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Gas hydrates in Lake Baikal

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ABSTRACT. Subsurface gas hydrates over all the area of their potential occurrence under the floor of Lake Baikal, the only freshwater body where they occur, have been sought and studied since 2000. Two of three known gas hydrates cubic structures (structure 1 biogenic methane hydrates and structure 2 biogenic methane and thermogenic ethane hydrates) have been found in the lake sediments. Large autogenic carbonaceous formations atypical for the lake have been discovered in the areas of gas hydrates occurrence. A new so-called "Baikal" mud volcanoes formation mechanism with shallow roots previously unknown in the seas is described. This mechanism is related to destruction of gas hydrates under their stability zone due to a tectonic activity and warm fluid income. The focus and source of the gas-saturated fluid are determined to be buried depositions of delta fronts, depocenters in the middle of the basins and subsurface ancient sedimentation masses at the eastern flank. The 2018 integrated geological and geophysical survey allowed to discover 54 hydrate-bearing structures represented by 26 mud volcanoes, 18 hydrate mounds, 9 seeps and 1 pockmark. Not only sedimentation masses of various age and many kilometers thick, but also the tectonic dislocation grid determine the distribution of these structures on the floor of Lake Baikal. The fluid pathways are formed through impaired vertical and gently inclined zones of the main rift faults and secondary faults as well as along permeable lithological sedimentation boundaries when the layers rise from the depocenters in the center of the basin to its flanks.

Keywords: Baikal, gas hydrates, mud volcanoes, carbonates

1. Introduction

History of study of sedimentary cover in the Lake Baikal includes several key points related to considerable achievement in investigation of the structure and geological development of the Baikal depression. It resulted in the changes of conceptions about the age, stages of development and processes in sediments. Discovery of gas hydrates in subsurface bottom sediments, substantiation of particular Baikal type of mud volcanoes activity as well as creation of high-resolution digital model of bottom topography (DMT) can be referred as turning-point in the Lake Baikal study. DMT was created based on new high-resolution survey of the lake bottom by multi-beam echo-sounders Seabeam 1050 in 2009 (Cuylaerts et al., 2012) and Kongsberg 710S (2015-2017) (Khlystov et al., 2016a; 2016b; 2017). Due to DMT, up to 90% of hydrate-bearing structures were discovered, the bottom topography was defined more exactly, and the history of Baikal depression and underwater elevations in the past was reconstructed. Phenomenon of formation of gas hydrates with different composition in the unique freshwater basin has a fundamental scientific significance. Results of hydrates investigations are also used for reconstruction of biogeochemical methane cycle in the bottom sediments and water column, as well as for understanding of geological reasons for occurrence of the hydrate-bearing structures in different bottom areas of Baikal.

2. Results

54 structures containing gas hydrates in subsurface sediments have been discovered since 2000 up to the present time (Fig. 1, Table 1). It has become possible not only due to the new DMT, but also due to results of other type of geophysical investigations, as well as visual observation from the MIR submersible. Generally, mud volcanoes represent gas hydrate-bearing structures (26 objects). Some of them (18 objects) are, probably buried (Fig. 1). In the sections of the latter, the mud breccias were not observed, whereas upper layer contained contemporary diatom ooze. However, based

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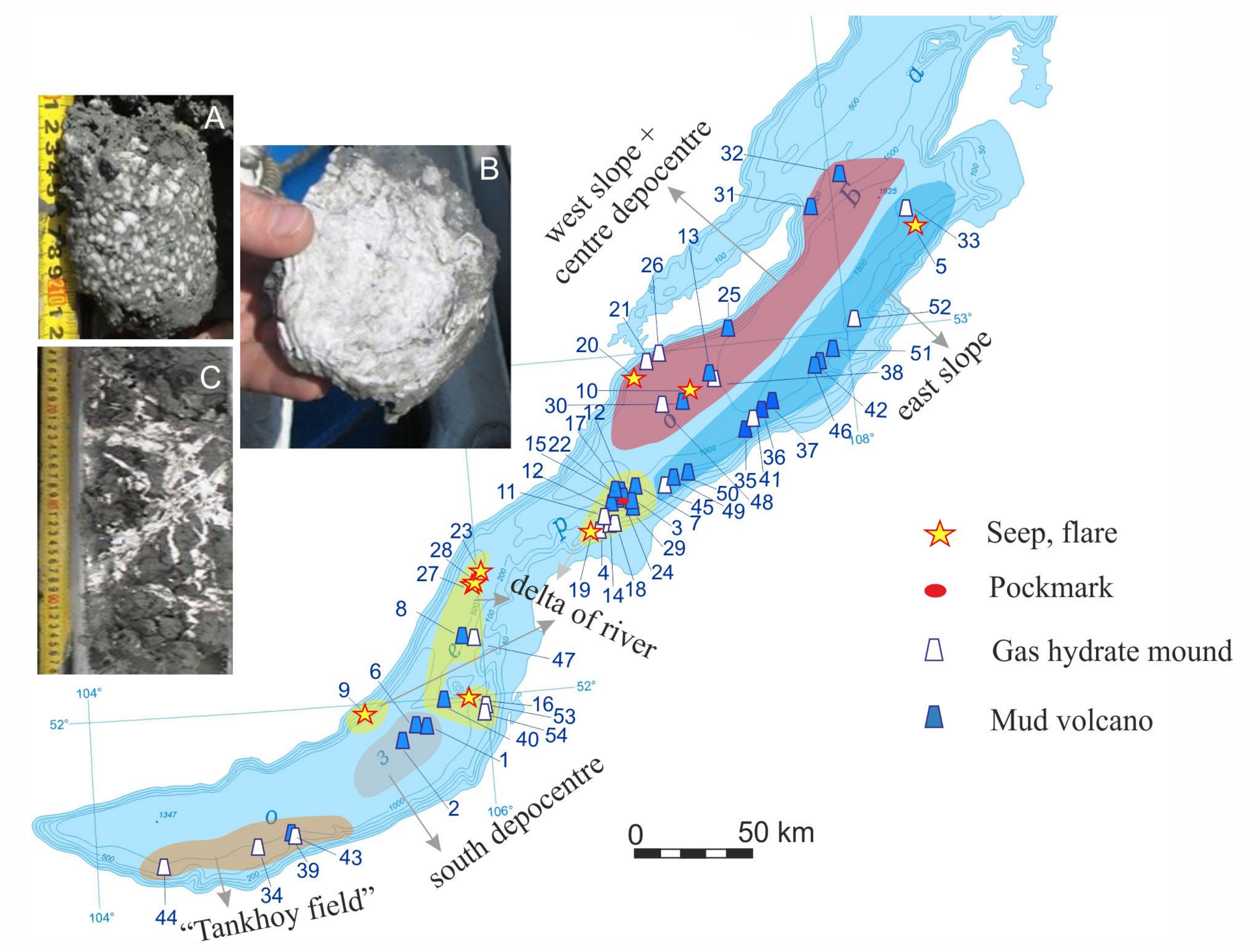

Fig. 1. Geographical distribution of the gas hydrate-bearing structures discovered in the South and Central Basins of Lake Baikal. Different types of the gas hydrate-bearing structures according to Table 1 are marked with the numerals. The structure distribution areas depending on the focus of the fluid are semitransparent. The picture shows different types and textures of gas hydrates: A – granules; B – massive; C – veins and streaks of different occurrence.

on morphological (positive topography) and geophysical data, they were similar to other mud volcanoes. This structure can be referred to gas hydrate mound of type “A” described by Matsumoto at Joetsu Basin (Matsumoto et al., 2011).

Mud volcanoes and gas hydrate mounds were mostly represented by single structures with a diameter from several hundreds meters to 1.5 km, but at the three areas they form groups and can merge into the large ridge or group of elevations (Cuylaerts et al., 2012; Khlystov et al., 2013; Akhmanov et al., 2018). Nine structures were represented by seeps, i.e. zones of focused gas or oil and gas discharge at the lake bottom without transformation of topography. Only one gas hydrate-bearing structure are associated with pockmark. Gas hydrates in the lake extend to the Southern and Central Basins, as well as over the underwater Akademicheskiy Ridge. This phenomenon influences considerably biodiversity and the processes of relief formation in various bottom areas.

Gas hydrates are usually observed in bottom sediments in the form of layers, veins and strings with different orientation, but sometimes they consist of “clinker” granules (see Fig.1). The latter are hydrates of crystallographic structure 2 and consist of the mixture between microbial methane and thermogenic ethane. The content of ethane in the hydrate-bound gas exceeds 13% (Kida et al., 2006). Other hydrates have structure 1 and include mainly microbial methane. Gas hydrates containing the thermogenic methane and ethane were obtained from the area of oil and gas seep “Gorevoy Utes”, gas seep “PosolBank”, and mud volcanoes “Kukuy” and “Kedr” (Kalmychkov et al., 2006; Hachikubo et al., 2010; 2017).

In addition to gas hydrates, relatively large (up to 5-6 cm) authigenic carbonates (siderites and rhodochrosites) were formed in the sediments of gas hydrates-bearing structures. Previously, it has been considered for a long time that the sediments of Lake Baikal are carbonate-free due to low alkalinity of the lake water and undersaturation of pore waters with respect to Ca by one-two orders relative to values required for calcite crystallization (Mizandrontsev, 1975). Soft and firm authigenic siderites were considerably enriched with heavy 13C isotope and had positive $\delta^{13}C$ values sometimes exceeding +30‰ VPDB. It indicates the close relation between the mechanism of their formation and processes of methane generation (Krylov et al., 2008a; 2008b; 2010). Subsurface authigenic carbonates enriched with 13C isotope to such degree were not ob-

Table 1. Gas Hydrate-bearing structures of Lake Baikal (2000-2018)

№	Name	Type	Year of discovery	Depth, m
1	Malenky	mv	2000	1306
2	Bolshoy	mv	2003	1352
3	K-2	mv	2005	875
4	K-0	gm	2006	419
5	Gorevoy Utes	seep	2006	860
6	Malyutka	mv	2006	1322
7	K-6	mv	2007	1033
8	P-2	mv	2007	821
9	Goloustnoe	seep	2008	396
10	St. Petersburg (SPb)	seep	2009	1410
11	K-10	gm	2009	542
12	K-1	mv	2010	668
13	Novosibirsk (N)	mv	2010	1391
14	K-8	gm	2010	432
15	K-9	mv	2010	763
16	PosolBank (PB)	seep	2010	514
17	K-4	mv	2011	828
18	K-11	gm	2011	424
19	K-12	seep	2011	502
20	Seep13	seep	2011	1258
21	Krest	gm	2011	1288
22	K-3	mv	2012	773
23	KrasniyYar (KrY)	seep	2012	740
24	K-P	pock-mark	2012	941
25	Ukhan	mv	2012	1392
26	Unshuy	gm	2012	1323
27	KrasniyYar-2 (KrY2)	seep	2013	759
28	KrasniyYar-3 (KrY3)	seep	2013	776
29	K-5	mv	2014	895
30	St. Petersburg-2 (SPb2)	mv	2014	1412
31	Khoboy	mv	2014	451
32	AcademRidge (AR)	mv	2014	691
33	Barguzin	gm	2014	1278
34	Mamay	gm	2015	520
35	Kamenny	mv	2015	937
36	Tonky	mv	2015	1019
37	Talanka	mv	2015	999
38	Novosibirsk-2 (N2)	gm	2015	1508
39	Kedr	mv	2015	593
40	PosolBank-2 (PB2)	mv	2016	732
41	Ostrov	gm	2016	953
42	Turka	mv	2016	678
43	Kedr-2	gm	2016	565
44	Solzan	gm	2016	706
45	Oblom	gm	2017	781
46	Turka-2	mv	2017	711
47	P-3	gm	2017	584
48	MSU	gm	2018	1380
49	Enkhaluk	mv	2018	682
50	Sukhaya	mv	2018	890
51	Kitami (KIT)	mv	2018	810
52	LIN SB RAS (LIN)	gm	2018	422
53	PosolCanyon (PC)	gm	2018	416
54	PosolCanyon-2 (PC2)	gm	2018	520

mv – mud volcano; **gm** – gas hydrates mound

served in the other regions. Other process responsible for crystallization of the carbonates in hydrate-bearing structures of the lake is destruction of the organic matter. In this case, the rhodochrosites with negative values of $\delta^{13}C$ are formed (Krylov et al., 2018).

Analysis of geological composition of all types of hydrate-bearing structures and adjoining areas of Lake Baikal, especially those discovered during the 2014-2017 expeditions, allow us to confirm that all studied structures are related to two principal ways of gas-saturated fluids migration. First, fracture zones of different rank, which dissect a part or entire sedimentary body of the lake, located directly at the source of gas-containing fluid (zones with elevated sedimentation rates, modern and buried delta systems, group ridges (remnants), and outcrops of the "old" sedimentary layers "Tankhoy field"). Second, the permeable inclined sedimentary layers ascended from the basin center to its flank at the lake slope. Fluid discharge and structure formation occurred there either in the secondary fracture zone, or in the places, where these layers outcroped at the lake bottom.

Now, several mechanisms explaining formation of gas hydrate-bearing structures are considered. Minami et al. reported potential deep-rooted fluid at two certain gas hydrate-bearing mud volcanoes in Lake Baikal (Minami et al., 2014; 2018). Another mechanism based on the model of gas hydrates dissociation at the zone of lower boundary of their stability due to ascending the warm fluids from the deeper layers can be adapted to formation of both mud volcanoes and seeps. Transformation of hydrates into gas and water lead to the pressure increase that result in penetration of gas saturated fluid, including deeper located fluid, to the lake bottom forming seeps and mud volcanoes. If this mechanism is accompanied by destruction of deeper "old" layers, then the underwater elevation consisting of mud breccias, mud volcano, is formed. Depth of the roots of these mud volcanoes determined by the level of lower boundary of gas hydrates stability and for Lake Baikal does not exceed 450 m. At the moment, we have only this evidence of relatively shallow position of mud volcanoes sources in the lake. Thus, the main reason for the formation of mud volcanoes is not the compression of sediments, as it occurred in all known onshore and offshore mud volcanoes, but the overpressure due to destabilization of gas hydrates. Therefore, this kind of mud volcanoes can be called "Baikal type" (Khlystov et al., 2018 in press).

3. Conclusion

In summary, the following factors serve as the sources for fluid material and play the dominant role in the distribution of the focused fluid discharging structures at the bottom of Lake Baikal: river deposits of the buried delta-fronts, areas with high sedimentation rates at the central parts of the depressions, and the shallow "old" sedimentary layers located at the eastern slope of the lake ("Tankhoy field"). Ways of fluid migration can be related to weak vertical and slightly inclined zones in the major rift-forming and secondary faults, as well as along permeable lithological boundaries, when the layers ascend from the centers with high sedimentation rates in the central part of the depression to its flanks. Destabilization of gas hydrates at the lower boundary of their stability is the main reason for the formation of mud volcanoes with shallow roots at the lake bottom, in spite of the fact that the Baikal rift system is the tension zone without wide areas having abnormally high strata pressure inside sedimentary section. Baikal model of the formation of mud volcanoes allow re-evaluation of the importance of mud volcanoes during the prospecting of oil and gas deposits in water basins, as well as estimation of the geological risks in the tectonically active and hydrate-bearing areas of the seas.

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References

Akhmanov G.G., Khlystov O.M., Soloveva M.A. et al. 2018. Discovery of a new hydrate-bearing structure at the bottom of the Lake Baikal. Moscow University Geology Bulletin 5: 113–119. (in Russian)

Cuylaerts M., Naudts L., Casier R. et al. 2012. Distribution and morphology of mud volcanoes and other fluid flow-related lake-bed structures in Lake Baikal, Russia. Geo-Marine Letters 32: 383–394. DOI: 10.1007/s00367-012-0291-1

Hachikubo A., Khlystov O., Krylov A. et al. 2010. Molecular and isotopic characteristics of gas hydrate-bound hydrocarbons in southern and central Lake Baikal. Geo-Marine Letters 30: 321–329. DOI: 10.1007/s00367-010-0203-1

Hachikubo A., Yamazaki R., Kita M. et al. 2017. Gas Analysis. In: Minami H. (Ed.), Operation Report of Multi-phase Gas Hydrate Project III 2016 (MHP III-16). Kitami Institute of Technology, pp. 124–130.

Kalmychkov G.V., Egorov A.V., Kuzmin M.I. et al. 2006. Genetic types of methane from Lake Baikal. Doklady Earth Science 411: 1462–1465. DOI: 10.1134/S1028334X06090285

Kida M., Khlystov O., Zemskaya T. et al. 2006. Coexistence of structure I and II gas hydrates in Lake Baikal suggesting gas sources from microbial and thermogenic origin. Geophysics Research Letters 33: 1–4. DOI: 10.1029/2006GL028296

Khlystov O.M., De Batist M., Shoji H. et al. 2013. Gas hydrate of Lake Baikal: Discovery and varieties. Journal of Asian Earth Sciences 62: 162 – 166. DOI: 10.1016/j.jseaes.2012.03.009

Khlystov O.M., Kononov E.E., Khabuev A.V. et al. 2016a. Geological and geomorphological characteristics of the Posolsky Bank and the Kukuy Griva, Lake Baikal. Russian Geology and Geophysics 57: 1759–1767. DOI: 10.1016/j.rgg.2016.11.001

Khlystov O.M., Kononov E.E., Minami H. et al. 2016b. Topography and Genesis of the Murinskaya Banka Underwater Upland (Southern Baikal). Geography and Natural Resources 5: 109–116. DOI: 10.21782/GiPR0206-1619-2016-5(109-116) (in Russian)

Khlystov O.M., Kononov E.E., Minami H. et al. 2018. New Evidence on the Relief of the Southern Underwater Slope in the South Baikal Basin. Geography and Natural Resources 39: 33–38. DOI: 10.1134/S1875372818010055

Khlystov O.M., Poort J., Mazzini A. et al. 2018. Shallow-rooted mud volcanism in Lake Baikal. Marine and Petroleum Geology. (in press)

Krylov A., Khlystov O., Zemskaya T. et al. 2008a. First discovery and formation process of authigenic siderite from gas hydrate bearing mud volcanoes in fresh water: Lake Baikal, Eastern Siberia. Geophysics Research Letters 35: L05405. DOI: 10.1029/2007GL032917

Krylov A., Khlystov O., Zemskaya T. et al. 2008b. Crystallization of Authigenic Carbonates in Mud Volcanoes at Lake Baikal. Geochemical International 10: 985–995. DOI: 10.1134/S0016702908100030

Krylov A.A., Khlystov O.M., Hachikubo A. et al. 2010. Isotopic composition of dissolved inorganic carbon in the subsurface sediments of gas hydrate-bearing mud volcanoes, Lake Baikal: Implications for methane and carbonate origin. Geo-Marine Letters 30: 427–437. DOI: 10.1007/s00367-010-0190-2

Krylov A.A., Hachikubo A., Minami H. et al. 2018. Authigenic rhodochrosite from a gas hydrate-bearing structure in Lake Baikal. International Journal Earth Science 107: 2011–2022. DOI: 10.1007/s00531-018-1584-z

Matsumoto R., Sato M., Hiromatsu M. 2011. Fluid flow and evolution of gas hydrate mounds of Joetsu basin, eastern margin of Japan Sea: constraints from high-resolution geophysical survey by AUV. In: 7th International Conference on Gas Hydrates (ICGH 2011), pp. 1404–1414.

Mizandrontsev I.B. 1975. On the geochemistry of pore waters. Trudy Baikalskoi limnologicheskoi stantsii AN SSSR [Proceedings of the Baikal Limnological Station of the Academy of Sciences of the USSR] 21: 203–231. (in Russian)

Minami H., Hachikubo A., Sakagami H. et al. 2014. Sequentially sampled gas hydrate water, coupled with pore water and bottom water isotopic and ionic signatures at the Kukuy mud volcano, Lake Baikal: ambiguous deep-rooted source of hydrate-forming water. Geo-Marine Letters 34: 241–251. DOI: 10.1007/s00367-014-0364-4

Minami H., Hachikubo A., Yamashita S. et al. 2018. Hydrogen and oxygen isotopic anomalies in pore waters suggesting clay mineral dehydration at gas hydrate-bearing Kedr mud volcano, southern Lake Baikal, Russia. Geo-Marine Letters: 38: 403–415. DOI: 10.1007/s00367-018-0542-x.