3. LAKE BAIKAL

3-1. Gas Hydrates of Lake Baikal

O. Khlystov, M. De Batist, H. Shoji, S. Nishio, L. Naudts and J. Poort

Abstract

This paper reviews some of the results of recent gas-hydrate studies in Lake Baikal, the only fresh-water lake in the world containing gas hydrates in its sedimentary infill. We give a historical overview of the different investigations and discoveries and highlight some recent breakthroughs in our understanding of the Baikal hydrate system. The importance of mapping mud volcanoes and gas seeps is stressed, as these are currently the only locations where gas hydrates at or very close to the floor of Lake Baikal. Also some particularities of the gas-hydrate composition and bedding for the different venting sites are described.

Keywords: gas, gas hydrate, mud volcano, seep, Lake Baikal

A unique setting for hydrate occurrences

Lake Baikal is the largest and the oldest fresh-water reservoir on our planet. The lake basin is located in Eastern Siberia on the border between the Siberian Craton and the Central Asian Fold Belt and it forms the central part of the large, intracontinental Baikal Rift Zone. The lake is more than 600 km long, 80 km wide (in the widest place) and its water depth amounts up to 1637 m. With a total basement subsidence of ~10 km, more than ¾ of this huge depression are filled up with several kilometers of sediments. Their total volume is estimated to be in the order of 75 000 km^3 [Logachev, 2003]. The age of the oldest sedimentary deposits in the Central and the Southern Basins of the lake surpasses 25 Ma (Oligocene), and there are some data testifying that the sediments in the Central Basin, near the delta of Selenga River, started to accumulate as far back as in Palaeogene (ca. 60 Ma) [Nikolayev, 1998]. Geophysical data indeed reveal a maximum thickness of the sedimentary infill (about 9 km) near the Selenga delta [Scholz et al, 2000]. Elsewhere in the Southern and the Central Basin, the sedimentary thickness does not exceed 7.5 km, while in the north-east of the Northern Basin it amounts to 4,4 km [Hutchinson et al., 1991]. Such a long sedimentation history and such large amounts of sediments containing a considerable amount of organic matter favored the formation and accumulation of different types of hydrocarbons. These oils and natural gasses migrate in free or dissolved state towards the lake floor where high pressures (corresponding with the large water depth) and low temperatures of the near-bottom waters (3.5° C approximately) are propitious for the formation of gas hydrates.

History and results of study on Baikal gas hydrates

The history of gas hydrate investigations in Baikal can be subdivided in three stages with key moments in 1997 and 2002.

Before 1997, the possible presence of gas hydrates was evoked in a few reports. The very first reference to hydrates in Baikal was made in a VNIIGAZ study, indicating a "site with possible gas hydrate accumulation" in sediments of Lake Baikal [Yefremova et al., 1980]. The discovery of the first Bottom-Simulating Reflector (BSR) during a multi-channel seismic survey in 1989 [Hutchinson et al., 1991] was the first real indirect geophysical indication for the presence of hydrates. Later, a predictive map depicting the base of the hydrate stability zone in Lake Baikal was published, which was based on geothermal modeling and heat-flow measurements [Golubev, 1997]. A more precise map of the base of the gas-hydrate layer, corresponding to the mapped BSR recognized on multi-channel seismic data from 1992, was published by Golmshtok et al. [1997]. Interestingly, the BSR was only observed the Southern and Central Basin and was not always parallel to the lake floor. These first estimates of the depth and extent of the gas hydrate stability zone were used to make the first assessments of the resource potential of the Baikal hydrate reservoir, yielding estimates varying from 8.8×10^{11} to 9×10^{12} m^3 (of gas at STP conditions) [Golubev, 2000, Vanneste et al., 2001]. A key discovery was made in 1997 when the first and only samples of deep gas hydrates were obtained during the International Baikal Drilling Project. While drilling the borehole BDP-97 from the ice, core samples taken from sub-bottom depths of 121 and 161 m contained frozen sand-silt material that released abundant amounts of gas while heated. Laboratory analyses of the sediment samples showed that the cement was, in fact, gas hydrates of cubic structure I (CS-I), composed mainly of methane of biogenic origin (CH_4 x $6H_2O$; $\delta^{13}C$ between -58 and -68 ‰) [Kuz'min et al., 1998].

From 1997 onwards, gas-hydrate research on Lake Baikal began to focus on hydrate occurrences at or near the lake bottom. Between 1997 and 2002, different geophysical studies were carried out in various regions of the Southern and the Central Basins [De Batist et al., 2002], aimed at mapping and characterizing a series of lake-floor structures related to the discharge of gas and/or gas-saturated water. Earlier, Ginsburg et al. (1994) had established that the main deposits of near-bottom submarine gas hydrates in oceans and seas occur in association with such seep structures. The new seismic, side-scan sonar and bathymetric data revealed four such seep structures along one of the main faults within the Southern Basin. On the side-scan sonar mosaics, these structures ranged from 200 to 2000 m in diameter and were up to 60 m in height, had practically isometric contours in the center of which one or more culminations could be seen; the echograms outlined positive topographic structures. The seismic data showed below these structures "muted" (transparent) acoustic signals and an irregular BSR behaviour. Owing to their size and morphological characteristics they were named "Bol'shoy" (Big), "Malen'kiy" (Small), "Malyutka" (Baby) and "Stariy" (Old) [Van Rensbergen et al., 2002, De Batist et al., 2002]. One year later, in 2000, coring of "Malen'kiy" structure allowed for the first time the recovery of surface (near-bottom) gas hydrates in the form of lenses, strata and massive formations within clayey sediments [Klerkx et al., 2003, Matveeva et al., 2003]. Hydrate and hydrate gas analyses demonstrated that these were CS-I methane hydrates of biogenic origin.

From 2002 to 2008, geological and geophysical studies focused further on the search for new sites of hydrocarbon discharge with gas-hydrate occurrences. Geophysical data, acquired in 2002 in the Central Basin, revealed four new structures in Kukuy Canyon, which were named "K-1","K- 2", "K-3" and "K-4", and two in the vicinity of Olkhon Island, which were labeled "Saint-Petersburg" and "Novosibirsk" [Klerkx et al, 2006] (Fig. 3-1-1). In 2003 and 2004, hydrates were retrieved from the "Bol'shoy" and "K-2" structures. Similar to the observations at the "Malen'kiy" structure, the hydrate-bearing sediment in the "Bol'shoy" and "K-2" structures consisted of a mud breccia, which was clearly different from the typical alternating diatomaceous and clayey layers normally found in the surface sediments of Lake Baikal [Khlystov, 2006]. The occurrence of hydrates in these seep structures was also indicated by the presence of strong reflectors on very-high-resolution sub-bottom profiler data (5 kHz). These strong reflectors correlate exactly with the locations of gas hydrate sampling [Khlystov et al., 2007]. More gas-hydrate-bearing structures were discovered in 2005, 2007 and 2008 during several side-scan sonar and acoustic profiling surveys: the "P-1" and "P-2" structures opposite of Peschanaya Bay (Southern Basin), the "K-0", "K-5" and "K-6" structures in the vicinity of Kukuy Canyon and new gas seeps "G-1", "G-2" and "G-3" in the area of Bolshoye Goloustnoye (Fig. 3-1-1). The geological and geophysical data showed that most of these hydrate-bearing structures, like the ones discovered in earlier years, share many characteristics with mud volcanoes [Khlystov et al., 2007, Hachikubo et al., 2009].

The near-surface hydrates in Lake Baikal occur over a water-depth range of almost 1 km (from ~1380 m in the "Bol'shoy" structure to ~390 m in the "G-2" structure (i.e. Goloustnoe flare)) and the hydrates display a wide variety of textures, including pseudoporphyritic, massive, layered and vein structures. In a single instance, hydrate in the form of cement was obtained from the "Malen'kiy" mud volcano. In the "K-2" mud volcano the hydrates occurred both as vertical veins and in the form of granules (Fig. 3-1-2). Both types were found in the same cores, either directly in contact with each other or separated by an erosive surface.

In most cases, dissolved gas and hydrate gas contained 98 % methane of bacterial origin. Hydrates containing thermogenic ethane were first found at the "K-2" structure, and thermogenic methane was later found at Gorevoy Utes [Kalmychkov et al., 2007]. Also, it was found that hydrates of cubic structure II (CS-II) existed in the "K-2" mud volcano [Kida, 2006]. In 2008, an unusual form of hydrate and bitum coexistance was discovered at the lake bottom near Gorevoy Utes [Khlystov et al., 2009].

Conclusions

Four mud volcano provinces uniting 14 mud volcanoes, the gas seep field "Goloustnoe" and the oil and gas seep field "Gorevoy Utes" were discovered until now on the lake floor of Lake Baikal. Subsurface gas hydrates of different textures were retrieved from the sediments of 8 mud volcanoes and of both of the seep fields. Samples of coexisting hydrates of different cubic structures (CS-I and CS-II) composed of mixed microbial methane and deep thermogenic methane and ethane were obtained from the mud volcano "K-2".

Acknowledgments

The authors would like to express their thanks to Academicians of Russian Academy of Sciences M.A. Grachev and A.E. Kontorovich, to promoters of international projects Prof. J. Klerkx, Dr. V.R. Degala and Dr. R. Sethuraman for their contribution to geological and geophysical work done during the last ten years in Lake Baikal and to the geophysical group SONIC (director: V. Gladyshev) for their technical support in side-scan sonar sounding and acoustic profiling.
This work was supported by Integration Project of Siberian Branch of Russian Academy of Sciences No 27.

Disclaimer: This review was made by Khlystov et al. (unpublished) from a paper submitted to Journal of Asian Earth Sciences, currently under review.

References

De Batist M, Klerkx J, Van Rensbergen P, Vanneste M. Poort J, Golmshtok A, Kremlev A, Khlystov O, Krinitsky P (2002) Active Hydrate Destabilization in Lake Baikal, Siberia? Terra Nova 14: 436-442

Ginsburg GD, Solovyev VA. (1994) Submarine Gas Hydrates. * Edited by V.L. Ivanov, Saint-Petersburg: p 199

Golmshtok AYa., Duchkov AD., Hutchinson DR. et al. (1997) Heat Flow Estimates in Lake Baikal according to Seismic Data on the Lower Boundary of Gas Hydrate Layer. Russian Geology and Geophysics 37: 1677-1691

Golubev VA. (1997) Geothermal Forecast of the Depth of Lower Boundary of Gas Hydrate Layer in Baikal Sediments. Russian Doklady RAN 352: 652-665

Golubev VA. (2000) Geothermal Forecast of Gas Hydrate Resources in Baikal Sediments. All-Russian Scientific Conference "Geology and Oil-and-Gas Content of West-Siberian Mega-Basin. Abstracts: 14-17

Hutchinson RD, Golmshtok AJ, Scholz CA et al. (1991) Bottom simulating reflector in Lake Baikal. EOS 72: 307-308

Kalmychkov GV, Egorov AV, Kuz'min MI, Khlystov OM (2006) Genetic Types of Methane from Lake Baikal. Dokl Earth Sci 411A: 1462-1465

Khlystov OM (2006) New Findings of Gas Hydrates in Baikal Bottom Sediments, Russ Geol Geophys 47: 979-981

Khlystov OM, Zemskaya TI, Grachev MA (2007) Gas Hydrates of Lake Baikal: History and Outlook of their Study. Collected papers of First International Scientific Conference "World Gas Resources and Leading-edge Technologies of their Exploration (WGRR-2007)

Khlystov OM, Zemskaya T.I., Sitnikova T.Ya. et al. (2009). Dokl Earth Sci 415: 682-685

Kida M, Khlystov O, Zemskaya T, Takahashi N, Minami H, Sakagami H, Krylov A, Hachikubo A, Yamashita S, Shoji H, Poort J, Naudts L (2006) Coexistence of Structure I and II Gas Hydrates in Lake Baikal suggesting Gas Sources from Microbial and Thermogenic Origin. Geophys Res Lett. Doi:10.1029/2006GL028296

Klerkx J., De Batist M, Poort J, Hus R et al. (2006) Tectonically Controlled Methane Escape in Lake Baikal. Advances in the Geological Storage of Carbon Dioxide. NATO Science Series, IV. Earth and Environmental Sciences. S. Lombardi, L.K. Altunina, Beaubien S.E. ed. Printed in the Netherlands: IOS PRESS. Springer 65: 203-219

Klerkx J, Zemskaya TI, Matveeva TV, Khlystov OM, Namsaraev BB, Dagurova OP, Golobokova LP, Vorob'eva SS, Pogodaeva TP, Granin NG, Kalmychkov GV, Ponomarchuk VA, Shoji H, Mazurenko LL,Kaulio VV, Solov'ev VA, Grachev MA (2003) Methane Hydrates in Deep Bottom Sediments of Lake Baikal. Dokl Earth Sci 393A: 1342-1346

Kuz'min MI, Kalmychkov GV, Geletii VF et al. (1998) The First Find of Gas Hydrates in the Sedimentary Rocks of Lake Baikal. Dokl Earth Sci 362: 1029-1031

Logachev NA (2003) History and Geodynamics of Baikal Rift. Russ Geol Geophys 44: 391-406

Matveeva TV, Mazurenko LL, Soloviev VA, Klerkx J, Kaulio VV, Prasolov EM (2003) Gas Hydrate Accumulation in the Subsurface Sediments of Lake Baikal (Eastern Siberia). Geo-Mar Lett 23: 289-299

Nikolayev V.G. (1998) Time of Beginnings of Baikal Depression. Russ Bulletin of MOIP, Geology Department 73: 13-16

Scholz CA, Hutchinson DR (2000) Stratigraphic and Structural Evolution of the Selenga Delta Accomodation Zone, Lake Baikal Rift, Siberia. Int. J. Earth Sci., 89: 212-228

Vanneste M, De Batist M, Golmshtok A et al. (2001) Multi-frequency Seismic Study of Gas Hydrate-bearing Sediments in Lake Baikal, Siberia. Marine Geology 172: 1-21

Van Rensbergen P, De Batist M, Klerkx J et al. (2002) Sublacustrine Mud Volcanoes and Methane Seeps caused by Dissociation of Gas Hydrates in Lake Baikal. Geology 30: 631-634

Yefremova AG, Andreyeva MV, Levshenko TV et al (1980) Gas in Baikal Sediments. Russ Gas Industry 2: 15-27

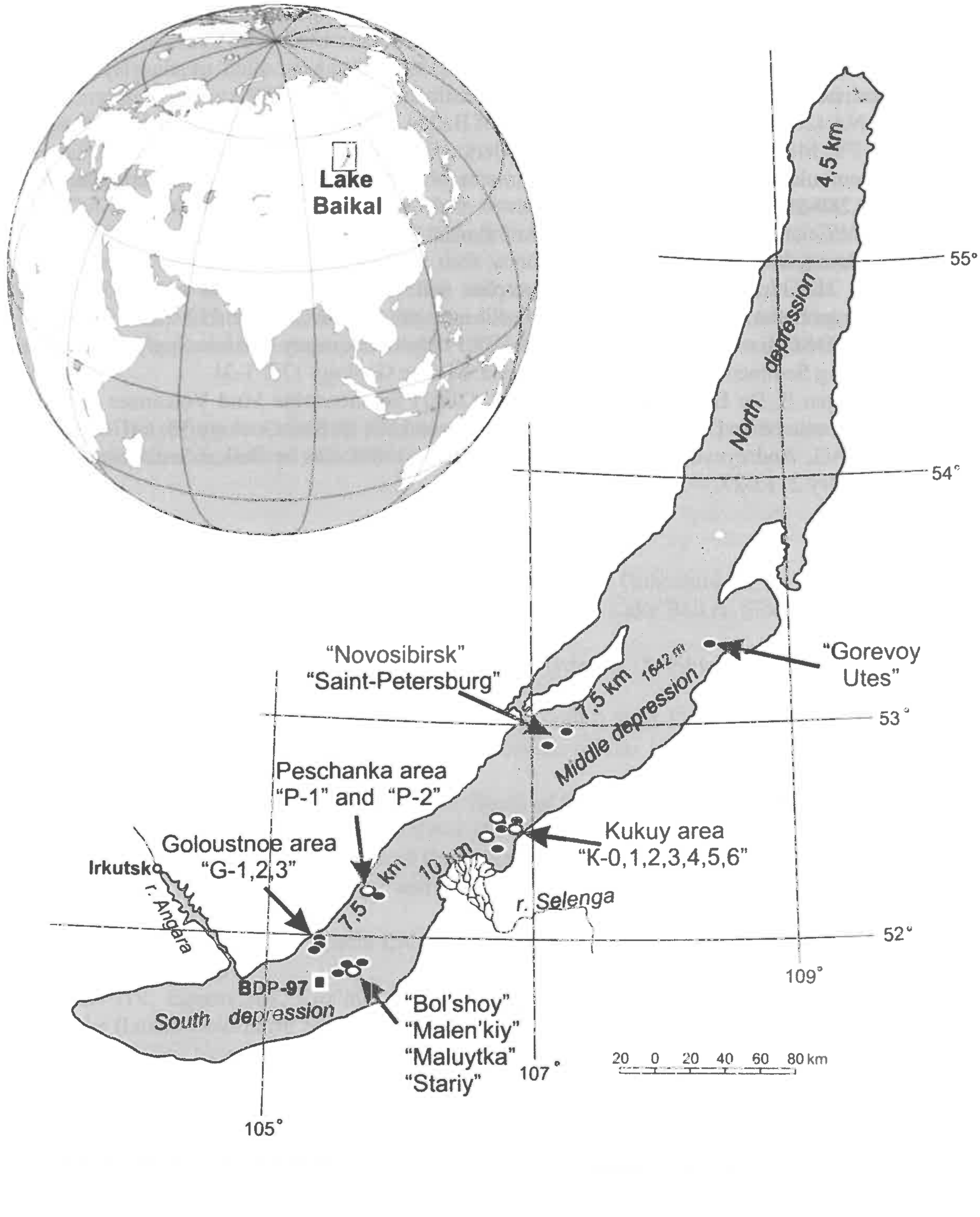

Fig. 3-1-1. Geographical distribution of the sites where gas hydrates have been studied in Lake Baikal. The square indicates the location of the BDP-97 borehole; circles show mud volcanoes or the sites of underwater discharge of gas or gas-saturated fluids. The black circles are the sites where gas hydrates were found. Numbers show the thickness of sediments (km) and the maximal water depth (m).

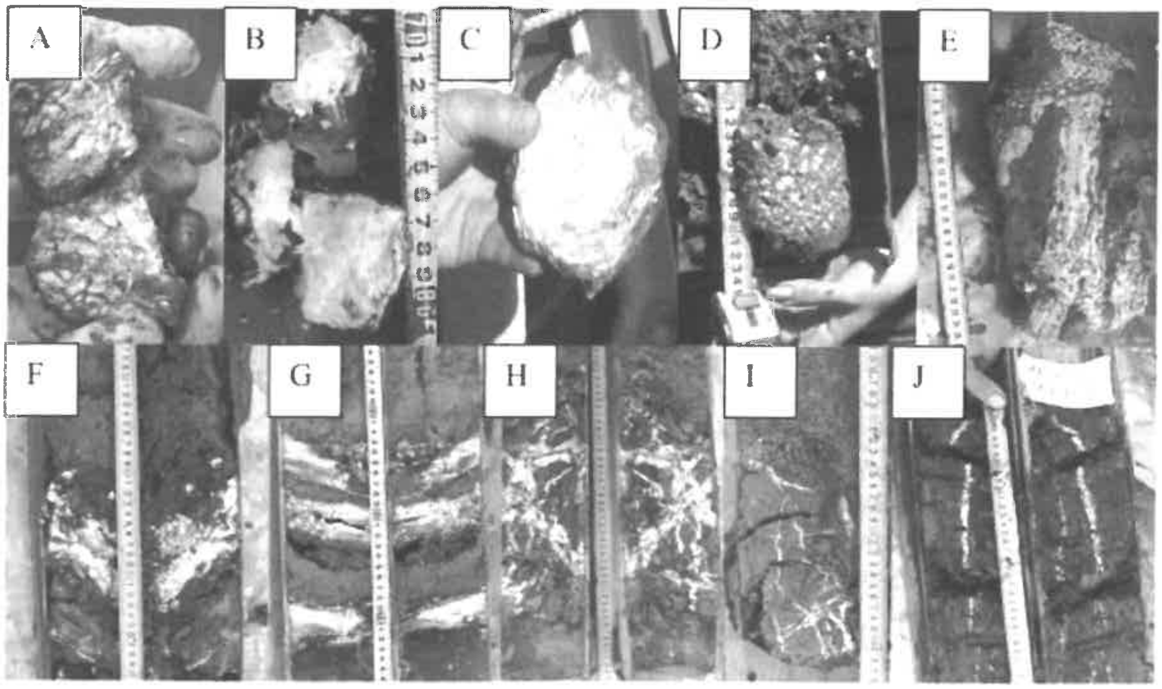

Fig. 3-1-2. Photos of different types and textures of gas hydrates in Lake Baikal. A: pseudoporphyritic; B,C: massive; D: granules; E: granules and vertical layers/veins; F: layers and cement-like hydrate between them (a grey sludge between white layers); G: layers; H, I, J: veins and streaks of different occurrence.