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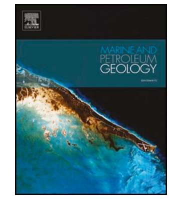

Research paper

Shallow-rooted mud volcanism in Lake Baikal

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ABSTRACT

Lake Baikal is the only freshwater basin containing sediments with gas hydrate accumulations, some of which are associated with mud volcano activity. Twenty-two mud volcanoes have already been identified in different areas of Lake Baikal, but the formation process and source depth remained unknown due to a lack of conclusive evidences. Here we discuss a set of geological and geophysical data to report the discovery of the hydrate-bearing Akadem mud volcanic complex (AMVC) on the Academician Ridge in central Lake Baikal. The obtained results allowed for the first time to concretely estimate the source depth of the mobilized fluids and sediments. Analysis of diatom skeletons present in the mud breccia revealed that the oldest diatom specimen is *Cyclotella Iris* et var. This species is characteristic for a short age interval ranging between 4.8 and 5.6 Ma. The same diatom was also detected between 230 and 310 m below the lake floor (mblf) in the borehole BDP-98 drilled near the AMVC. Combining biostratigraphic correlation and seismostratigraphy, it is estimated that the same interval is located at 200–300 mblf below the mud volcanic field. The elevated heat flow measured at AMVC indicates that the original base of gas hydrate stability (regionally located at ~212 mblf) is currently shifted upwards of ~100 m.

The acquired data are consistent with a scenario envisaging the rise of warm fluids throughout the mud volcano complex zone. We suggest that migration of deep fluids could have initiated the gas hydrate dissociation and, in turn, rapidly generated overpressured shallow mud chambers. The ultimate piercing and triggering of the mud volcanoes activity resulted in the eruption of mud breccia and formation of densely packed crater sites in the study area. The depicted scenario can be applied to many mud volcanoes in Lake Baikal where similar anomalous heat flow conditions have been measured. These findings also emphasize that the genetic association between gas hydrate dissociation and the initiation of eruptive activity explains numerous peculiarities of the "Baikal" sedimentary volcanism (e.g. lack of lithified rocks among mud breccia clasts, gas hydrates, moderately elevated heat flow). This type of mud volcanism differentiates from the typically deeply rooted piercements observed worldwide in mature (marine) sedimentary basins. Ultimately our findings open a new prospective for mud volcano research worldwide, emphasizing that gas hydrates are not just one of the common features for sedimentary volcanism, but may have an active role as a triggering mechanism for the process itself.

1. Introduction

The discovery and study of mud volcanoes (MVs) in Lake Baikal (Russia) has been strongly linked to gas-hydrates studies. The first MVs were discovered in 2000 during the search for hydrates in the near-surface sediments of the Posolsky Fault area in the South Baikal basin [Klerkx et al., 2003). These hydrate sites were characterized by positive topographic structures, high acoustic backscatter signals, high heat flow, and vertical feeder channels observed on seismic profiles (Van Rensbergen et al., 2002; De Batist et al., 2002). Multichannel seismic

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Table 1
List of known mud volcanoes in Lake Baikal (in July 2018).

№	Name	Year of discovery	Latitude, degrees	Longitude, degrees	Water Depth, m	L-W-H[a], m
1	Malen'ky	2000	51.918	105.636	1241	1300-550-20
2	Bolshoy	2003	51.880	105.552	1284	850-800-20
3	Kukuy 2 (K-2)	2005	52.590	106.769	875	1000-900-45
4	Malyutka	2006	51.909	105.602	1256	500-500-10
5	Peschanka 2 (P-2)	2007	52.173	105.812	780	550-400-30
6	Kukuy 6 (K-6)	2007	52.601	106.815	981	1200-550-40
7	Kukuy 1 (K-1)	2010	52.566	106.716	635	1800-800-150
8	Kukuy 9 (K-9)	2010	52.587	106.728	725	1200-750-50
9	Novosibirsk	2010	52.934	107.254	1321	750-750-15
10	Kukuy 4 (K-4)	2011	52.586	106.751	828	600-350-40
11	Kukuy 3 (K-3)	2012	52.594	106.747	773	1700-1400-100
12	Ukhan	2012	53.049	107.360	1392	500-350-45
13	Kukuy 5 (K-5)	2014	52.575	106.805	895	1100-680-50
14	Khoboy	2014	53.395	107.893	451	4000-1200-70
15	Center of AMVC	2014	53.477	108.082	691	6000-1700-70
16	Kamenny	2015	52.765	107.473	937	1500-700-120
17	Tonky	2015	52.827	107.594	1019	1500-400-80
18	Talanka	2015	52.853	107.648	1000	1800-800-150
19	Kedr	2015	51.610	104.902	593	1500-800-40
20	PosolBank 2	2016	52.009	105.701	732	1500-500-70
21	Turka	2016	53.039	108.006	711	3700-100-220
22	Turka 2	2017	53.002	107.967	584	1100-700-90

[a] **L**ength, **W**idth, **H**eight of mud volcanoes.

data in the area revealed the presence of a strongly irregular Bottom Simulating Reflection (BSR) (Hutchinson et al., 1991 Golmshtok et al., 1997, Golmshtok et al., 2000). More than forty sites with shallow gas hydrates have now been discovered in the deep basins of Lake Baikal (Cuylaerts et al., 2012; Khlystov et al., 2013). To date twenty-two of these sites have been identified as MVs (Table 1, Fig. 1 A). These structures are only found in the Southern and Central Baikal basins at water depths ranging from 500 to 1500 m at faulted sedimentary depocenters.

Sedimentological studies of the sampled structures revealed the presence of specific mud breccia deposits mostly associated with shallow gas hydrates (Khlystov, 2006; Khlystov et al., 2013). In contrast to the "classic" mud breccia known from most (marine) mud volcanic provinces (e.g. Staffini et al., 1993; Cita et al., 1980; Akhmanov, 1996; Premoli et al., 1996; Akhmanov et al., 2003; Giresse et al., 2010; Gennari et al., 2013; Mazzini and Etiope, 2017), the sediments recovered from the Baikal MVs do not contain lithified rock fragments, but rather dry, relatively small and poorly-lithified clayey clasts. Some other typical MV features, such as mud flows, a well-defined caldera around the crater, and e.g. christmas-tree-shaped stacked flow structures on seismic profiles (Xing and Spiess, 2015), have never been observed in Lake Baikal. To date, combined geological and geophysical data has not allowed to precisely estimate the source depth of the breccia for any of the MVs in the lake.

De Batist et al., (2002) and Van Rensbergen et al., (2003) investigated the Posolsky Fault area in Lake Baikal combining heat flow measurements and seismic data. For the first time the authors suggested that the local mud volcanism (MVism) could be triggered by the rapid formation of large volumes of fluids originating from a localised dissociation of hydrates originally stable down to 350–400 mblf. Shallow hydrate destabilization as the driving source for MVism represented a novel hypothesis compared to the more traditional mechanisms described in the literature. These mechanisms typically invoked gravitational instability and deeper over-pressured layers resulting from hydrocarbon generation [e.g. Dimitrov, 2002, Kopf, 2002, Kholodov, 2002, Revil, 2002; Mazzini and Etiope, 2017).

The Academician Ridge represents one of the regions that have been recently targeted for fluid flow investigations and, more broadly, for evidence of MVism. This underwater high is located between the Central and North Baikal basins (Fig. 1A and B), and has been the site of previous deep-drilling operations (BDP-96 & 98 site) and seismic surveys (Zonenshain et al., 1992, Zonenshain et al., 1995, Kazmin et al., 1995, Moore et al., 1997, Grachev et al., 1998, Mats et al., 2000, Khlystov et al., 2000;Antipin et al., 2001; Khlystov et al., 2001). These studies provided detailed descriptions of the investigated stratigraphic sequences and new, important insights in the geological structure of the region.

Here we report the discovery of a new mud volcanic field on the Academician Ridge containing gas hydrates. We use a multidisciplinary approach, including bathymetry mapping, bottom sampling, *in-situ* temperature measurements, geochemical analyses, biostratigraphy, and seismic data, to investigate the targeted area and integrate the results with previously acquired data from the region. The goal of this paper is also to investigate the depth of the roots of this newly discovered hydrate-bearing MV province and to infer its triggering mechanism.

2. Geological setting

Lake Baikal fills the central depression of the Baikal continental rift zone. Morphologically the lake can be subdivided into three basinal areas (i.e. the South, Central and North Baikal basins) that are separated by inter-depression structural highs. The South and Central Baikal basins are separated by a depositional high formed by the coalescence of the deltas of the Buguldeyka and Selenga Rivers. The Central and North Baikal basin are separated by a SW-NE-oriented tectonic high comprising subaqueous as well as emerged parts. The Academician Ridge forms the submerged part of this high, and Olkhon Island is the subaerial continuation towards the south-west, together with the Ushkany Islands archipelago in the northeast (Fig. 1A).

The underwater Academician Ridge is a tectonic block restricted by the Olkhon fault to the south-east. The fault separates lithospheric blocks with different thickness, detaching the younger North Baikal basin (crust thickness ~42–44 km) from the central one (crust thickness ~35 km). In the north-west, the Ridge is bordered by the smaller Ushkany and Zunduksky faults. The Academician Ridge is asymmetric and divided into two blocks by the arched Akademicheskiy fault. This main fault is slightly displaced by a transversal fault, exactly where the study area is located (Fig. 1B). Seismic profiles have shown that the Ridge and its flanks are affected by many faults rooted within the basement (Moore et al., 1997). The north-western block of the Academician Ridge is more elevated than the south-eastern one and has a thinner sedimentary cover. Locally, the basement may outcrop: the

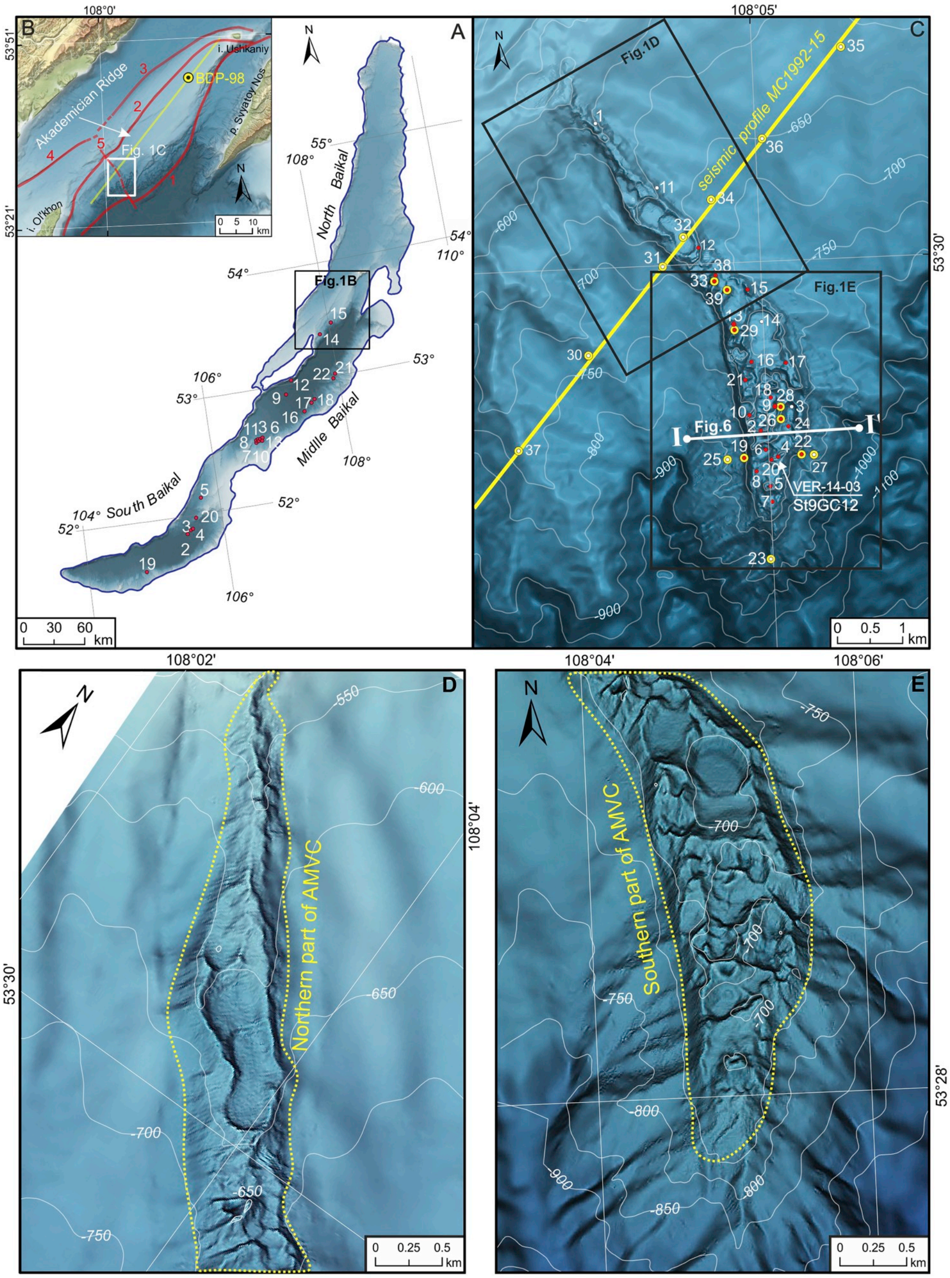

Fig. 1. Overview scheme of the relief in the research area near the Academician Ridge. (A) Lake Baikal with locations of mud volcanoes (red dots with numbers) listed in Table 1. The black frame indicates the area of the underwater Academician Ridge; (B) Detailed bathymetry of the Academician Ridge. The black dot with yellow circle indicates the site BDP-98 drilled in 1998; the solid yellow line traces a fragment of the multichannel seismic profile MC1992-15; red lines indicate faults (1 - Olkhon fault, 2 – Akademichesky, 3- Ushkany, 4 – Zunduksky, 5 - transversal fault). The white frame indicates the study area of Akadem mud volcanic complex (AMVC); (C) AMVC and sampling locations (dots) listed in Table 2; circled in yellow the sites where temperature gradients were measured; the red dot indicates the locality of core with mud breccia, white dot – without mud breccia; "VER-14-03 st 9GC12" indicate core for extensive analyses (see text for details); white line shows the location of the profile I-I′ schematized in Fig. 6. The black frame indicates the northern (D) and southern (E) part of AMVC, yellow contour is highlighted AMVC. D-E: 3D view of the acquired bathymetry highlighting the numerous circular calderas present in the northern and southern part of the AMVC (yellow line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

south-eastern block features a system of tectonic ledges that descend stepwise towards the central basin. Here the thickness of the sediments reaches 1–1.5 km (Zonenshain et al., 1995; Kazmin et al., 1995; Moore et al., 1997; Mats et al., 2000; Khlystov et al., 2000; Antipin et al., 2001).

This block of the ridge had been previously considered as a low sedimentation rate area, and thus selected for deep-water drilling studies (BDP-98 borehole) aiming to investigate the effects of global palaeo-environmental changes in Central Asia (Antipin et al., 2001). The results reported by our study reveal that the region also represents a unique locality for mud volcano studies.

3. Data and methods

Several interesting lake floor structures were identified in the study area after re-interpretation of a multibeam dataset collected in 2009 onboard RV "G. Titov". The acquisition was done using a Seabeam 1050 system that resulted in a resolution of 10–15 m at the studied water depth interval (i.e. 200–900 m) (Cuylaerts et al., 2012). Since 2013, several additional expeditions have been conducted by the RV "G.Yu. Vereschagin", completing 39 coring stations using 3 and 5 m long gravity corers (Table 2, Fig. 1 C). The recovered intervals interpreted as mud breccia deposits were observed in most of the cores and were targeted for more detailed laboratory analyses. Numerous cores also revealed the presence of gas hydrates typically between 1 and 4.5 mblf.

Subsamples from the cored sediments were studied at the Limnological Institute in Irkutsk (LIN SB RAS) and the results were compared with previously obtained data from borehole BDP-98. Diatom analysis on the cored sediments included counting of diatom frustules with the use of a binocular microscope. The preparation of the samples included the suspension of the dried sediment initially soaked in water and centrifuged, then soaked in 5% sodium pyrophosphate for 2 h and washed several times. The resulting suspension was coated onto thin slides in three replications, and the valves were counted at 800-fold magnification. More details about the methodology are provided in Grachev et al. (1998).

Table 2
Key observations for the stations completed at the AMVC between 2014 and 2017.

№	Year	Latitude, degree	Longitude, degree	Cruise	Station	Water depth, m	Mud Breccia	Gas hydrate	Thermal gradient, mK/m	Error, mK/m
1	2014	53.51995	108.0465	VER14-03	ST9GC1	529				
2	2014	53.47675	108.0816	VER14-03	ST9GC10	674	+	+		
3	2014	53.47984	108.0889	VER14-03	ST9GC11	709				
4	2014	53.47308	108.0853	VER14-03	ST9GC12	689	+			
5	2014	53.46905	108.0833	VER14-03	ST9GC13	684	+	+		
6	2014	53.47409	108.0825	VER14-03	ST9GC14	721	+	+		
7	2014	53.46692	108.0835	VER14-03	ST9GC15	706	+	+		
8	2014	53.47120	108.0802	VER14-03	ST9GC16	706	+	+		
9	2014	53.47992	108.0861	VER14-03	ST9GC17	682	+	+		
10	2014	53.47892	108.0791	VER14-03	ST9GC18	687	+	+		
11	2014	53.51074	108.0601	VER14-03	ST9GC2	589				
12	2014	53.50223	108.0690	VER14-03	ST9GC3	627	+			
13	2014	53.49103	108.0765	VER14-03	ST9GC4	646	+	+		
14	2014	53.49173	108.0829	VER14-03	ST9GC5	709				
15	2014	53.49621	108.0799	VER14-03	ST9GC6	658	+			
16	2014	53.48623	108.0801	VER14-03	ST9GC7	658	+	+		
17	2014	53.48595	108.0881	VER14-03	ST9GC8	665	+			
18	2014	53.48125	108.0842	VER14-03	ST9GC9	721	+			
19	2015	53.47312	108.0775	VER15-03	ST13GC1	722	+		61	6
20	2015	53.47270	108.0838	VER15-03	ST13GC3	689	+	+		
21	2015	53.48380	108.0785	VER15-03	ST13GC4	667	+	+		
22	2015	53.47326	108.0908	VER15-03	ST13GC6	732	+		89	9
23	2015	53.45905	108.0827	VER15-03	ST13GC7	841			27	3
24	2015	53.47720	108.0880	VER15-03	ST13GC8	725	+	+		
25	2017	53.47297	108.0737	VER17-01	ST5GC1	788			57	6
26	2017	53.47825	108.0864	VER17-01	ST5GC2	685	+		24	2
27	2017	53.47314	108.0936	VER17-01	ST5GC3	780			45	5
28	2017	53.47994	108.0864	VER17-01	ST5GC4	685	+		85	9
29	2017	53.49076	108.0766	VER17-01	ST5GC5	641	+	+	346	35
30	2017	53.48808	108.0426	VER17-01	ST6GC1	720			65	7
31	2017	53.49988	108.0606	VER17-01	ST7GC1	689			61	6
32	2017	53.5038	108.0656	VER17-01	ST8GC1	641			54	5
33	2017	53.49757	108.0724	VER17-01	ST9GC1	641	+		18	2
34	2017	53.50881	108.0724	VER17-01	ST10GC1	669			47	5
35	2017	53.52902	108.1039	VER17-01	ST11GC1	618			48	5
36	2017	53.51692	108.0849	VER17-01	ST19GC1	657			50	5
37	2017	53.47538	108.0256	VER17-01	ST21GC2	716			55	6
38	2017	53.49834	108.0727	VER17-01	ST22GC1	641	+			
39	2017	53.49631	108.0753	VER17-01	ST23GC1	657	+		14	1

*The cores taken outside the AMVC are marked in gray.

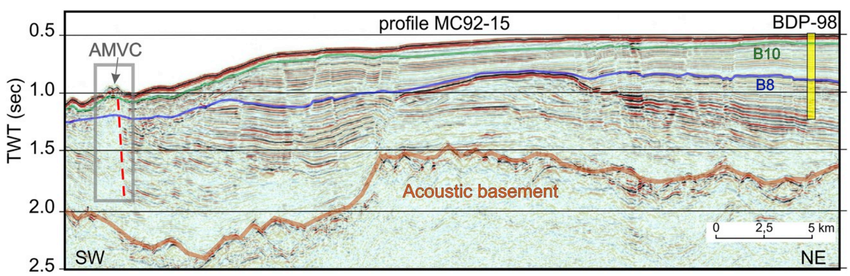

Fig. 2. Multichannel seismic profile MC1992-15 shot in 1992 along the Academician Ridge (Fig. 1B) interpreted by Moore et al., (1996). The seismic boundaries discussed in the text are marked in colours. The yellow vertical line indicates the BDP-98 borehole. Framed in gray the AMVC study area with diffused vertical blanking. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

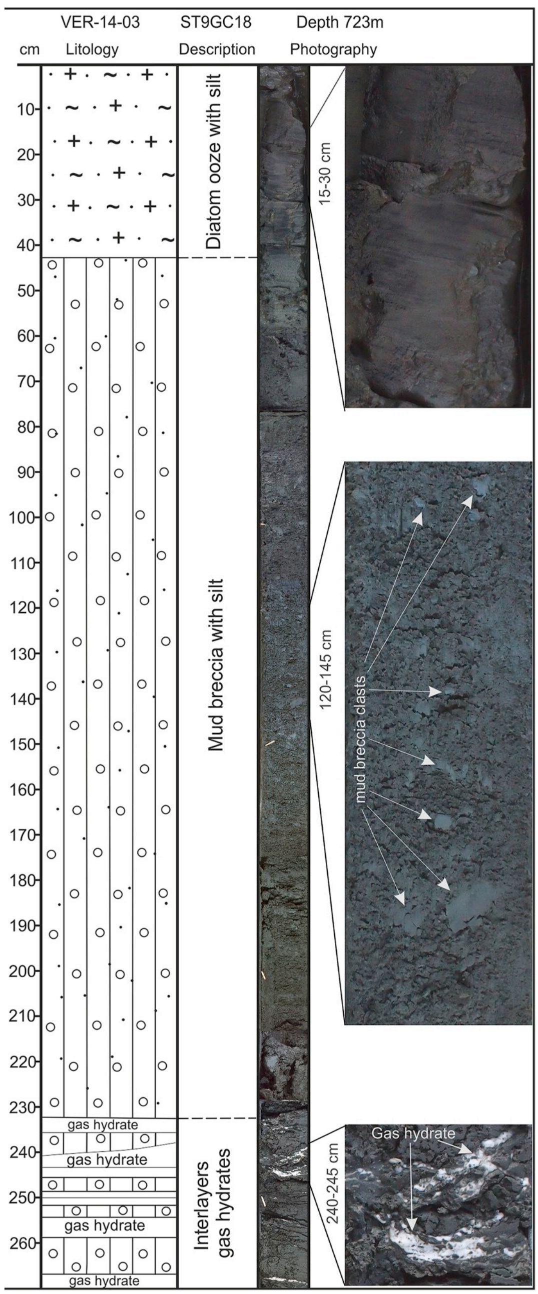

Fig. 3. Geological cross section of cores with mud breccia and gas hydrate from AMVC.

The hydrate-bound gases were collected onboard using a funnel and plastic bucket filled with water. Gas hydrates were decomposed in water and the released gas was stored in vials (volume: 5 mL) sealed with butyl septum stoppers. 0.3 mL of benzalkonium chloride was introduced into the vial using a syringe to avoid microbial activity. Gas composition (from C_1 to C_3) of the collected gas hydrates was analysed using a Shimadzu GC-2014 gas chromatograph (Kitami Institute of Technology, Japan) equipped with a thermal conductivity detector for high concentrations of hydrocarbons, and a flame ionization detector for low concentrations of hydrocarbons along with a packed column (Shimadzu Sunpak-S). The two detectors were connected in series. The glass column had a length of 2 m and an inner diameter of 3 mm (Hachikubo et al., 2010). The analytical error estimated by multiple injections of standard gases was less than 1.2% for each gas component.

In-situ thermal measurements were carried out at 18 coring stations using five THP loggers attached to the gravity corer at intervals of 0.5 m. The use of THP loggers on the corer allowed to have thermal data exactly on the sites of sediment and hydrate sampling (Poort et al., 2012). The THP loggers are autonomous temperature data loggers with an accuracy of 0.007 °C and a resolution of 0.0007 °C at 20 °C. Corer inclination was registered with an accuracy of 1° using a tilt meter mounted at the top of the corer. The loggers allowed to obtain the vertical temperature gradients in the sediments down to 3 mblf. Overall the thermal gradients at the different coring sites ranged between 14 and 346 mK/m with an error of about 10%.

Additionally, we performed a stratigraphic correlation based on the data of the BDP-98 drilling core (Antipin et al., 2001; Kuzmin et al., 2009) and seismic multi-channel profiles acquired during the Russian-American joint survey in the area in 1992 (Hutchinson et al., 1992; Moore et al., 1997). The obtained seismic data allowed the identification of the major stratigraphic reflectors intersected by the borehole, and their correlation with those present in our study area (Fig. 2).

4. Results and interpretation

4.1. Bathymetric observations of the study area

Detailed bathymetric analysis of the available multibeam data revealed a complex positive structure located in the middle of the southern slope of the Academician Ridge (Fig. 1B and C). This well-defined structure has a width of < 2 km and extends over a length of 6 km between 500 and 800 m water depth (Fig. 1 C). Morphologically the structure can be subdivided into two portions: a northern part, oriented NW-SE and located between 500 and 700 m water depth (Fig. 1 D), and a southern part with N-S orientation and located between 700 and 800 m water depth (Fig. 1 E). The southern part is characterised by many superposed and merged crater-like depressions and topographic highs (up to ~ 80 m), while the northern part reveals fewer subcircular depressions. At least eight of these well-defined circular depressions resemble the typical MV calderas studied in other geological settings worldwide (Fig. 1D and E) (Dupré et al., 2008; Lykousis et al., 2009; Skinner and Mazzini, 2009; Foucher et al., 2010; Mazzini and Etiope, 2017). Most of the cores collected from these craters recovered sediments with mud breccia, while all outer stations contained normal hemipelagic sequences. These converging data provide evidence for MV activity. In particular, in the southern part of this elongated structure (i.e. where the craters are more abundant), mud breccia was associated with gas hydrates. Seismic profiles intersecting

Table 3
Diatom content in mud breccia intervals of the core VER-14-03 St9GC12.

	Interval, cmblf								
	78	105	123	135	155	195	205	215	216
Total diatoms (million valves per gram)	**9.35**	**4.31**	**7.79**	**9.89**	**17.28**	**9.62**	**3.88**	**19.36**	**6.68**
Modern species									
Aulacoseira ambigua	0.04	0.01	0.04	0.00	0.04	0.03	0.05	0.04	0.04
Aulacoseira baicalensis	0.46	0.08	0.32	0.35	0.48	0.12	0.05	0.12	0.05
Aulacoseira skvortzowii	0.64	0.22	0.01	0.50	0.13	0.45	0.06	0.11	0.22
Aulacoseira subarctica	0.02	0.01	0.46	0.24	0.72	0.34	0.08	0.18	0.01
Cyclotella baicalensis	0.08	0.01	0.00	0.06	0.14	0.06	0.02	0.02	0.02
Cyclotella minuta	2.30	0.27	0.00	0.60	0.15	0.26	0.02	0.11	0.07
Cyclotella ocellata Pantocsek	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00
Cyclostephanos dubius	0.02	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00
Synedra acus subsp. *radians*	0.04	0.04	0.00	0.02	0.00	0.04	0.04	0.00	0.00
Synedra ulna var. *danica*	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.03	0.01
Total amount of modern species (million valves per gram)	**3.62**	**0.65**	**0.83**	**1.80**	**1.72**	**1.30**	**0.32**	**0.62**	**0.42**
Total amount of modern species (%)	**38.72**	**15.08**	**10.65**	**18.20**	**9.95**	**13.51**	**8.25**	**3.20**	**6.29**
Ancient species (million valves per gram)									
Cyclotella bradburyi	0.00	0.02	0.06	0.00	0.00	0.00	0.00	0.00	0.00
Cyclotella gracilis	0.12	0.03	0.05	0.00	0.02	0.00	0.01	0.01	0.08
Cyclotella praeminuta	0.04	0.02	0.35	0.06	0.60	0.04	0.03	0.02	0.00
Cyclotella comtaeformica	0.05	0.02	0.13	0.21	0.28	0.14	0.08	0.16	0.16
Cyclotella comtaeformica var. *spinata*	0.05	2.00	0.06	0.07	0.14	0.17	0.07	0.12	0.04
Cyclotella tempereiformica	2.20	0.54	3.40	4.10	9.80	2.40	1.02	6.20	1.90
Cyclotella distincta	1.30	0.33	1.00	0.74	0.80	0.85	0.25	1.44	0.94
Cyclotella Iris et var.	0.54	0.02	1.54	2.00	3.00	3.40	1.24	10.10	2.62
Stephanodiscus flabellatus	0.00	0.06	0.00	0.02	0.00	0.04	0.01	0.00	0.00
Stephanodiscus formosus	0.32	0.14	0.01	0.18	0.28	0.33	0.12	0.14	0.16
Stephanodiscus carconeiformis	0.18	0.30	0.00	0.08	0.01	0.02	0.10	0.02	0.04
Stephanodiscus grandis var.	0.52	0.04	0.03	0.28	0.09	0.18	0.35	0.26	0.25
Stephanodiscus distinctus var.	0.08	0.06	0.11	0.12	0.22	0.26	0.03	0.02	0.02
Stephanodiscus princeps	0.06	0.01	0.02	0.00	0.01	0.06	0.02	0.03	0.00
Stephanodiscus binderanoides	0.14	0.02	0.00	0.03	0.00	0.11	0.03	0.08	0.01
Stephanodiscus asteroides var. *baicalensis*	0.04	0.00	0.00	0.04	0.01	0.13	0.14	0.03	0.01
Stephanodiscus williamssii	0.04	0.02	0.02	0.08	0.02	0.01	0.01	0.07	0.00
Stephanodiscus majusculus	0.00	0.00	0.03	0.03	0.02	0.01	0.03	0.00	0.00
Tertiarius baicalensis	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Stephanopsis costatus	0.04	0.01	0.00	0.02	0.02	0.01	0.00	0.00	0.01
Teriariopsis imperseptus	0.00	0.01	0.14	0.02	0.23	0.15	0.02	0.04	0.02
Total amount of ancient species (million valves per gram)	**5.73**	**3.66**	**6.96**	**8.09**	**15.56**	**8.32**	**3.56**	**18.74**	**6.26**
Total amount of ancient species (%)	**61.28**	**84.92**	**89.35**	**81.80**	**90.05**	**86.49**	**91.75**	**96.80**	**93.71**

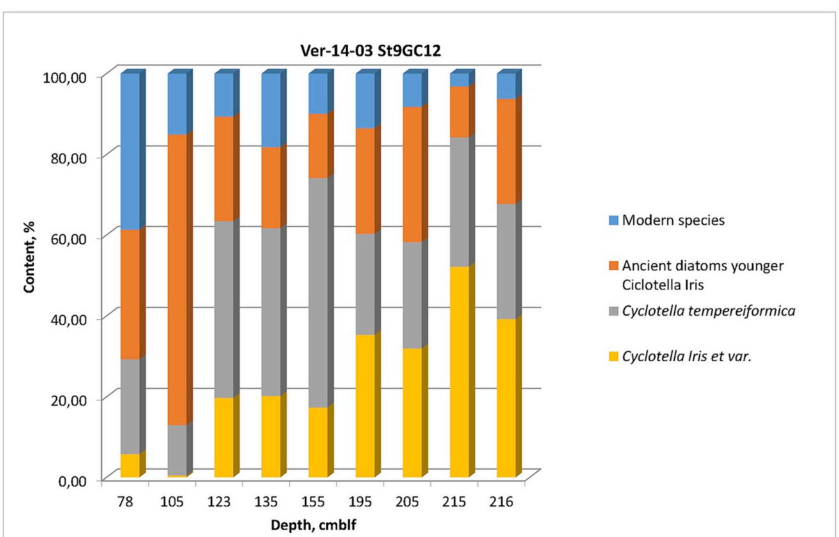

Fig. 4. The distribution histogram of diatoms in defined intervals of the core VER-14-03 St9GC12 (see also Table 3). *Cyclotella Iris* et var. is the oldest species found in core. The age of this oldest species is Late Miocene - Early Pliocene (4.6–5.6 Ma) (Kuzmin et al., 2009).

the study area (e.g. Fig. 2) reveal the presence of acoustic blanking of the seismic signal, which may indicate the presence of advective vertical fluid migration processes (Judd and Hovland, 2007; Andresen, 2012).

These observations provide compelling evidence that numerous MV structures are populating the area. Taking into account the high density of MVs and their occasional overlap, we propose to use the term “mud volcanic complex” for the whole area and thus refer to whole structure

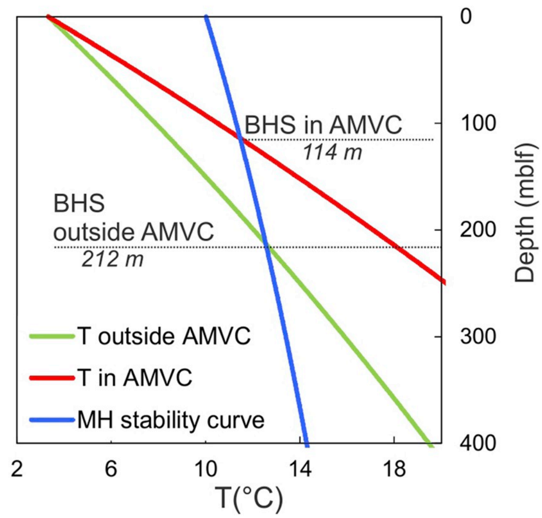

Fig. 5. Clathrates stability in the AMVC. Estimates of Bottom of methane Hydrate Stability (BHS) depth for sediments inside and outside of the AMVC area.

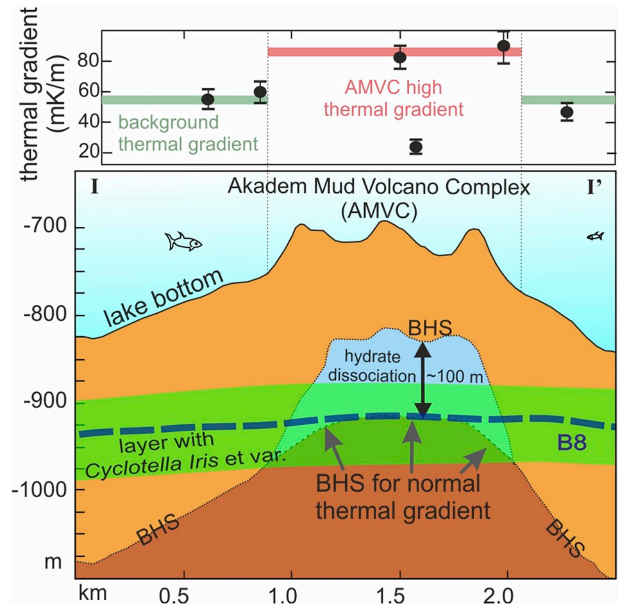

Fig. 6. Schematic section through AMVC along line I-I" (see location on Fig. 1). The model shows how below AMVC the BHS is uplifted by approximately 100 m as indicated by the higher thermal gradient (85–89 mK/m in the southern part of AMVC) compared to the background thermal gradient outside of the mud volcanic area (50–60 mK/m). The upper plot shows the thermal gradient measurements collected along or in close proximity of line I-I", the remaining measurements are reported in Table 2. The sediment source layer (original green interval) of the mud breccia containing ancient diatoms (*Cyclotella Iris* et var.) is estimated exactly at the depth affected by gas hydrate dissociation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

as "Akadem mud volcanic complex" (AMVC). This area represents the first MV field discovered on the Academician Ridge accommodation zone, and is thus far the northernmost MV discovery location in Lake Baikal.

4.2. Diatom investigations in the mud breccia

The mud breccia recovered at the AMVC consists of poorly lithified clayey clasts dispersed in a clayey structureless matrix. In the southern part of the study area these deposits are exposed directly at the lake floor or, in fewer instances, overlain by a diatom ooze layer, up to 70 cm thick (Fig. 3). In contrast, fewer cores from the northern part of the area recovered mud breccia, and only the upper diatomic layer was observed in most of the instances. These observations highlight that mud volcanism was active until quite recently over large part of the southern sector of the AMVC.

Different diatom species were recognized in the recovered sections. In the mud breccia intervals 31 species and varieties of diatoms were found and compared with larger diatom assemblages present in diatom ooze of ordinary lake sediment. As an example, the diatom content in the mud breccia interval of core VER-14-03 St9GC12 is illustrated in Table 3 and Fig. 4. The mud breccia is characterized by the presence of *Cyclotella Iris* et var., the oldest species found in all cores. Two extinct diatom species, *Cyclotella Iris* et var. (found in an amount of up to 10.1 million valves per gram) and *Cyclotella tempereiformica* (found in amount of up to 9.8 million valves per gram) were the most abundant species observed in the mud breccia intervals and were not detected in recent diatom ooze units in the uppermost part of the cores. The species currently thriving in the lake were also detected in the studied mud breccia intervals. This is likely the result of mixing with recent sediments during eruptive events. However, it should be noted that recent species are nearly five times less abundant than ancient species. For example, the modern species *Cyclotella minuta* was found in amount of up to 2.3 million valves per gram. Overall, considering all the cores and all the intervals of mud volcanic deposits of AMVC, the total amount of valves of the modern species reached a maximum value of only 5.8 million valves per gram, whereas the ancient species were detected in amount of up to 18.7 million valves per gram.

4.3. Correlations with the BDP-98 section

Diatom assemblages provide information about the age of the sediments and, in the case of mud breccia, about the stratigraphic horizon that acted as source of the erupted mud. The oldest diatoms described in the AMVC mud breccias were also observed in the BDP-98 borehole on the Academician Ridge (Figs. 1 and 2). The extinct diatom specie *Cyclotella Iris* et var., the most abundant in the mud breccia deposits, appears to be typical for the drilled interval of 230–310 mblf (Antipin et al., 2001). The age of this interval is estimated as Late Miocene - Early Pliocene (4.6–5.6 Ma) (Kuzmin et al., 2009). This constrains the origin of the erupted AMVF mud breccia to the same stratigraphic interval.

The multichannel seismic line 92-15 (Fig. 2 (Moore et al., 1997)) intersects both the AMVC and the BDP-98 borehole. This line is therefore ideal to correlate the Late Miocene - Early Pliocene deposits and the roots of the studied MVs. The distance between the AMVC and the BDP-98 borehole is 34 km. The seismic data show that the acoustic basement is present at a depth of 1–1.5 km below both the AMVC and the BDP-98 site. Seismic stratigraphic units described by Moore et al., (1997) and are correlated with the BDP-98 site by biostratigraphy, and can be recognized all along the seismic line up to the AMVC area. Seismic reflectors B10 and B8 were recognized below the BDP-98 site at sub-bottom depths of 100 and 270 m with equivalent ages of 2.5 and 5.2 Ma, respectively (Antipin et al., 2001). In the AMVC the same reflectors lay at ~90 and 250 mblf, respectively (Fig. 2). Reflector B8 can be safely considered as representative of the Late Miocene - Early Pliocene interval. According to diatom analysis of the mud breccia, the sediments erupted at the surface are coeval with the dated interval B8. Hence the feeder conduits of the AMVC structures are rooted at about 200–300 mblf.

4.4. Base of the gas hydrate stability zone near AMVC

The abundance of gas hydrates recovered from the AMVC demonstrates that the whole area is hydrate prone. Gas analysis of the recovered hydrates revealed a composition of 99.95% methane. We can estimate the theoretical depth of the base of the gas hydrate stability (BHS) by coupling in-situ pressures and temperatures to an empirical methane hydrate stability curve. We used the CSMHYD software of Sloan (1998) and adopted the fresh-water condition of Lake Baikal. We applied a purely methane gas composition, a measured bottom water temperature of 3.33 °C, and a thermal conductivity profile based on BDP-96 drilling measurements (Golmshtok et al., 1997). Our new thermal measurements show a typical background gradient of 45–65 mK/m outside of the AMVC (Poort and Klerkx, 2004; Golubev, 2007). Within the MV complex area, the thermal gradient reveal anomalous values with 346 mK/m measured at a gas flare site in the boundary between northern and southern part, and maximum values up to 85–89 mK/m in the southern part of AMVC. Considering the water depth of the southern part of the AMVC, the BHS is therefore calculated at 212 mblf outside and 114 mblf within the MV complex region (Fig. 5). This indicates a current shallowing of the BHS of ~100 m within the more active part of the AMVC.

5. Discussion

5.1. AMVC shallow-rooted mud volcanism

In most mud-volcano provinces, mud volcanism is sourced from deep roots. There are a few examples of mud volcanoes that are linked by a feeder pipe to a buried deep-rooted mud-volcanic edifice that acts as a secondary mud chamber at an intermediate depth, i.e. the Dhaka mud volcano in Alboran Sea (Somoza et al., 2012). Deeper sourced fluids and mud breccia, have been suggested to control the overpressure charge of these shallow chambers and in turn to govern the MV eruptive activity. The mud-volcanic activity in the AMVC is not sourced from deep roots, not directly and not through a secondary mud chamber at intermediate depth. On Lake Baikal, the formation and activity of shallow-rooted MVism cannot be explained by "classic" and broadly accepted mechanisms (typically a combination of gravitational instability of shales and fluid overpressures built at depth in sedimentary basins) [e.g. Mazzini and Etiope, 2017 and refs. therein]. Hence, different mechanisms should be envisaged to explain the initiation and eruption dynamics for the shallow-rooted AMVC (i.e. 200–300 mblf, in Late Miocene - Early Pliocene strata). Here we explore the shallow hydrate destabilization scenario proposed by De Batist et al., (2002) and Van Rensbergen et al., (2003) and test if this hypothesis can be applied as the driving source for MVism of the AMVC.

Our newly obtained data reveal that there is a good correlation between at least two key observations:

(1) The depth interval, from which the oldest mud breccia diatom species originates, ranges between 200 and 300 m.
(2) The calculated the regional BHS (212 m) has been shifted ~100 m upwards or is completely absent in the area of the AMVC.

These combined observations indicate that the dissociation of the local hydrates at the BHS and the related MV activity at the AMVC was triggered by the advective heat transfer resulting from the upward migration of warm fluids along faults and fracture zones. This advective heat transfer increased the thermal gradient at the AMVC creating locally strong thermal anomalies (Fig. 6).

5.2. Hydrate dissociation model for AMVC formation

Our new multidisciplinary dataset provides converging evidences for a shallow-rooted MVism in the AMVC (Fig. 6). The suggested conceptual model includes:

1. The localized migration of warm fluids from deeper units (i.e. an elevated measured thermal gradient of 1.6 times the background value) shifted the BHS upwards;
2. The warmer fluids triggered widespread dissociation of gas hydrates originally stable at ~212 mblf;
3. The dissociation resulted in localized pore-pressure increase and liquefaction of the already unlithified clayey strata;
4. These new conditions resulted in the focused release of overpressure with the expulsion of the liquefied sedimentary units and the formation of MVs at the surface.

5.3. Comparison with classic type mud volcanism

The depicted scenario for MV formation is quite specific and is consistent with 1) all the sediments recovered, 2) the bottom measurements, and 3) the regional geophysical observations. Further, this mechanism is able to explain many features that are common at numerous MV sites in Lake Baikal namely: a) the lack of lithified rocks among mud breccia clasts, b) typically higher geothermal gradients compared with the surrounding regions, c) localized presence of gas hydrates, d) lack of evidence of deep-rooted MVs conduits. The suggested model is potentially applicable and typical for many other sedimentary basins on the planet, in which gravitational instability and pore-fluid overpressure due to sediment accumulation in deeply buried strata are not (yet) present. We therefore highlight the importance of differentiating between the identified "Baikal" type of mud volcanism from the classic deeply rooted sedimentary volcanism known from mature sedimentary basins (e.g. Caspian Sea, Black Sea, Mediterranean Sea, Gulf of Cadiz, Alboran Sea, Gulf of Mexico). Worldwide the depth of MV roots, from which fluids and rock clasts originate, may vary depending on the geological setting. Feeder channels of some structures have been suggested to reach up to 15–25 km depth (Sobissevitch et al., 2008; Mazzini and Etiope, 2017 and refs. therein).

The high overpressure and buoyancy contrast that can be achieved at deeply-rooted MVs, are unlikely to occur for significantly shallower structures such as those observed in Lake Baikal. The model that we propose here may also explain why the MVs in Lake Baikal have relatively low elevation since the gathered overpressure is not sufficient to trigger powerful explosive eruptions (i.e. like what happens for deep-rooted structures) able to build tall conical structures with properly developed crates similar to those of the magmatic volcanoes (i.e. see the spectacular MV examples in Jakubov et al., 1971). The Baikal MVs are rather pie shaped or laterally extensive, owing to the poorly lithified nature of the erupted sediments. The poor consolidation of the water-saturated sediments in the upper column may also facilitate the formation of wider craters even with relatively low amount of gas venting. Indeed data from the drill core BDP-98, reveal the presence of non-lithified clay up to a depth of ~300 m with gradually increasing aleurite admixture with depth. Denser clay layers occur only at layers deeper than 500 m.

6. Conclusions

We report on the discovery of a new mud volcano field on the Academician Ridge in Lake Baikal. The field consists of many overlapping gas hydrate bearing mud volcanoes grouped along an elongated ridge-like structure stretching over 6 km. We named this field the "Akadem Mud Volcanic Complex" (AMVC). The presence of ancient diatoms in the mud breccia allowed to define the source layer of the erupted sediments at depth of 200–300 mblf. We demonstrate that the BHS below the AMVC (originally at ~212 mblf) was shifted upwards of ~100 m. We suggest that the vertical migration of deep and warm fluids induced the dissociation of the inferred deep gas hydrates, which liquefied the host sediments at a depth of ~212 m and generated overpressure. These unstable conditions triggered shallow-rooted mud volcanism. Similar characteristic diatom assemblages and absence of lithified clasts in the mud breccia are observed in most of the other mud volcanoes in Lake Baikal. These observations are consistent with shallow-rooted mud volcanism. This "Baikal" type of mud volcanism differs significantly from the classic, deep-rooted phenomena known from other mature (marine) sedimentary basins.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpetgeo.2019.01.005.

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