Southern Basin of the Lake Baikal, Eastern Siberia, *Abs. 6th Int. Conf. on Gas in Marine Sediments, St. Petersburg, 2000,* pp. 91–93.
18. Kuz'min, M.I., Kalmychkov, G.V., Geletii, V.F., Gnilusha, V.A., Goreglyad, A.V., Khakhaev, B.N., Pevzner, L.A., Kavai, E., Ioshida, N., Duchkov, A.D., Ponomarchuk, V.A., Kontorovich, A.E., Bazhin, N.M., Makhov, G.A., Dyadin, Yu.A., Kuznetsov, F.A., Larionov, E.G., Manakov, A.Yu., Smolyakov, B.S., Mandel'baum, M.M., and Zheleznyakov, N.K., First Discovery of Gas Hydrates in the Bottom Sediments of Lake Baikal, *Dokl. Akad. Nauk*, 1998, vol. 362, no. 4, pp. 541–543.
19. Lindstrom, M.E., and Somers, L., Seasonal Study of Methane Oxidation in Lake Washington, *Appl. Environ. Microbiol.*, 1984, vol. 47, no. 6, pp. 1255–1260.
20. Kuznetsov, A.P., Strizhov, V.P., Kuzin, V.S., Fialkov, V.A., and Yastrebov, V.S., News in Lake Baikal Ecology: Discovery of a Community Based on Bacterial Chemosynthesis, *Izv. Akad. Nauk SSSR, Ser. Biol.,* 1991, no. 5, pp. 766–772.