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ПУЗЫРЬКОВЫЕ ВЫХОДЫ ГАЗА НА ДНЕ ОЗЕРА БАЙКАЛ: ЭХОЛОКАЦИОННОЕ НАБЛЮДЕНИЕ И ОЦЕНКА ПОТОКА МЕТАНА, СВЯЗЬ ЭТОГО ПОТОКА С ВЫСОТОЙ ГАЗОВЫХ ФАКЕЛОВ

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Представлены результаты эхолокационных измерений потока газа из его пузырьковых выходов на дне озера Байкал, полученных в 2005—2014 г. Впервые выявлена связь между высотой струи всплывающих пузырьков газа и величиной потока метана. Анализ полученной зависимости показал, что все выходы газовые разделяются на три основных группы в зависимости от их глубины истечения: мелководные, промежуточные и глубоководные. Обсуждаются зарегистрированные факты извержения газовых выходов. Показано, что объем метана в первой порции выброшенного газа более чем на порядок больше, чем в среднем для стационарного режима истечения конкретного выхода газа. Диапазон изменения радиусов пузырьков во время извержения оценивался по скорости всплытия облаков пузырьков газа.

Ключевые слова: выходы газов, оценка потока метана, газовые гидраты, озеро Байкал.

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BUBBLE GAS ESCAPES FROM THE BOTTOM OF LAKE BAIKAL: OBSERVATION WITH HELP OF THE ECHOSOUNDER, ESTIMATION OF METHANE FLUX AND CONNECTION OF THIS FLUX WITH BUBBLE FLARE HEIGHT

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The paper summarizes the results of echolocation measurements of gas flux from the bubble gas escapes at the bottom of Lake Baikal, obtained in 2005—2014. For the first time the relationship between the height of the acoustic image of the rising bubbles jet and the corresponding methane flux was established. An analysis of this dependence shows that all gas flares are divided into three groups depending on their depth: shallow, intermediate and deep gas seeps. The results of unique observations of three events of gas eruption are discussed. It is shown that the methane flux in the first emissions was by more than an order of magnitude higher than the average, typical for the steady-state emission regime. The range of bubbles radii variation was estimated by ascent rate of bubbles clouds boundaries localized by depth.

Key words: gas discharge, methane seep, estimate of methane flux, gas hydrates, Lake Baikal.

Nowadays, the problem of global climate change is one of the most acute problems the world community encounters. Methane is a greenhouse gas, and changes of its concentrations in the atmosphere need detailed quantitative assessment. The studies of methane flux at the interface «bottom-water» are of great importance from scientific and applied viewpoints. Methane, being a part of the organic carbon cycle, is involved in biochemical processes occurring in bottom sediments. Reduced marine sediments are the world's largest reservoir for methane in a dissolved form in pore waters and in a form of gas hydrates [1].

Hydroacoustic methods allowed the detection of a bubble gas escapes in many shelf areas of the oceans, marginal and inland seas, and in freshwater lakes. Among the numerous publications on this subject, we note

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here a certain systematic studies conducted over several years using the same methodology. For example, similar work was conducted in the Black sea since 1979 in the area of the paleo-delta of the Dnieper river. There are identified and mapped 2 650 local sites of gas escapes at depths 35—835 m. The vast majority of the detected seeps are located at depths of up to 725 m [2]. Numerous bubble gas seeps have been discovered in the Sea of Okhotsk. First jet of methane bubbles from bottom sediments into the water were discovered in 1988 in the Western part of the Okhotsk Sea at a depth of 700 m [3]. During the study period from 1988 to 2011, more than 500 bubbling methane seeps were found. In 2012, during the cruise of RV «Akademik M. A. Lavrentyev» stream of methane bubbles was discovered from bottom sediments on the south-western slope of the Kuril basin. The sea depth in this place is 2 200 m; the height of the bubble gas is more than 2 000 m. Probably this is the highest bubble jet in the whole ocean [4].

Gas escapes at Lake Baikal have been known since the 19th century [5]. The sites of near-surface occurrence of methane hydrates were discovered into the bottom sediments of Lake Baikal in 2000—2009 [6]. Lake Baikal is the only freshwater body, in which gas hydrates (GH) have been found in the bottom sediments [7, 8]. They can exist in bottom sediments of Lake Baikal due to the large depth and low temperature. The disturbance of thermodynamic stability may cause the release of methane and, in the long term, be a reason of ecological disaster. Numerous bubble gas escapes (BGE) from the lake bottom sediments have been registered in Lake Baikal [9]. Regular search and monitoring of BGE have been performed since 2002.

Gas escapes were registered in all basins of Lake Baikal and at all depths beginning from tens of meters down to 1 400 m. One of the reasons of the occurrence of gas escapes at Lake Baikal may be the decomposition of gas hydrates at the lower boundary of *GH* stability zone. The upper boundary of *GH* stability in the lake occurs at a depth of about 380 m [10]. Its depth does not change with time and remains approximately the same in all basins of the lake, as the temperature in deep zone of Lake Baikal is almost stable [11].

Lake Baikal is a unique natural laboratory that is ideal for hydroacoustic measurements of the characteristics of a bubble gas escapes. First, weather conditions in summer, allow obtaining the high quality, low noise echolocation recordings. Calm weather allows precise maneuvering of the vessel for multiple crossing of BGE. Secondly, the limited lake area and systematic long-term expeditions allowed to discover and visit majority of known gas escapes in Southern and Central basins of the lake Baikal few times during the year.

The aims of this work were to assess methane flux from the hydroacoustic survey data of 2010—2014, to compare the data obtained with the height of flares and to search for dependence of the flare height on the gas (methane) flux. Three non-stationary «eruptions» of the two seeps — «Saint-Petersburg» and «Malenky» are also discussed in this paper.

Instruments and methods

Facilities. Search, monitoring, and studies of bubble gas escapes at Lake Baikal were performed using a software-device complex «Echo-Baikal», developed on the basis of the modernized echosounder Furuno FGV-1100 with single-beam 28 and 200 kHz transducers. The power of transducers was 3 kW; the width of directivity diagram at the −3 dB level was 24° and 6° for 28 and 200 kHz transducers, respectively. The data of the 28 kHz channel were used for the assessment of bubble gas flux, whereas the data of the 200 kHz channel were used for precise definition of gas flare position. The pulse duration during acoustic surveys of deep-water flares was 3 milliseconds (at sound speed of 1 430 m/s, length of sounding pulse was 2.15 m). According to the standard technique [12], acoustic calibration of the echosounder was performed using a standard calibration copper sphere with a diameter of 63 mm, and the target strength TS of−34.4 dB [13]. The acoustic survey of *BGE* was carried out during both the *R*/*V* drift and its movement at a speed of 2—4 knots. Registration, retention and mapping of the acoustic data of the echosounder were carried out using an author programme «Echo-Client». This programme obtains digital data from echosounder and then builds and stores graphical echograms with description files. The saved echograms allowed us to efficiently adjust the *R*/*V* route during search for *BGE*.

Methods. A modified technique described for the first time in [14] was used to calculate a bubble methane flux. This technique is based on the principle of incoherent summation of echosignal intensities from a large number of scatterers (bubbles) getting into the pulse volume of the echosounder [15]. This principle is applicable when the so-called approximation of single scattering is used only. It is possible if the «optic thickness of the scattering layer» $L = N\sigma R$ is much less than 1. Here, N is the volume concentration of particles, σ is the mean scattering cross-section of a particle, and R is the layer thickness. In our case, R must be equal to the spatial resolution of the echosounder: $R = C\tau_p/2$ (τ_p is the pulse duration and C is the sound speed).

The assessment given in [10] shows that this inequality is fulfilled for typical *BGE* and pulse duration. The method, proposed in [14] for the calculation of the total bubble flux *J* and based on volume scattering cross-section σ_v, also takes into account the bubble size distribution (*BSD*) $N(r) = N_0F(r)$, resonance dependence of the scattering cross-section of the bubble on its radius *r*, attenuation coefficient δ, and frequency of sounding f_0. To calculate specific flow *j* (per area unit), we used *BSD* and dependence of ascending speed of bubbles $U_{\text{rise}}(r)$ on their radius.

The considerations given in [14] lead to the linear relationship between the specific flow of gas mass $j(h, l)$ and volume scattering cross-section $\sigma_v(h, l)$ of the gas escape (ρ_g is the gas density in the bubble depending on the depth *h*, *l* is the current position of the ship along the trace):

$$j(h,l) = \rho_g(h) K\left(r_{\text{res}}(f_0,h), \delta, \alpha, r_c\right) \sigma_v(h,l).$$

The following formula was derived in [14] for the proportionality coefficient:

$$K(...) = \frac{\displaystyle\int_{r_{\tilde{n}}}^{\infty} \frac{r^2 \exp(-\alpha r)}{\left(\left(\frac{r_{\text{res}}(f_0,h)}{r}\right)^2 - 1\right)^2 + \delta^2} dr}{\displaystyle\frac{4}{3}\pi \int_{r_{\tilde{n}}}^{\infty} r^3 U_{\text{rise}}(r) \exp(-\alpha r) dr}, \tag{1}$$

$$r_{\text{res}}(f_0,h) = \frac{1}{2\pi f_0}\sqrt{\frac{3\gamma(P_0 + \rho_{\text{w}} g h)}{\rho_{\text{w}}}},$$

where P_0 is the atmospheric pressure, *g* is the gravity acceleration, ρ_w is the water density, and γ is the adiabatic index for gas in the bubble (for methane γ = 1 314).

Here, the formula $F(r) = \exp(-\alpha r)$ at $r > r_c$ and $F(r) = 0$ at $r < r_c$ proposed in [14] was used for the normalized, non-dimensional part of BSD *F*(*r*). This simplified formula helped reveal that the exponent index affects significantly the coefficient value *K*(…). Compilation of a number of experimental data on optical estimation of BSD parameters, including that for the «Stupa» source in Lake Baikal, showed that this value varies within the range from 1.1 to 1.87 1/mm. The following value was obtained for «Stupa»: α = 1.85 1/mm and r_c = 1.3 mm [10]. In this paper, we used an intermediate value α = 1.5 1/mm to calculate a flux from formula (1). Noteworthy, experimental values α = 1.85 and α = 1.2 used in [10] will lead to the decrease and increase of estimates by approximately 50 %, respectively. We should point out that the authors of the work [16] deduced a formula for the flux similar to (1) much later.

The same approach is used in [17]. Only instead of the volume scattering cross-section S_v authors used target strength of gas flare TS, which is calculated taking into account the position of the gas flare in the directivity diagram, and then averaged over several pulses. In these studies splitbeam echosounder was used.

Such an approach (see [14]) allows us to obtain realistic estimates of the bubble flux, as it takes into account a considerable contribution of small bubbles into scattering (including bubbles with resonance radii), which contribute insignificantly into the flux but considerably into scattering. This is likely to cause the decrease of the coefficient *K*(…) and allows the avoidance of overestimation of the flux.

Since formula (1) was derived for the specific flux, the calculation of the full gas flux for any localized source needs integration of the spatial field of volume scattering cross-section $\sigma_v(x, y)$ produced by this source. In [14], this field was restored with the help of two-dimensional interpolation from its several transects. In [10], first the integration σ_v was performed along the ship's path over the insonified bottom area corresponding to (2), and then these results were averaged additionally using several transects of the flare. Similar processing of the data was performed for the stationary gas flow in this paper.

$$J(h) = \rho_g(h) K(...) 2h \cdot \tan\beta \int_{L_1}^{L_2} \sigma_v(h,l) dl, \tag{2}$$

where *h* is the depth at which the echo signal intensity was measured, β the half of the width of the echosounder directivity pattern (β of 12° for the 28 kHz transducer) and L_1 and L_2 the limits of integration of the ship trajectory. The gas density $\rho_g(h)$ inside the bubbles was calculated using the van der Waals equation of state for methane.

A set of programmes was used for data processing of the hydroacoustic surveys, such as: reading of binary records; compilation of echograms; recalculation (taking into account calibration and parameters of the echosounder) of these records into the volume scattering cross-section σv or $S_v = 10\lg(\sigma_v)$, and, if necessary, into the full scattering cross-section of the flux σfull or $TS = 10\lg(\sigma_{full})$. With the help of one of these programmes, in the interactive mode we chose sections of echograms with the records of intersections of gas fluxes and depths, where profiles S_v were measured, and then we calculated the gas flux at the chosen depth using the method described above.

Results

Description of gas seep sites. The first echogram of the deep-water bubble gas escape was registered at Lake Baikal in May of 1995 from board the *R/V G. Yu. Vereshchagin* during the hydroacoustic survey of commercial fish, using a scientific echosounder Simrad EY-500 (Kongsberg Maritime) [18]. To date, numerous gas seeps have been registered at Lake Baikal. Gas escapes occurring beneath the depth of 380 m are referred to «deep-water» seeps, whereas those above this depth are «shallow-water» seeps. There are over 100 shallow seeps and about twenty deep seeps registered at Lake Baikal. A significant number of shallow escapes (over 90 %) have been recorded in the Selenga River delta, including Posolsk Banka. Shallow and deep gas seeps have been found in all basins of Lake Baikal (fig. 1) [9].

In some areas (e.g., the mud volcano «Saint Petersburg», «Stupa», «Kharauz», and Cape Khoboy), several flares were episodically recorded simultaneously. Such groups of closely located flares are represented by one gas seep in the scheme (fig. 1). To estimate a gas flux, we used data of hydroacoustic surveys of flares located in Southern and Central Baikal obtained from 2010 to 2014 (table 1).

The deep flare «Saint-Petersburg» (*SPB*) is situated in Central Baikal, registered for the first time on September 20, 2005. At present, this is the deepest (about 1 400 m) gas seep at Lake Baikal. The flare height varies from 500 to 960 m during different time observations. The maximal flare height was registered on August 21, 2009. The mean rate of the gas cloud ascending is 19.5 cm/s, which is equivalent

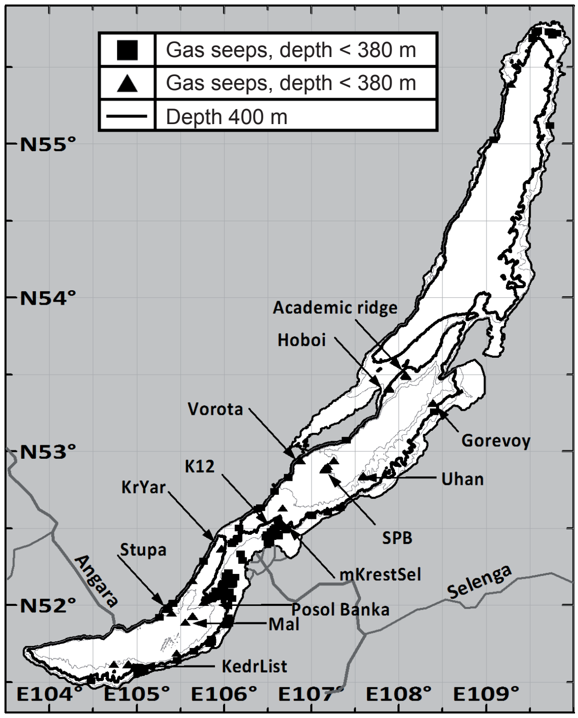

Fig. 1. Scheme of bubble gas seeps.

Table 1

Acoustic surveys of BGE using data on methane flux calculations

Flare name	Coordinates Lat/Lon	Survey number	Depth, m	Height, m	Flux, *t*/year
Academichesky Ridge	53.4903/108.0766	3	665—705	380—430	52.0—156.0
Gorevoy Utes	53.3045/108.3912	3	870—895	260—460	5.3—7.0
Khoboy	53.4034/107.8833	6	510—550	145—245	0.3—55.4
KedrList	51.5908/105.0211	3	323—608	775—897	26.9—30.8
KrasnyYar	52.3584/105.9694	4	725—735	295—410	5.9—29.9
K12	52.5059/109.6065	2	480—550	140—295	4.9—9.4
Malenky	51.9200/105.6400	3	1305—1345	535—875	15.0—29.0
mKrestSel	52.5430/106.6400	1	726	476	69.6
PosolskBanka	52.0346/105.8182	9	205—760	205—495	0.2—61.6
Saint Petersburg	52.8952/107.1898	4	1370—1425	505—815	74.2—92.1
Stupa	51.9758/105.3497	8	390—520	245—445	7.6—80.4
Ukhan-Tonky	52.8265/107.5950	2	1055—1060	495—645	14.2—115.3
Vorota	52.9336/106.8700	3	1280—1285	860—870	146.1—438.5

to the gas bubbles diameter of 3.6 mm [19]. The eruption of gas was recorded on July 19, 2012 during the acoustic survey at *SPB*. The studies in this area revealed that the flare could shift along the fault at a distance of 3 km.

The «Malenky» flare (Mal) is located in Southern Baikal at a depth of 1 296 m, registered for the first time on June 19, 2006. The flare height varied in different years from 432 m to its maximal height 1 025 m, which was recorded on July 23, 2011. This flare has been episodically registered on echograms [9]. Two events of this flare eruption were observed on July 18, 2012 and September 6, 2012.

The bubble gas escape «Stupa» is located northwards from Cape Kadilny (Southern Baikal), registered for the first time on August 20, 2007. Annual monitoring performed in this area showed that there are a few bubble gas seeps changing their locations. Visual investigations on board the deep-water manned submersibles *MIR*1 and *MIR*2 discovered an underwater canyon, on whose walls gas seeps originated. This canyon has not been registered with an echosounder. It was possible to calculate the ascending rate of the bubble ensembles from 22 to 25 cm/s, which corresponds to the bubble diameter 8—12 mm.

The deep-water flare «Gorevoy Utes» is located in the north-west from Cape Gorevoy Utes close to Barguzin Bay (Central Baikal), which was first recorded on September 20, 2005 [9]. The natural seep of oil was registered here. The drops of this oil reached the surface forming rainbow patches on it. Gas bubbles ascended from the depths of 870—895 m to the surface at a speed of 10—12 cm/s, being lower than that characteristic of other deep-water gas seeps.

The deep-water flare «Khoboy» is located at Cape Khoboy (Olkhon Island, Central Baikal) registered on June 30, 2009. Five spatially spaced gas seeps were observed in this area. Further, the number of gas seeps decreased to one. The gas seepage is located at the depth of 510—550 m, and the flare height varies within 145—245 m.

The gas flare «Academichesky Ridge» was registered in the area of the Academichesky Ridge on June 4, 2013. The bubble gas escapes ascend from the depth of 665—705 m with the range of the flare height of 380—430 m.

The gas flare «KrasnyYar» (Southern Baikal) was registered for the first time on July 13, 2007. Its occurrence is at the depth of 725—735 m, the flare height varying from 295 to 410 m. Sometimes two gas flares were observed.

The gas flare «Ukhan-Tonky» is located in Central Baikal. It was first recorded on June 30, 2010 at the depths of 1 055—1 060 m with the range of the flare height 495—645 m.

The gas flare «Vorota» is located in the area of small Olkhonskiye Vorota (the Strait of Olkhon Gate, Central Baikal). It was first registered on June 30, 2009. The depth of its occurrence is 1 280—1 285 m and flare height reaches 860—870 m in different years.

Eruption of gas seeps. In 2012, three cases of the «eruption» were registered: it was the beginning of the activity of bubble gas seeps. Two of these cases were observed at the mud volcano «Malenky» on July 18, 2012 and two months later on September 6, 2012. The echogram in fig. 2 shows that the first portion of gas bubbles (bubble cloud) began to ascend from a depth of 1 295 m at 1:22 a.m. The mean rate of the cloud ascending was 16 cm/s. It took the bubble cloud an hour to reach a depth of 480 m, and then the flare height stopped increasing. The maximal flare height was 815 m. Later on, less intense gas eruptions took place with the intervals 2—7 min. The volume flux in the first portion of gas was 2.04×10^{-4} m^3/s; it was 40 times larger than the gas flow in the «stationary regime» of the flare activity.

The second eruption is shown on the echogram in fig. 3. Unlike the previous eruption, a weak reflection from the background flux was registered on the echogram before the first gas seep at the depths from 700 to 1 000 m. Mean rate of ascending of the first portion of gas was 17.5 cm/s. It took the flare 70 min to reach a depth of 450 m. The next gas portions, which were not so intense, discharged with the intervals from 3 to 8 min. The flux in the first portion of gas amounted to 1.34×10^{-1} m$^3\times$s^{-1}. Its quantity was lower than two months ago but larger than the gas flux under the steady-state conditions. The mass flux of methane was approximately 500 t/year (1 mol/s) at the moment of the first crossing on board the *R*/*V* above the eruption. The volume of gas escape and methane mass in it were 0.013 m^3 and 1.4 kg, respectively.

It is clearly seen at the beginning of the eruptions on both echograms that the vertical size of the bubble cloud increased with ascending. This may be attributed to the presence of bubbles of different sizes in the cloud. Mean rates of the ascending of the upper and lower boundaries of the cloud were 16.4 and 14.3 cm/s for the first case and 18 and 16.8 cm/s for the second case, respectively. Considering that bubbles are covered with

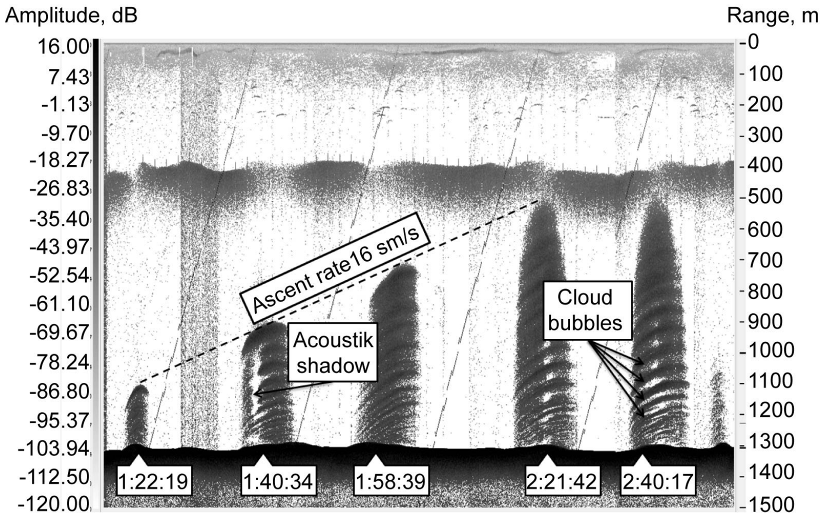

Fig. 2. Gas seep eruption in the area of the mud volcano Malenky on 18 Jul 2012.
Starting eruption at 1:22:19 a.m. The maximum height of the plume 815 m at 2:21:42 a.m.
The average ascending rate 16 cm/s. Gas erupted portions with a period of 2 to 7 min.

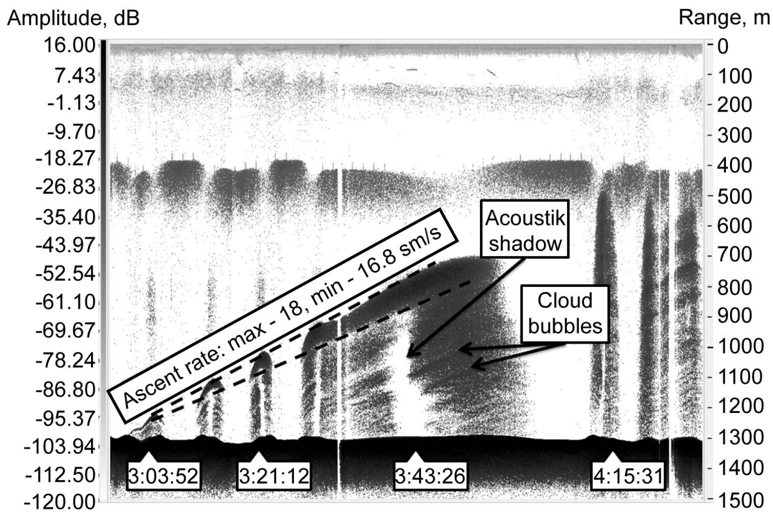

Fig. 3. Gas seep eruption in the area of the mud volcano Malenky on 6 Sep 2012.
Starting eruption at 3:03 a.m. The maximum height of the plume 800 m at 4:15 a.m.
The average ascending rate 17.5 cm/s. Gas erupted portions of the period from 3 to 8 min.

a film of gas hydrate, i. e., they are «dirty», and therefore the inverse function $r = r(U_{rise})$ is single-valued [19], it is possible to calculate radii of the bubbles from the rates of their ascending U_{rise}: 1.1 and 0.85 mm for the first case and 1.6 and 1.2 mm for the second case. A more detailed analysis of echograms shows that the rate of ascending of the upper boundary of gas eruption decreases with its ascending. The maximal rate (22 cm/s) in the first case at the beginning of the ascending is higher than the mean one, which corresponds to the bubble radius of 5 mm. At the end of ascending, the rate drops to 14 cm/s (the bubble radius is 0.8 mm). Thus, we may state that the average size of bubbles at the moment of eruption decreases with ascending because of methane diffusion into the water, which is partially compensated by the influx of nitrogen and oxygen. This effect is predicted by different modifications of a model of the single bubble dynamics [19, 20] as well as by experimental data [21].

In the interval between eruptions in the area of the *BGE* «Malenky», an eruption of *BGE* was registered at the «Saint-Petersburg» on July 19, 2012. It took the flare 79 min to reach the height of 905 m (fig. 4). Mean rate of ascending of the first portion of gas bubbles was 18.8 cm/s (maximal and minimal rates were 18.2 and 19 cm/s, respectively). Like in the first case, the next portion of gas began erupting with the intervals from 7 to 11 min. The flux of the first portion of gas was $1{\times}10^{-4}$ $m^3{\times}s^{-1}$: that was an order of magnitude larger than

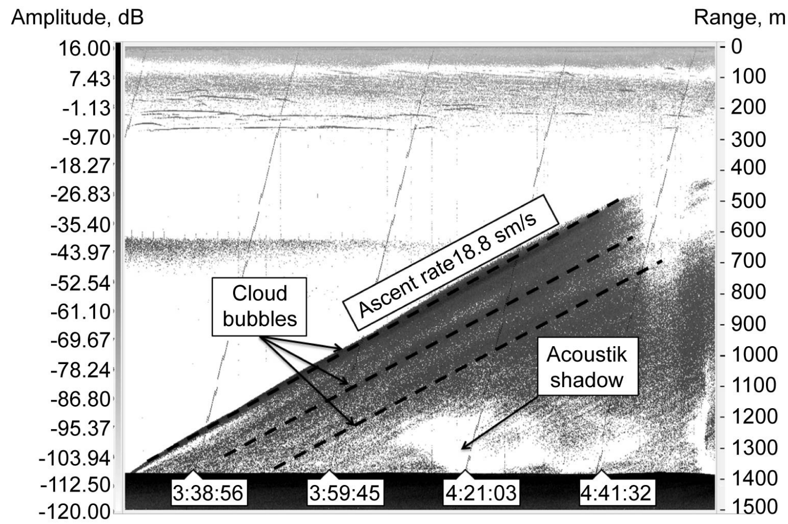

Fig. 4. Gas seep eruption at Saint-Petersburg on 19 Jul 2012.
Starting eruption at 3:28:49 a.m. The maximum height of the plume 902 m at 4:47:21 a.m.
The average ascending rate 18.8 cm/s. Gas erupted portions with a period of 7 to 11 min.

the gas flux under the steady-state conditions. Mass methane flux was approximately 500 t/year (1 mol/s), volume of discharge 0.016 m^3, and methane mass in it 1.6 kg.

The echogram shows that the seep widensalong the height during ascending. Like in the case with the discharge at the BGE «Malenky», this may be attributed only to the difference in the ascending rates of bubbles, which caused this escape, as well as to the difference in their sizes. In this case, the echosounder is not able to register single bubbles, but is able to estimate the ascending rate of the upper and lower boundaries of the eruption and the maximum (peak) of scattering. The upper and lower boundaries were identified from the value of −10 dB relative to the scattering peak. On average, all ascending rates of the upper and lower boundaries diminished with the decrease of depth. It means that the average size of bubbles decreased. The mean rate of the peak diminished from 0.22 to 0.15 m/s. This corresponded to the decrease of the average bubble radius from 5 to 1 mm. Extreme values of the ascending rates of the upper and lower boundaries of eruption were within the same limits, and these values were recorded at the beginning of ascending. Thus, the initially observed acoustic eruption was caused by bubbles of 1—5 mm in the radius.

Discussion

Flare heights and gas fluxes from bottom sediments. The bubble methane flux was calculated according to [10, 14]. Totally, 51 acoustic records of gas escapes from different depths were estimated, among them two records of shallow and 10 of deep flares. The majority of flares were calculated from the data of hydroacoustic surveys performed between 2010 and 2014. The variations of bubble methane flux were measured individually for each flare. The depth of the flare top was also estimated. To exactly determine the depth of the flare, we used the threshold value of the volume cross-section of scattering (−85 dB rel. 1/m). Based on the data obtained, we built the graph of dependence of flare height on bubble methane flux (fig. 5) and the depth of the flare (fig. 6).

According to these graphs, three groups of the flares can be distinguished: deep-water (the depth over 1 000 m), medium (the depth from 380 to 1 000 m), and shallow-water (the depth up to 380 m). Logarithmic approximations were found for each group of the flares using the following equation:

$$H = H_0 + k\lg\left(Flux\right), \quad (5)$$

where H_0 is the offset of approximating dependence, k is the regression coefficient, and Flux is the gas flux. Approximation coefficients and corresponding standard deviations (SD) are given in table 2.

Table 2

Coefficients of logarithmic approximation

Gas Seep	H_0	k	SD
Deep	380	202	113
Mid	110	158	62
Shallow	198	60	41

For flares, erupted from depths less than *GH* stability zone of 380 m, with the gas fluxes from 0.1 to 30 t/year the corresponding flare height varies from 180 to 220 m. In many cases, they reach the surface.

The flares included in the medium groups (erupted from depths from 380 to 900 m), in most cases, rise above the *GH* stability zone, but only in rare cases (when gas flux is greater than 100 tons/year) reach the surface. The height of such flares varies from 150—200 m for the fluxes of 1—3 t/year up to 400—550 m for the fluxes of 80—110 t/year.

The bubble gas seep «Gorevoy Utes», a unique site at Lake Baikal, because gas bubbles ascend together with oil. It is likely that the oil film functions as a screening effect for a bubble. The rate of gas dissolution from the bubble decreases and, as a result, the gas bubble ascends closer to the surface.

The behavior of flares changes qualitatively if the depths is more than 900 m. Although they never rise above GH stability zone (fig. 6) their height is on 300—400 m more than height of medium group flares with the same gas fluxes (fig. 5). The height can reach up to 900 m with gas fluxes of 100—300 t/year. This fact is further confirmed by the dependence of the flares height on corresponding gas flux for two sites: «Stupa» (390—520 m deep) and «St.-Petersburg» (1 400 m deep) (fig. 7). These dependencies once again prove the described above growth of flare height with gas flux increasing and demonstrates its variability over time.

There are increasing flare height with gas flux. Apparently it has a simple explanation: the more bubbles occur at the bottom, the more ones reach a predetermined depth and, therefore, a fixed threshold value (−85 dB) will be achieved at a lesser depth. At the same time, it is known that the dynamics (rate of dissolution) of bubbles is influenced by the presence on their surface of the methane hydrate crystals crust (REF), which occurs when the bubble is formed in the area of GH stability zone. Abrupt increase in the height of the flares that occurred at depths greater than 900 m, indicates that the properties of GH-shell and bubble dynamics qualitatively changed with increasing depth. Whether this effect is the feature of deep freshwater lake Baikal, or it is also typical for a deep salty ocean water? Additional studies can answer this question.

Eruption of gas seeps. Three cases of eruptions of bubble gas seeps was registered. Mass gas fluxes (500—700 t/y) and volumes of first discharge are rather similar in all

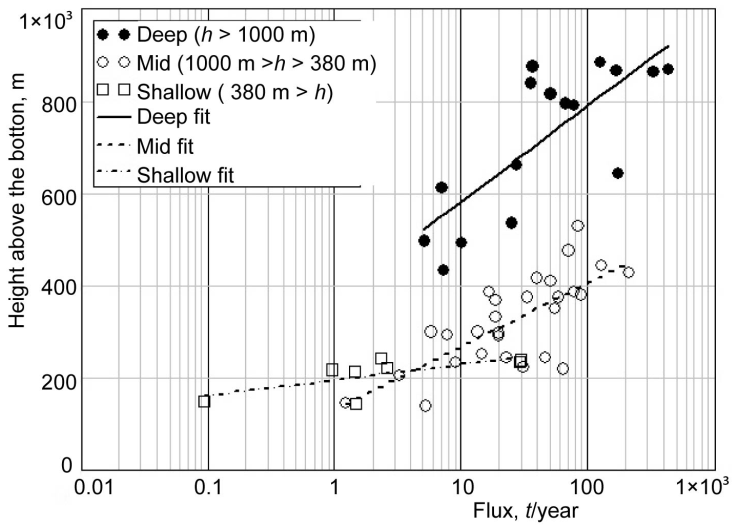

Fig. 5.Dependence of flare height on gas flux.

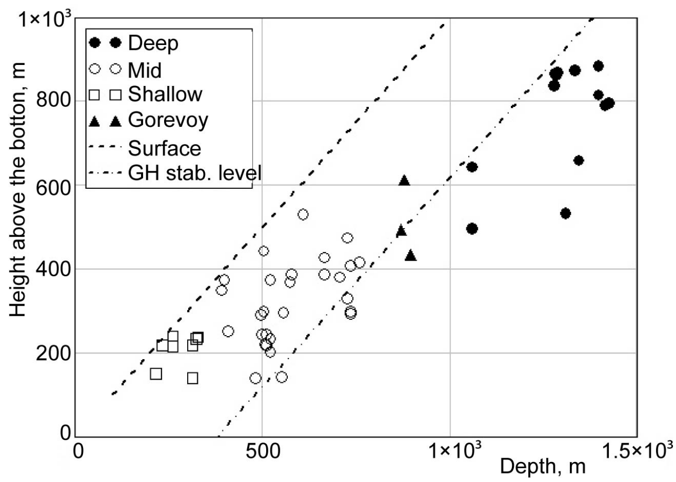

Fig. 6. Dependence of bubble flare height on depth.

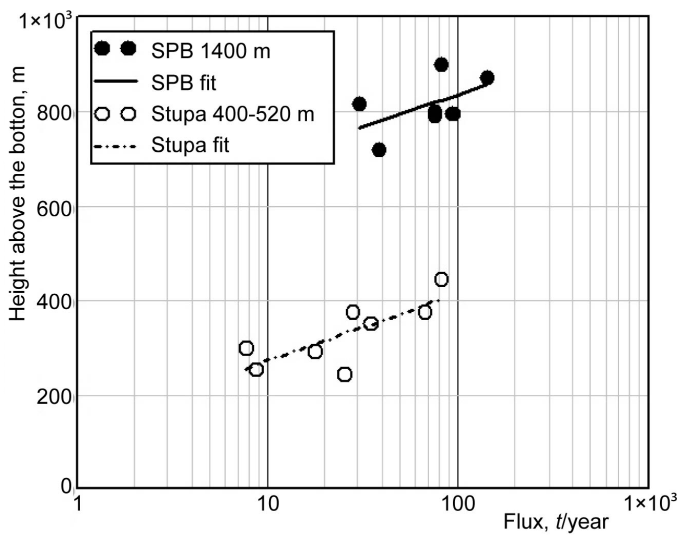

Fig. 7. Dependence of flare height on fluxes at two sites with different depths.

cases. It is likely that there is a single mechanism of gas accumulation and its discharge, which causes namely this volume of seep. The reasons starting this mechanism have not been elucidated.

The flux in the first portion of gas bubbles exceeds the flux under the steady-state conditions by 1—1.5 orders of magnitude. In all three cases, however, the first eruption is followed by a series of eruptions that are less intense. Taking into account that the mean escape duration is 100 s, the repetition period is from 450 to 600 s, and the flux is 500 t/y, then the mean flux is 100—87 t/y. This value is in agreement with the values observed for *BGE* at «Saint-Petersburg» under the steady-state conditions. Therefore, eruptions will not affect long-term estimates of the fluxes. On the other hand, temporary disappearance of flares, which have been repeatedly registered at Lake Baikal, should be obligatory taken into consideration.

The range of bubbles radii variation was estimated by ascent rate of bubbles clouds boundaries localized by depth. Radii vary from 1 to 5 mm, which is in agreement with optical observations of bubbles at the bottom of Lake Baikal [10].

Summary and conclusion

Based on the 51 cases of hydroacoustic observation of 13 bubble methane escapes from the bottom of Lake Baikal we have established the connection between the height of the flares and the gas flux: the flare height is approximately proportional to the logarithm of the flux. For flares, erupted from depths less than *GH* stability zone of 380 m, the corresponding dependence has the minimal slope. In many cases, they reach the surface. This slope increases for the flares occurring in the medium depths between 380 and 900 m. Such flares in most cases, rise above the *GH* stability zone, but only in rare cases (when gas flux is greater than 100 tons/year) reach the surface. Maximal slope was calculated for the deepest flares at the depths more than 900 m. The height of these flares is on 300—400 m more than height of medium group flares with the same gas fluxes. But they never reach the surface. For the explanation of this qualitative change of the flare behavior an additional investigation is needed.

The dependence established between the flare height and the corresponding flux can be used for the express-evaluation of the flux during hydroacoustic surveys.

Some of deep *BGE* demonstrate the eruptive activity. The results of unique observations of three events of gas eruption were analysed. It was shown that the methane flux in the first emissions was by more than an order of magnitude higher than the average, typical for the steady-state emission regime. The range of bubbles radii variation (1—5 mm) was estimated by ascent rate of bubbles clouds boundaries localized by depth. This is in agreement with optical observations of bubbles at the bottom of Lake Baikal [10].

Mass gas fluxes 1—1.4 mol/s and volumes of first discharge are rather similar in all cases. It is likely that there is a single mechanism of gas accumulation and its discharge, which causes namely this volume of seep. The reasons starting this mechanism have not been elucidated.

Noteworthy, in all three cases the ascending rate of the first bubble cloud diminishes with the depth. This fact confirms the hypothesis that the process of bubble dissolution prevails over the size increase because of the decrease of hydrostatic pressure. The acoustic registered on the echograms means that the bubble density in the first gas portion is high. This has been confirmed by the volume of the discharged gas, which is 8-40 times higher than the gas flux under the steady-state conditions. The range of bubbles radii variation was estimated by ascent rate of bubbles clouds boundaries localized by depth. Radii vary from 1 to 5 mm, which is in agreement with optical observations of bubbles at the bottom of Lake Baikal [10].

The flux in the first portion of gas bubbles exceeds the flux under the steady-state conditions by 1—1.5 orders of magnitude. In all three cases, however, the first eruption is followed by a series of eruptions that are less intense. Taking into account that the mean escape duration is 100 s, the repetition period is from 450 to 600 s, and the flux is 500 t/y, then the mean flux is 100—87 t/y. This value is in agreement with the values observed for BGE at «Saint-Petersburg» under the steady-state conditions. Therefore, eruptions will not affect long-term estimates of the fluxes. On the other hand, temporary disappearance of flares, which have been repeatedly registered at Lake Baikal, should be obligatory taken into consideration.

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