Near-surface sediment mobilization and methane venting in relation to hydrate destabilization in Southern Lake Baikal, Siberia

PIETER VAN RENSBERGEN[1,6] JEFFREY POORT[1], ROLF KIPFER[2], MARC DE BATIST[1], MAARTEN VANNESTE[1,6], JEAN KLERKX[3], NICK GRANIN[4], OLEG KHLYSTOV[4] & PETR KRINITSKY[5]

[1]*Renard Centre of Marine Geology, University of Gent, Gent, Belgium (e-mail: pieter_vanrensbergen@yahoo.com)*
[2]*EAWAG, Dübendorf, Switzerland*
[3]*Department Geology and Mineralogy, Royal Museum of Central Africa, Tervuren, Belgium*
[4]*Limnological Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia*
[5]*VNIIOkeangeologia, St. Petersburg, Russia*
[6]*Present address: Department of Geology, University of Tromsø, Norway*

Abstract: Four seeps and mud extrusion features at the lake floor were discovered in August 1999 in the gas hydrate area in Lake Baikal's South Basin. This paper describes these features in detail using side-scan sonar, detailed bathymetry, measurements of near-bottom water properties, selected seismic profiles and heat flow data calculated from the depth of the hydrate layer as well as obtained from *in situ* thermoprobe measurements. The interpretation of these data is integrated with published geochemical data from shallow cores. The seeps are identified as methane seeps and appear as mud cones (maximum 24 m high, 800 m in diameter) or low-relief craters (maximum 8 m deep, 500 m in diameter) at the lake floor. Mud cones (estimated to be approximately 50–100 ka old) appear to be older than the craters and have a different structural setting. Mud cones occur at the crest of rollover structures, in the footwall of a secondary normal fault, while the craters occur at fault splays. The seeps are found in an area of high heat flow where the base of the gas hydrate layer shallows rapidly towards the vent sites from about 400 m to about 160 m below the lake floor. At the site of the seep, a vertical seismic chimney disrupts the sedimentary stratification from the base of the hydrate layer to the lake floor. Integration of these results leads to the interpretation that focused destabilization of gas hydrate caused massive methane release and forced mud extrusion at the lake floor and that the gas seeps and mud diapirs in Lake Baikal do not have a deep origin. This is the first time that methane seeps and/or mud volcanoes associated with gas hydrate decomposition have been observed in a sub-lacustrine setting. The finding suggests that gas hydrate destabilization can create large pore fluid overpressures in the shallow subsurface (<500 m subsurface) and cause mud extrusion at the sediment surface.

Lake Baikal is the only fresh-water basin with demonstrated presence of gas hydrate in the subsurface (Kuzmin *et al.* 1998). Presence of gas hydrates in the subsurface was also inferred from detailed seismic experiments (e.g. Golmshtok *et al.* 2000; Vanneste *et al.* 2001). In the summer of 1999, several gas seeps and mud extrusion features were discovered in Lake Baikal's South Basin. In this paper, we use side-scan sonar mosaics from a detailed study area, in combination with echo-sounding data, CTD casts and a number of seismic profiles to investigate the nature of the expelled fluids and gases, the morphology of the vent sites and their structural setting in relation to the thickness distribution of the hydrate-bearing section and lateral heat flow variations. The study suggests that the seeps in the southern part of Lake Baikal are gas seeps that most probably originate from methane release by hydrate decomposition at the base of the hydrate stability zone and infer that gas release in the shallow subsurface can cause extrusion of lacustrine mud at the lake floor.

In the Southern Baikal Basin (SBB) and Central Baikal Basin (CBB) extensive gas hydrate accumulations occur in the subsurface (Fig. 1a). The presence of gas hydrate in Lake Baikal was first inferred by Golmshtok *et al.* (1997) on the basis of the observation of a 'bottom-simulating reflection' (BSR) on multi-channel seismic profiles. The BSR was interpreted to mark the base of the hydrate stability zone (BHSZ), which was estimated from the seismic data to be between 35 m and 450 m thick (Golmshtok *et al.* 1997). The BSR could be observed in the area around the Selenga River delta (Fig. 1a) at water depths exceeding 580 m, i.e. on the deeper delta slope and the generally flat basin floors of the adjacent sub-basins.

The first samples of gas hydrate in Lake Baikal sediments were brought to the surface in a 'Baikal

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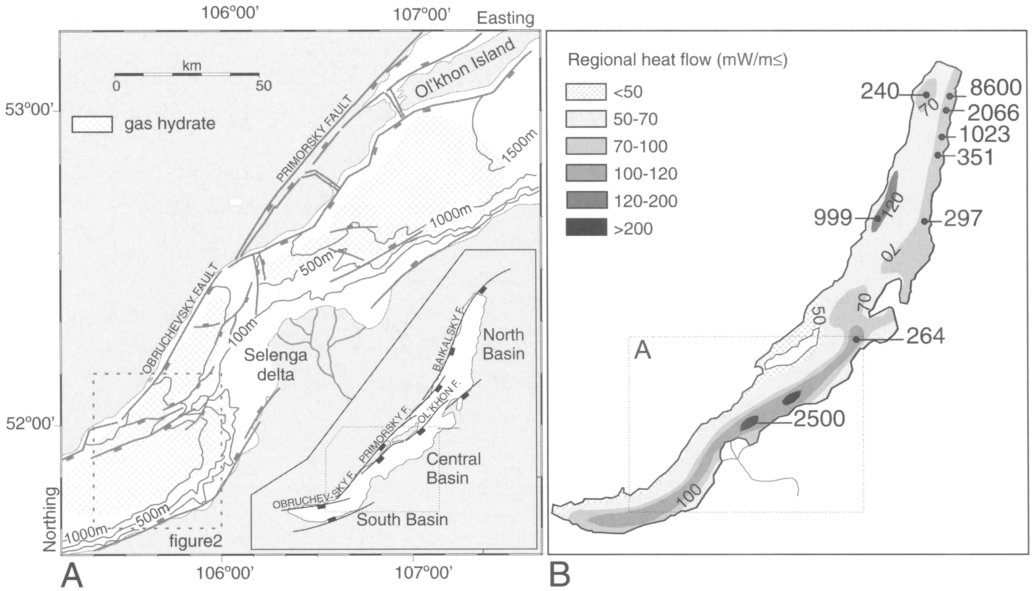


Fig. 1. A. Structure of Lake Baikal (inset) and the Selenga delta region, distribution of hydrate occurrence in the Baikal South Basin and Central Basin mapped on basis of a regional seismic grid (Golmshtok *et al.* 1997).
B. Heat flow distribution in Lake Baikal based on thermoprobe measurements along regional transects (after Golubev 2000).

Drilling Project' (BDP) core in 1997 (Kuzmin *et al.* 1998). The 224 m long core was taken in 1427 m water depth and the hydrates were found in coarse sandy turbidites at 121 m and 161 m sub-bottom depth. The hydrates in the collected samples occupied approximately 10% of the pore space (Golubev pers. comm. in Vanneste *et al.* 2001). The total volume of hydrate in Lake Baikal was calculated based on the above observations to be about 7.6×10^9 m^3, which represents about 1.24×10^{12} m^3 of methane at STP conditions (Vanneste *et al.* 2001). Chromatographic analysis of the gases emitted by the BDP samples showed that methane was the only hydrocarbon in the sample representing $>99\%$ of the total gas volume (Kuzmin *et al.* 1998; Kuzmin *et al.* 2000). Carbon isotopic composition ($\delta^{13}C$) ranges between 58 ‰ and -68 ‰ (Kuzmin *et al.* 1998; Kuzmin *et al.* 2000), indicating a bacterial origin via methanogenesis (Kvenvolden 1998; Sloan 1998). Hydrate distribution in Lake Baikal is limited to the area around the Selenga delta and the gas of the gas hydrate is most probably derived from organic matter supplied by the Selenga River, the main source of terrigenous organic matter to the lake.

Sedimentation rates at the basin floor in Lake Baikal are in the order of magnitude of 0.3 mm/yr; the organic carbon in the lake floor sediments ranges from 2–4% for interglacial sediments to about 0.2% for glacial-age sediments (Colman *et al.* 1996). Under such conditions methane generation from organic diagenesis can form hydrate *in situ* (Sloan 1998), but most likely the methane concentration in the hydrate stability zone was enriched over geological time with methane from hydrate decomposition at the base of the hydrated sediment layer due to continued sedimentation ('methane recycling'; Paull *et al.* 1994). Baikal water is pure and characterized by high oxygen concentrations throughout the water column (Kipfer *et al.* 1996) and very low concentrations of dissolved solids (Faulkner *et al.* 1991) and it is under-saturated for carbonates. As a result there are no authigenic or biogenic carbonates formed or preserved in Lake Baikal (Colman *et al.* 1996).

More than 50 hot springs have been mapped in the Baikal Rift, mainly along the eastern margin of the Northern Baikal Basin (NBB) and the CBB (Pinneker & Lomonosov 1973). Hydrothermal activity is associated with zones of high geothermal heat flux related to basement fault zones. The water temperature in onshore hot springs ranges from 40 °C to 80 °C. At an offshore hydrothermal vent site in Frolikha Bay in the NBB, temperatures reach 16 °C at 0.5 m in the subsurface (Shanks & Callender 1992). This sub-lacustrine vent is located in a water depth of 440 m and the discharge of saline water can be traced deep into the NBB (Kipfer *et al.* 1996). Shanks & Callender (1992) interpreted stable-isotope data of the pore water in the proximity of the hydrothermal discharge to be

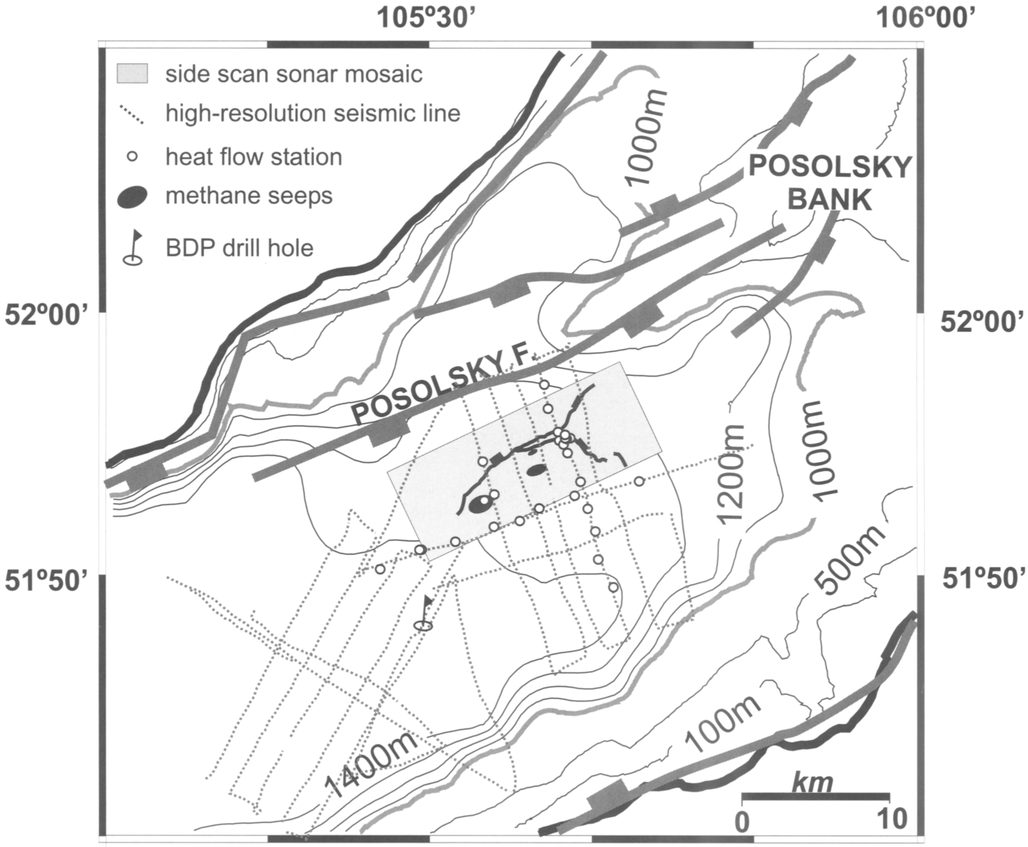


Fig. 2. Location map of the high-resolution seismic lines, heat flow stations and the side-scan sonar mosaic (shown in Fig. 3).

the result of intrusion of meteoric water from onshore mountain ranges along active rift faults into the bottom sediments of Frolikha Bay. Leaching of Cambrian evaporitic rocks near Lake Baikal is probably the cause of the increased salinity of the hydrothermal discharge. The sub-lacustrine hot spring at Frolikha Bay is related to an advective heat flow anomaly that reaches 8600 mW/m^2 (Fig. 1b; Crane *et al.* 1991; Golubev *et al.* 1993); background heat flow in the Baikal Rift is about 40–70 mW/m^2 (Golubev 2000). Other narrow positive heat flow anomalies in the NBB (Golubev & Poort 1995) occur at near-shore faults extending along bottom foothills. In the CBB, heat flow anomalies are also associated with faults in the subsurface. In the SBB a prominent positive anomaly occurs over an area of 30 km wide (Fig. 1b). Golubev (2000) suggests that all heat flow anomalies in Lake Baikal can be attributed to groundwater penetrating beneath the rift shoulders and rising as thermal waters along faults in the lake basin. Such regional heat and fluid circulation by groundwater has been suggested to be feasible by numerical modelling (Poort & Polyansky 2002).

The study area is located in a zone where on regional multi-channel seismic profiles the base of the hydrate stability zone (BHSZ) is irregular and not at all mimicking the lake floor as a 'bottom-simulating reflection' (Golmshtok *et al.* 2000) and where several gas seeps and mud extrusion features have recently been discovered (Van Rensbergen *et al.* 2002). The study area is located over the hanging wall of a major rift fault, the Posolsky Fault, in a water depth of 1320 m to 1440 m (Fig. 2). The Posolsky Fault, just north of our study area, is an active fault that forms the SE flank of the Posolsky bank and continues basinwards in a SW direction for about 30 km. It has a maximum throw of over 1.5 s (about 3 km) below the SW margin of the Selenga delta (Scholz & Hutchinson 2000). However, just north of the observed seeps the Posolsky Fault offsets the lake floor by about 200 m. A number of small secondary faults with throws of less than 20 m occur within the study area.

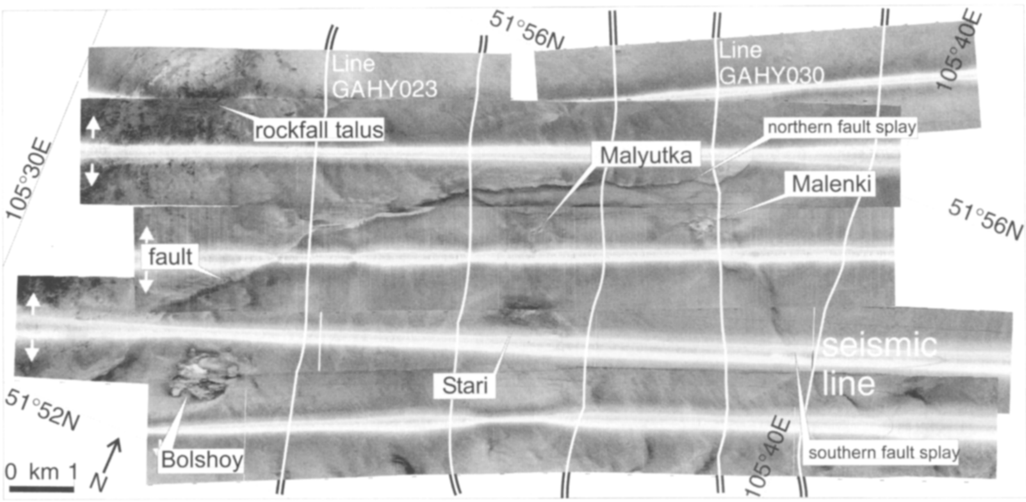


Fig. 3. Side-scan sonar mosaic over the discovered methane seeps.

Data and methods

The data discussed here are located in a study area of about 15 km × 16 km in the SBB and were acquired in August 1999 (Fig. 2). In this study area, a side-scan sonar mosaic covers an area of about 90 km^2. The 30 kHz SONIC sonar was towed at about 80–250 m above the lake floor; 0.8 km was imaged at each side of the track-line and the across-track footprint of the acoustic beam ranges from 0.75 m to 3.8 m. In addition, nine single-channel airgun seismic reflection profiles with a total length of about 180 km were obtained in the study area. A 3 litre IMPULSE-1 airgun (frequency range of 45–330 Hz) was used yielding a penetration up to 600 ms two way travel time (about 480 m) and a vertical resolution of about 3 m.

One of the seeps was studied in detail using a 12 kHz echo sounder and 11 CTD casts (measurements of temperature, conductivity/salinity, light transmission, and oxygen concentration) were taken during two different surveys two weeks apart.

Additional data were provided by 23 thermo probe measurements taken along two seismic profiles (Fig. 2) to calculate the lateral variation in heat flow. The 2 m long GEOS-T thermo probe applies the continuous heating method and allows the obtaining of temperature gradient measurements and thermal-conductivity values over four 0.5 m intervals in the upper sediments.

Attempts to core in the seep area during the August 1999 expedition failed, but during the March 2000 coring expedition, from the ice-covered lake, samples of hydrate in diatom-rich silts and silty clays were retrieved. The sampled hydrates are shallow accumulations (about 20 cm below the lake floor) restricted to the seep area. The cores did not penetrate the more extensive deeper hydrate layer, the base of which is imaged on the seismic profile. The geochemistry of hydrate samples and sediment pore waters were analysed by Matveeva *et al.* (2000). In the discussion section, the geochemical results will be integrated with geophysical data from this study.

Description and interpretation

Surface and shallow subsurface expression of the methane seeps

Four seeps were found in the study area (Fig. 3). They were named 'Bolshoy' (large), 'Stari' (old), 'Malyutka' (very small) and 'Malenki' (small) (Van Rensbergen *et al.* 2002). The seeps occur over a roll-over structure in the footwall of a small fault antithetic to the Posolsky Fault (downthrown side to the north). The fault offsets the lake floor by about 20 m and the seismic profiles show the throw to increase with depth to a maximum of 100 m (about 80 m). This antithetic fault runs across the side-scan sonar mosaic as an undulating trace with high backscatter strength. The fault turns from a N30E direction in the western part of the study area to a N70E direction in the centre (parallel to the Posolsky Fault) where it splits into two perpendicular splays (N20E and N110E respectively) with a throw of about 10 m each. Malenki and Malyutka are low-relief craters; Bolshoy and Stari are mud cones on the lake floor (Fig. 3).

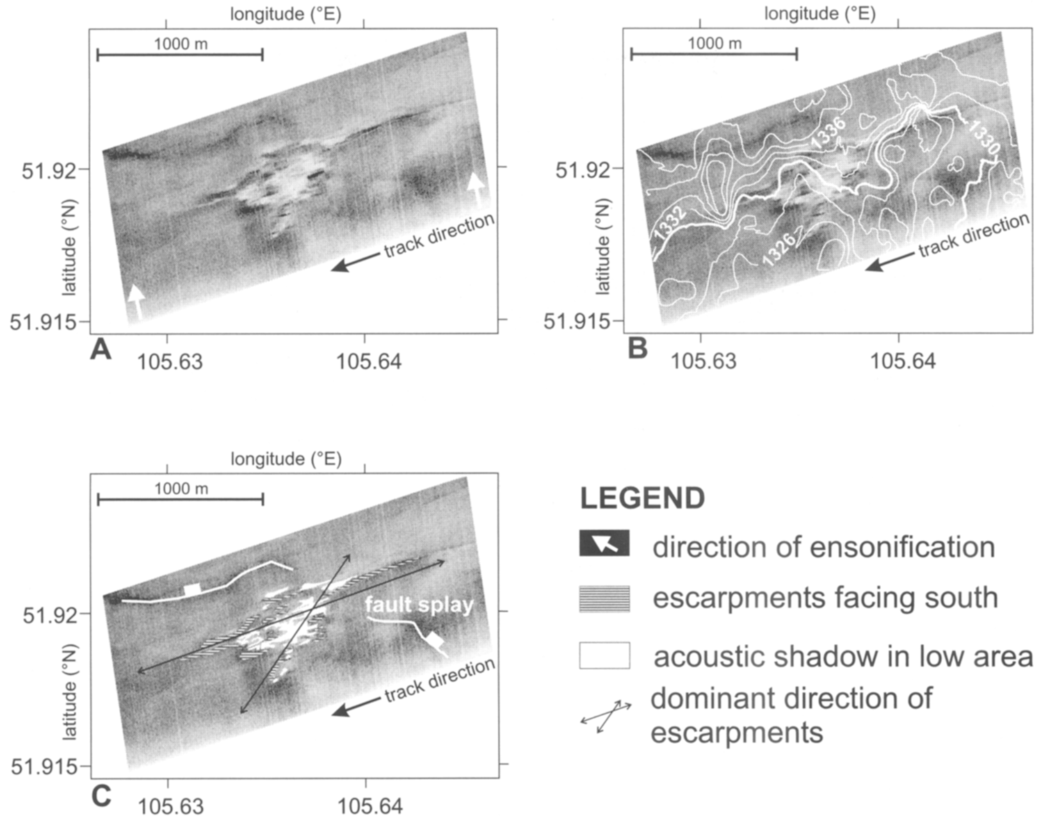


Fig. 4. Detail of the side-scan sonar image of the Malenki crater (A), with overprint of bathymetry from echo-sounding surveys (B), and interpretation (C).

Low-relief craters. Malenki and Malyutka are located next to the southern fault splay. At Malyutka the fault splay orientation is parallel to the main fault trace (070°N); at Malenki the fault splay has turned to the more southerly direction (110°N). Short parallel fault escarpments, again with a 070°N orientation, are observed at both craters. At Malenki, one larger fault escarpment runs parallel to the northern fault splay direction (020°N).

Malenki (Fig. 4) is the larger of the two craters, it has a maximum depth of 8 m and a diameter of about 500 m. Malyutka is only 200 m wide. At both sites, seep activity reveals itself on echo-sounding data as a 10–15 m high reflective plume in the lake water.

The base of the hydrate stability zone (BHSZ) is generally marked on seismic records by a BSR, a continuous high-amplitude reflection sub-parallel to the lake floor and not affected by intra-basin fault traces or dipping stratigraphic reflections (Kvenvolden 1998). On high-resolution seismic data, such as the data used in this study, a BSR does not appear to consist of a continuous high-amplitude reflection but of a series of bright spots attributed to free gas pockets accumulated below the BHSZ (Vanneste *et al.* 2001). In Lake Baikal, the depth of the BSR corresponds well to the theoretical depth of the BHSZ (Vanneste *et al.* 2001), hence it is considered here to be a good approximation for the depth of the BHSZ. It has to be mentioned that in some marine hydrate provinces the correlation between BSR and BHSZ is ambiguous. Reflections similar to a BSR may occur both within the hydrate stability zone (e.g. Mienert & Posewang 1999; Nouzé & Baltzer 2003) as well as below the BHSZ (Xu & Ruppel 1999; Wood & Ruppel 2000).

In the study area, bright gas-enhanced reflections reveal an undulating BHSZ, strongly disrupted in the footwall of the antithetic fault (Fig. 5). They appear to be displaced along faults although their apparent vertical displacement is in places much larger than the actual fault displacement. Their distribution indicates that in places the BHSZ shallows up to a sub-bottom depth of about 150 m in the footwall block of the fault (as opposed to *c.* 400 m in the surrounding areas). The fault segment along which this occurs is about 10 km long; adjacent segments

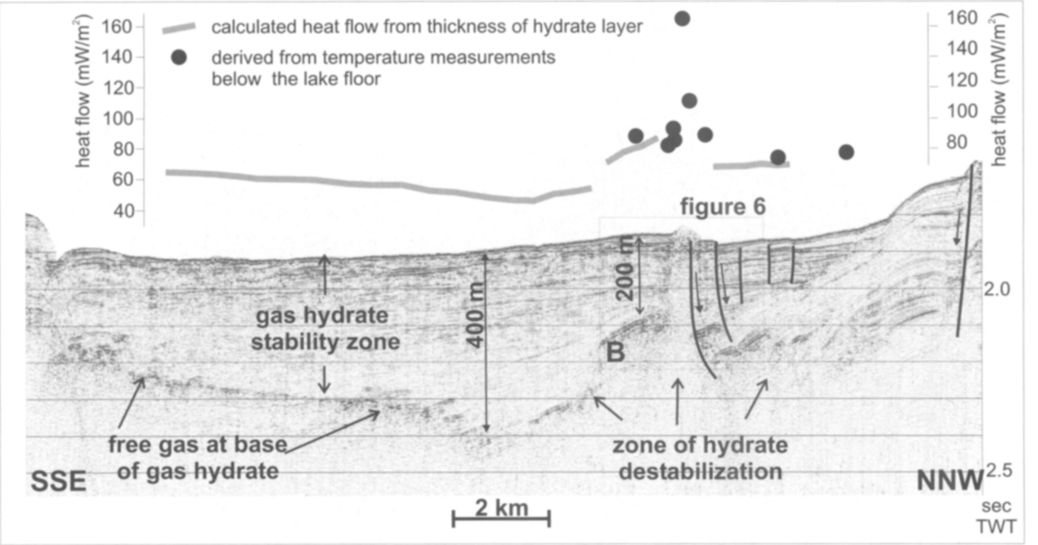


Fig. 5. Airgun seismic profile GAHY030 through the Malenki seep shows enhanced reflections at the base of the hydrate stability zone shallowing towards the Malenki vent site. Heat flow values calculated from the depth of the base of the hydrate layer and heat flow values derived from *in situ* thermoprobe measurements along the profile are plotted above the seismic section.

of the same fault show no anomalies in the BHSZ morphology.

On a seismic profile through the Malenki seep area (GAHY030), a narrow vertical zone of chaotic reflections – a 'seismic chimney' (Fig. 6) – extends up to 200 m high, from the crest of the dome-shaped BHSZ to the seep at the lake floor. Such a 'seismic chimney' is most commonly interpreted as a vertical fluid conduit caused by hydraulic fracturing of the overburden by overpressured, often gas-charged, fluids (Van Rensbergen *et al.* 1999). The apparent width of the 'seismic chimney' is due to noise caused by acoustic velocity effects at shallow depth and does not represent the true width of the fluid conduit. Except for a few high-amplitude reflections immediately below the lake floor, no amplitude enhancement (indicators of free gas accumulations) or blanking (a possible indication of dense hydrate accumulations) occur along the 'seismic chimney'.

There are no traces of sediment outflows on the side-scan sonar data (Fig. 4) or on the high-resolution seismic data, nor is there any indication of past sediment deformation in the seep area (Fig. 6). This characteristic surface and subsurface expression, lacking extrusive mudflows or well-developed craters, suggests that the Malenki and Malyutka seeps are young features. The striking parallelism of escarpments within both seep areas with fault orientations indicates a close connection between the formation of the Malenki and Malyutka seeps and the present stress regime.

Mud cones at the lake floor. Bolshoy is the largest of the four vents. It appears as an irregular cone 24 m high and 800 m in diameter (Fig. 7), about 500 m SE of the antithetic fault trace. On side-scan sonar images, the Bolshoy cone appears to be composed of several smaller cones giving a rough appearance to the slopes. Lake-floor sediments accumulate against the NW flank of the cone, locally smoothing the irregular topography and causing a difference in level of 10 m between the opposing sides of the mud cone. Erosional moats occur at the southern and northern flanks of the cone. Again, the side-scan sonar data show no traces of mudflows at the lake floor. An area of anomalously low backscatter occurs at the apex of the cone on side-scan sonar images and is attributed to gas venting from the Bolshoy cone. On echo-sounding data parts of the Bolshoy area are obscured below a 15 m high reflective plume in the lake water. Stari lies about 2 km south from the fault trace. It is an ellipsoidal mound about 500 m long with an irregular surface and a maximum height of 10 m. Some visible lineaments may indicate fault escarpments but the parallelism characteristic for the Malenki and Malyutka craters is lacking. Seismic profiles about 1 km away from Stari do not show any sediment deformation features related to the Stari seep.

There is no seismic line through the larger Bolshoy seep but the closest seismic profile (GAHY023) shows gas trapped at the margin of the dome-shaped BHSZ (Fig. 8). The BHSZ has an

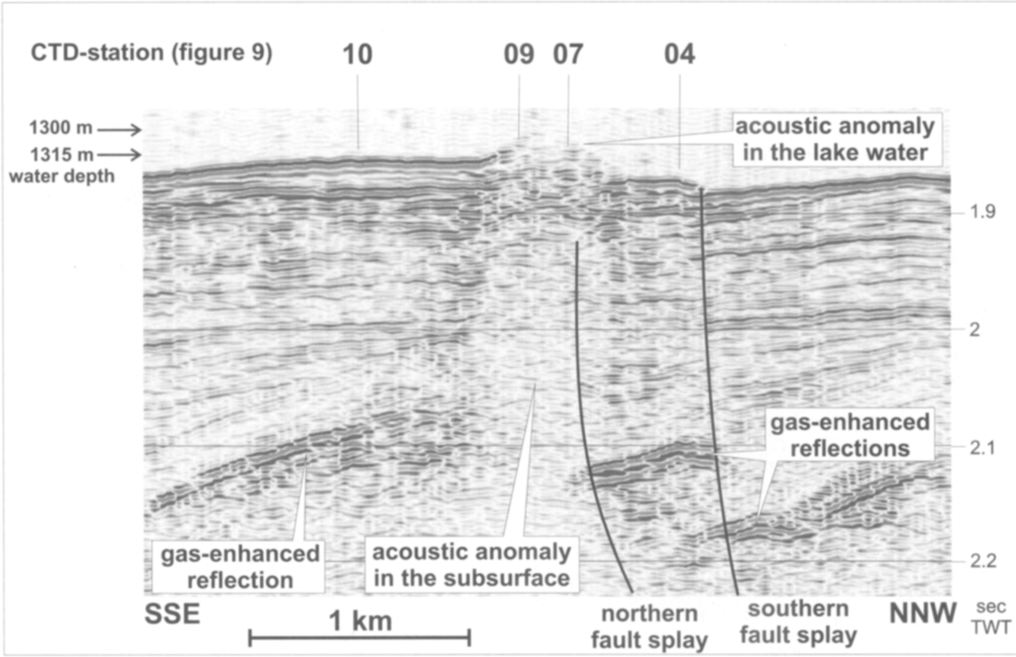


Fig. 6. Detail of the high-resolution seismic section at the Malenki crater shows a vertical feeder pipe from the base of the hydrate layer to the lake floor. Methane bubbles escaping at the Malenki crater probably cause acoustic reflections in the water columns.

irregular mushroom shape within the crest of the rollover structure in the footwall of the antithetic fault. Extraction of the average energy (square of the reflection strength) in the seismic profile GAHY030 emphasizes the amplitude differences (Fig. 8b). Bright reflections occur below the BHSZ, most likely generated by small pockets of free gas. Bright reflections also occur below small (200 m deep, 500 m wide, up to 20 m thick) reflection-free lenses. These are interpreted as gas pockets below shallow mudflow lenses or below shallow gas hydrate accumulations. In a 100 ms (about 80 m) thick zone directly above the BHSZ, amplitude blanking can be observed across different seismic facies. Although amplitude blanking is not a direct indicator of gas hydrate and vice versa, it is probable that its occurrence is due to the presence of gas hydrate in the pore spaces of the sediments, effectively reducing impedance contrasts within the sediment (Rowe & Gettrust 1993). On the seismic line GAHY023, shallow sedimentary disturbances that may be related to mud extrusion at the Bolshoy seep are covered by a drape of continuous, undisturbed sediment about 20 m thick. It confirms the interpretation from the side-scan sonar data that no mud extrusion occurred recently and that the mud volcano is being buried by lake-floor sediments. Applying an average sedimentation rate of 0.3 mm/yr (Colman *et al.* 1996), the timing of mud extrusion can be roughly estimated at 50–100 ka. On this basis, the Bolshoy and Stari cones are interpreted to be older than the Malenki and Malyutka seeps.

The Bolshoy and Stari cones are different from the low-relief craters. They are characterized by mud extrusion at the lake floor during some phase of their evolution but not in recent times. Their location and morphology does not show as strong a relationship with active faults as the two low-relief seeps.

Heat flow anomalies and their implications for the source of methane

Detailed heat flow data were obtained from thermal gradient and thermal conductivity measurements in the upper 2 m of the lake sediment at 23 stations in the study area. These *in situ* measurements are compared with calculated heat flow values obtained from the depth of the BHSZ on seismic data, following the procedure of Golmshtok *et al.* (2000). Along profile GAHY030 through the Malenki seep, the correlation between measured heat flow values and values inferred from the depth of the BHSZ is very good, the difference is only about 5% (within the range of the methodological error). In exception, a high peak value was measured in the Malenki seep where the

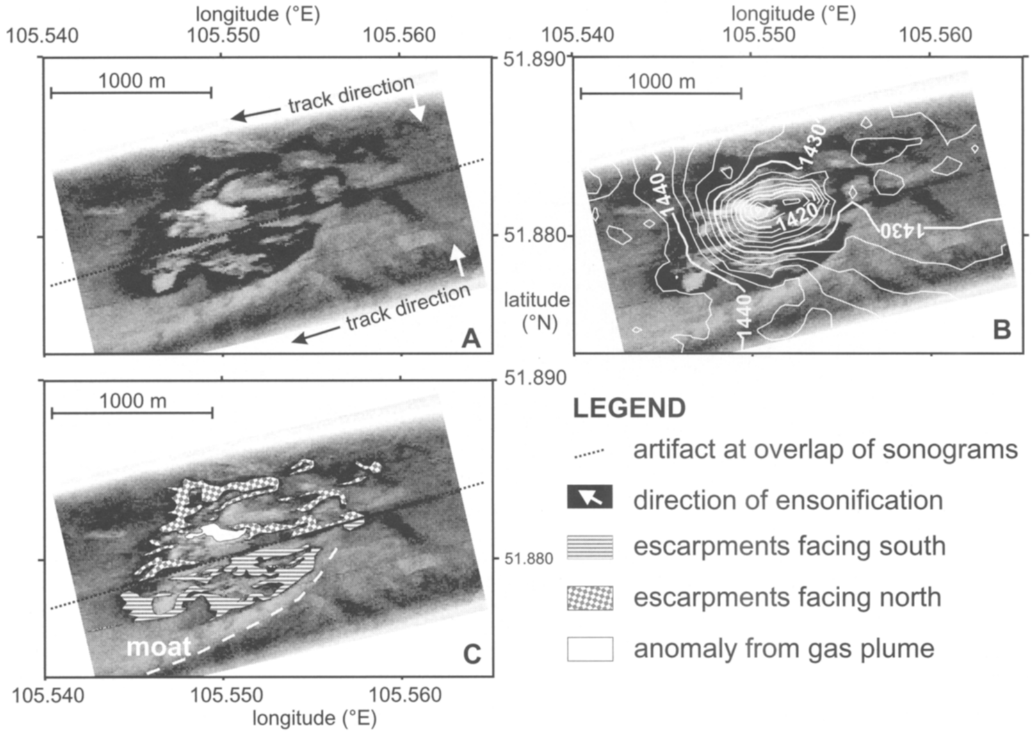


Fig. 7. Detail of the side-scan sonar image of the Bolshoy mud cone (A), with overprint of bathymetry from echo-sounding surveys (B), and interpretation (C).

corresponding BHSZ cannot be detected on seismic data (Fig. 5).

Near the Malenki seep, *in-situ* measured heat flow varies between 55 mW/m^2 and 110 mW/m^2, slightly higher than the average heat flow values for the SBB (50–70 mW/m^2). In the Malenki seep crater a peak value of 165 mW/m^2 was measured, which is much higher than any other measurement in this part of the SBB. The shape of this local heat flow anomaly is typical for the upward flow of warm fluids and quite similar to the local heat flow anomalies observed at thermal springs in the NBB (Golubev 2000)

A contour map of inferred heat flow (Fig. 9), derived from the thickness of the BHSZ, shows the dome-shaped zone of the base of the hydrate-bearing sediment layer in the footwall of the antithetic fault (Vanneste 2000). The map is not accurate near the Bolshoy seep because of the outline of the seismic grid. Two areas of maximum heat flow are inferred, one in the vicinity of the Bolshoy seep and one associated with the Stari/Malyutka seeps. The Malenki seep, where the highest measured heat flow values were made, is located laterally from the inferred heat flow maximum. This again suggests that the base of the hydrated-sediment layer is not in equilibrium with temperatures at the BHSZ.

Near bottom water properties in the Malenki seep area

Nine vertical CTD casts are located at and around the Malenki crater. Figure 10 shows a series of four CTD casts measured within a few hours of each other (see station locations on Fig. 6). The data show a small positive temperature anomaly and a negative anomaly in oxygen concentration, but no significant variations in light transmissivity or conductivity. The temperature and oxygen anomalies occur in an interval of 60 m above the NW part of the crater. To the NW of the crater, this anomaly occurs in an interval between 70 m and 125 m above the lake floor. These temperature and oxygen anomalies are transient phenomena: CTD casts at almost the same locations measured a week earlier do not show any significant anomalies.

At station four, the average temperature increase over the anomalous temperature interval is 1.5 ± 0.7 mK; the average negative oxygen anomaly over the interval is about 0.087 ± 0.024 mgO_2/kg. The temperature and oxygen anomalies can be attributed to the oxidization of methane. The measured average oxygen deficiency corresponds to an oxidization of 1.36×10^{-6} mole/l CH_4 free gas, which results

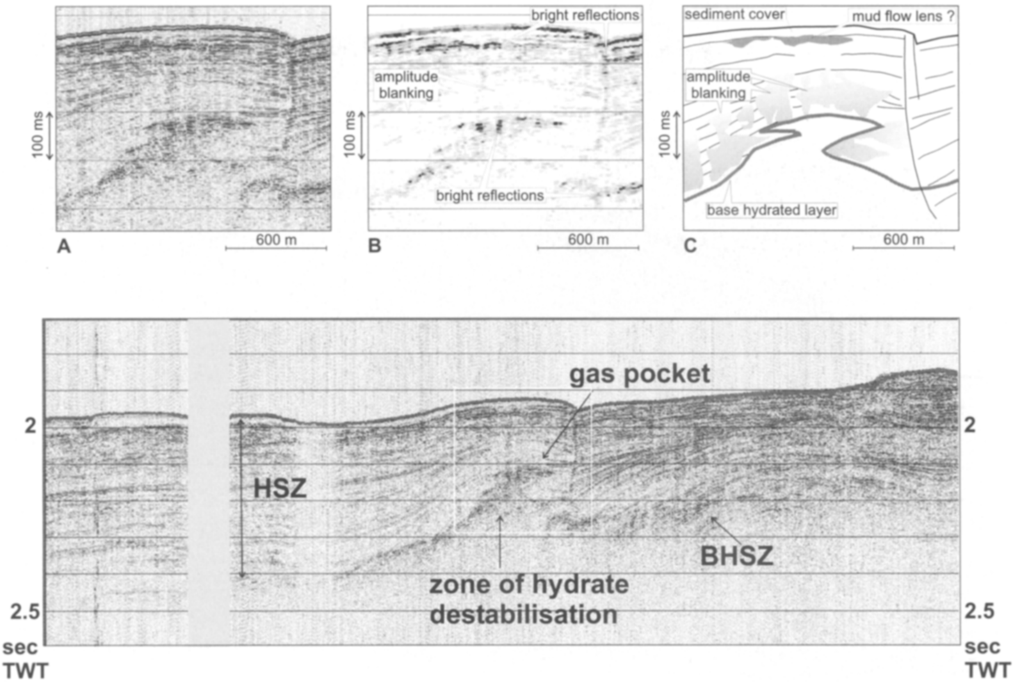


Fig. 8. A. Airgun seismic profile GAHY023 near to the Bolshoy seep shows again a shallowing base of the hydrate layer towards the seep.
B. A detail of the high-resolution seismic profile shows a free-gas pocket trapped below the dome-shaped base of the hydrate layer.
C. The relative energy attribute (square of the reflection strength) highlights bright spots caused by free gas in the sediment, as well as amplitude blanking, a possible indicator of hydrate-bearing sediments.
D. An interpreted line drawing combines observations from seismic attribute analysis.

in an estimated temperature increase of about 0.3 ± 0.1 mK. The estimated temperature increase is in agreement within a factor of two of the measured average temperature increase within the anomaly interval. The anomaly can therefore be explained by oxidization of rising CH_4 and is related to the reflective plume observed on echo-sounding data. At Station seven, located at the Malenki seep and within the area covered by the acoustic plume, the temperature anomaly starts abruptly at 13 m above the lake floor, at the top of the plume. To the north, outside the area covered by the acoustic plume, the temperature anomaly shifts to higher levels. The acoustic plume in the lake water is therefore attributed to rising methane bubbles at the seep dissolving in the water column. Once dissolved, methane will oxidize to CO_2. Deep water currents and the initial jet of the upward moving methane bubbles will cause the buoyant dissolved methane cloud to drift away from the active degassing site of Malenki. As a result, we assume that the temperature and oxygen anomalies related to methane oxidation are found at higher levels in Station four, located about 600 m NW of the Malenki crater.

These observations indicate that it is probable that only methane is escaping at the Malenki crater. If other fluids are expelled at Malenki they cannot be much different from the lake water in terms of temperature and salinity.

Discussion

Geochemical characteristics of shallow hydrate at the Malenki seep area

At the Malenki site, shallow gas hydrate accumulations are found at sub-bottom depths of 16 to 42 cm. This shallow gas hydrate is restricted to the Malenki seep area and occurs independently from the deeper, laterally extensive hydrate layer. Gas hydrate samples were analysed for the gas composition by Matveeva *et al.* (2000), sediment pore water was sampled and analysed by Matveeva *et al.* (2000) and Granina *et al.* (2001).

In the shallow gas hydrate layer, hydrate occurs as

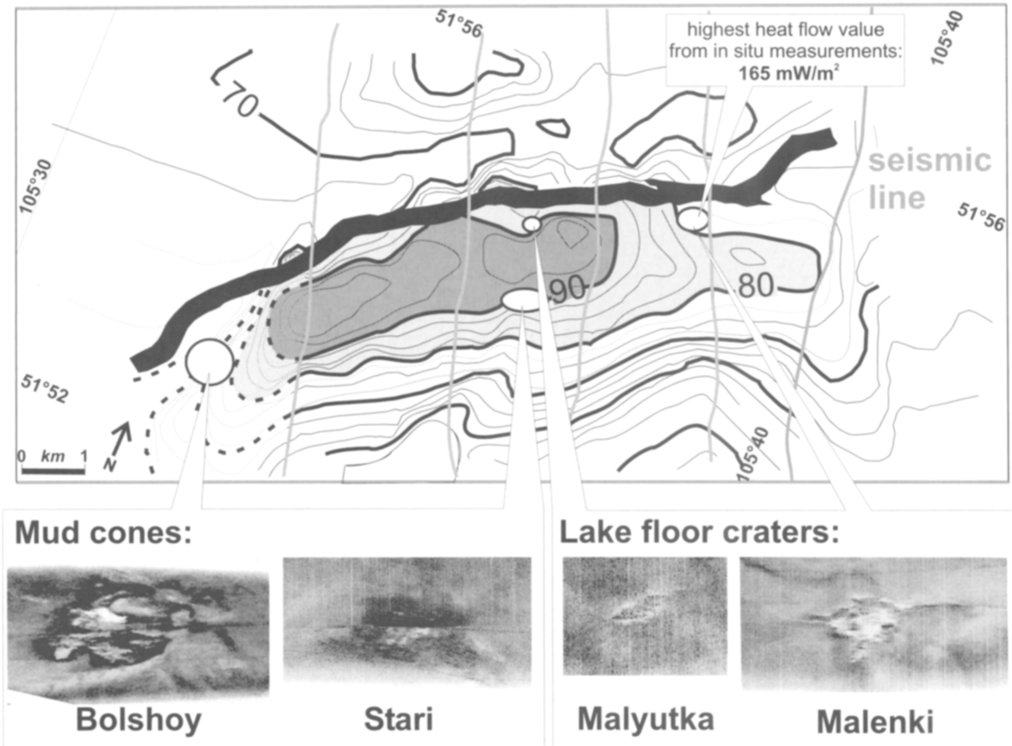


Fig. 9. Heat flow map based on heat flow values calculated from the thickness of the hydrate layer along the seismic lines. The SW part of the map (hatched lines) is unrealistic due to poor data coverage. The positions of the mud cones and craters in relation to heat flow and structure are indicated.

massive lumps of up to 7 cm in diameter, and as cm-sized inclusions throughout the muddy host sediment. At spontaneous degassing, the clathrated gas consists (by volume) of 99.0% methane with minor to trace amounts of ethane (0.11%), propane (2.10^{-4}), butane (3.10^{-4}), nitrogen (0.4%) and carbon dioxide (0.5%) (Matveeva *et al.* 2000). The C1/C2 ratio is 900, which is according to Sloan (1998) indeterminate to the thermogenic (C1/C2 < 100) or biogenic (C1/C2 > 1000) origin of the gas in the sample. The relative absence of propane suggests a biogenic origin (Sloan 1998) but it may also be a mixture of biogenic with some hydrocarbons from a deeper, thermogenic, source.

The pore waters in the Malenki seep area show a typical increase in chloride and sulphate concentrations compared to average pore water composition in Lake Baikal. Granina *et al.* (2001) found that the mean concentration of chloride in sediment pore waters (11.8 mg/l) is 15 times higher compared to average pore water concentration in SBB (0.8 mg/l). At the same location, Matveeva *et al.* (2000) also found the ion content increasing from *'near-bottom lake water'* over *'sediment pore water'* to *'water from gas hydrate-bearing sediments'*. A similar evolution exists for oxygen and deuterium isotopic compositions that become heavier from lake water to water in hydrate-bearing sediment, indicating isotopic fractionation during hydrate formation (Matveeva *et al.* 2000). Matveeva *et al.* (2000) reported also that 'very dense' sediments with low water content occurred above the hydrate-bearing interval. Shallow hydrate formation from a flow of free gas, in this case originating from the BHSZ, will draw water from the surroundings (Ginsberg & Soloviev 1997) and can create haloes of saline water due to incomplete diffusion of excluded salt together with water depletion in the vicinity of concentrated hydrate lenses (Clennell *et al.* 1999).

Both Matveeva *et al.* (2000) and Granina *et al.* (2001) interpret the data as evidence of injection of saline thermal water into the shallow subsurface sediments. In our opinion, the effect of ion exclusion by hydrate formation can cause the observed geochemical and isotopic signatures. The measurements are considered normal for shallow hydrate-bearing sediment in a gas seep area and do not – in our opinion – provide evidence for injection of thermal water into shallow sediment. This interpretation also fits with the CTD measurements at the

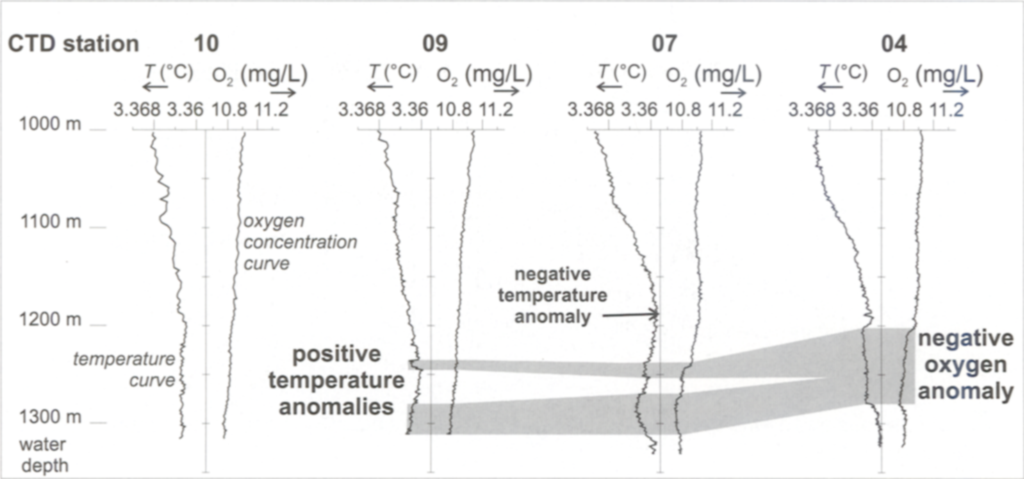


Fig. 10. Temperature curves and oxygen concentration curves from 4 CTD stations projected onto the seismic section show the good correlation of a positive temperature anomaly with a negative oxygen anomaly attributed to oxidization of methane in the near-bottom Baikal water.

Malenki seep where no expulsion of saline or warm fluids was detected.

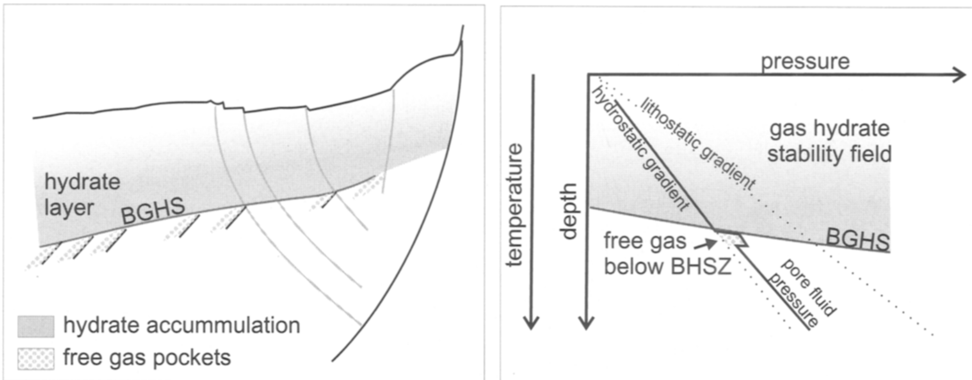
Integration of results

The observed methane seeps and mud cones in Lake Baikal occur in an area of subsurface gas hydrate accumulation and of varying heat flow within a larger region of elevated heat flow. The variations in heat flow are interpreted to result from migration of thermal water along active fault segments and dipping permeable beds. Heat redistribution by infiltrated meteoric water is inferred to be the cause of heat flow variations in all of the Baikal sub-basins (Golubev 2000). The narrow, high-amplitude heat flow anomaly at the Malenki seep is interpreted to be a short-term event, not a steady-state situation. Consequently, it is interpreted, on the basis of the arguments below, that a pre-existing, laterally continuous hydrate layer was locally affected by a recent elevation of heat flow at the BHSZ, about 400 m subsurface (Fig. 11).

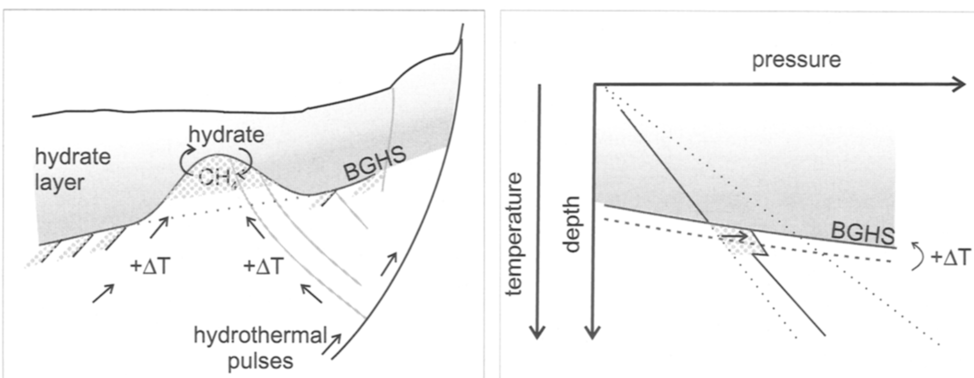
The arguments for the seeps being the result of a recent perturbation of the regional geothermal field and local decomposition of a pre-existing hydrate layer are as follows:

(1) Active seeps are limited to the area above the anomaly, there are no seeps observed in the area with regular BSR.
(2) The active seeps and mud diapirs are young features (estimated <100 ka), there is no indication of any older activity on the high-resolution seismic data.
(3) The young age of the seeps is in agreement with the heat flow data that indicate a non-equilibrium condition exist at the site of the Malenki seep.
(4) The Malenki seep appears to be a gas seep; no warm fluids are expelled. This indicates that there is no direct fluid-flow pathway from the deep subsurface to the sediment surface.
(5) A gas chimney occurs in the shallow subsurface at the site of the Malenki seep. Because of point four, the gas chimney probably roots in the zone of elevated BSR and extends from the top of the updoming BSR to the lake floor. This indicates that overpressures below the dome-shaped BHSZ increased to values greater or equal to the fracture gradient. Since the rate of overpressure increase was much higher than the rate of pore fluid pressure dissipation, it indicates a relatively rapid overpressure increase.
(6) Shallow hydrate accumulated just below the sediment surface in the Malenki seep crater. Despite numerous cores, no shallow hydrates were found outside of the Malenki crater. The gas in the shallow hydrates is most likely of bacterial origin, possibly a mixture with gas of thermogenic origin, and does not have the geochemical signature of gas migrating directly from deeper thermogenic sources.

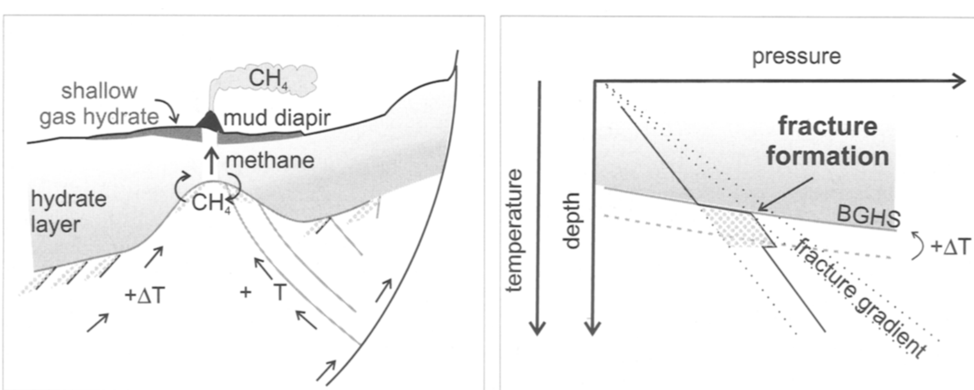
Figure 11 shows the interpreted suite of events following a heat pulse at the base of the hydrated sediment layer. Heat transfer to the BHSZ probably caused the rise of the BHSZ to the present depth of about 150 m in the seep areas. The gas release from



A. Continuous gas hydrate layer, possibly with free gas pockets at the base of the hydrate stability zone (BHSZ)



B. A thermal pulse shifts the BHSZ upwards, methane is released from hydrate decomposition, and pore fluid pressure below BHSZ rises.



C. Gas blow-out occurs when pore fluid pressure reaches the fracture gradient. Shallow hydrates form out of the gas flow below the sediment surface and draw water from the surroundings. Mud may be extruded as a stiff plug into a mud cone.

Fig. 11. Conclusion cartoon showing the inferred decomposition of a laterally continuous hydrate layer (A) by a pulse of increased thermal flux at the base of the hydrate layer (B, C).

hydrate decomposition is accompanied by an increase in pore fluid pressure, as one volume of methane hydrate may hold 150–180 volumes of free gas (Kvenvolden 1988). Pore fluid pressure at the BHSZ probably rose up to the fracture gradient and caused formation of vertical fractures and gas expulsion. The occurrence of young active seeps and mud diapirs illustrates the forcible nature of the gas expulsion. In the seep areas, local shallow hydrate formed out of the flow of free gas and accumulated almost immediately below the sediment surface. The shallow hydrates have a halo of saline pore water and isotopically heavier oxygen.

Initially, oceanic gas hydrates were also interpreted to be the source of mud volcanoes but over the years, more detailed measurements established the deep origin of methane expelled at the sea floor and of methane in hydrate. We do not wish to exclude this possibility but except for the disagreement with oceanic studies, there is no indication of a direct transfer of methane from a deep source. The bulk of the hydrated gas, sampled in a deep core of the Baikal Drilling Project, is of bacterial origin (Kuzmin *et al.* 1998) and formed via methanogenesis of organic matter supplied by the Selenga River. There are no alternative sources of biogenic or thermogenic methane known in Lake Baikal. Based on the observations above it is inferred that the largest available source of gas in Lake Baikal is probably the extensive hydrated sediment layer that occurs to a depth of about 300–400 m.

The Malenki seep is a gas seep; there is no indication of seepage of mineralised or thermal waters in the Malenki area. The entire expulsion mechanism seems to be driven by free gas; methane hydrate dissociation releases large amounts of free gas; free gas is expelled at the Malenki seep and only goes into solution after it enters the lake water. Shallow gas hydrates at the Malenki seep also from out of free gas and pore water. Additionally, shallow hydrate formation will extract fluids form the sediment, further decreasing the likelihood of fluid expulsion and fluidization of the sediment. The crater morphology is therefore not shaped by mudflows. The Bolshoy and Stariy cones may be extruded as a stiff plug of sediment without fluidization. The driving force of the mud extrusion may be the buoyancy of the gas-charged sediment, possibly in combination with a pore fluid pressure gradient.

On the basis of morphology, localization and probably also age, the four seeps can be grouped into mud cones (Bolshoy and Stari) and low-relief craters (Malenki and Malyutka). Malenki and Malyutka seem to be recent features located along active fault segments. Thermal waters responsible for hydrate dissociation at the BHSZ most likely migrated upwards along these active fault segments. Bolshoy and Stari especially are older features (estimated to be about 50–100 ka old). They are located away from the fault at the crest of the rollover structure in the footwall of the antithetic fault. Thermal fluids may have migrated upwards along tilted, permeable beds. The difference in morphology may be caused by the age of the seeps (older seeps having extruded a plug of mobilized mud), but may also be related to the localization of the seeps. Fluid flow along the antithetic fault segment in the study area may be recent but also ephemeral, causing short-lived pulses of gas escape, whereas thermal fluids focused in structural traps may form a more constant source of heat, releasing larger quantities of methane.

Methane seeps attributed to hydrate decomposition are quite common in oceanic hydrate provinces. In these contexts, the methane is considered to originate from the regional, gradual (bottom-up) destabilization of hydrates at the BHSZ and the BHSZ is usually not characterized by distinct anomalies. Methane is usually released at the sea floor by dispersed seepage over large areas, e.g. in pockmark or crater fields (Ginsberg 1998; Solheim & Elverhoi 1993) or by more focused escape along faults (Ginsberg *et al.* 1993; Mienert & Posewang 1999; Suess *et al.* 1999; Wood & Ruppel 2000). Such methane seeps are usually not accompanied by sediment extrusion at the sediment surface. The Lake Baikal example seems to indicate that localised destabilization of hydrates may create large overpressures in the shallow subsurface (<500 m) and that the consequent gas blow-out is capable of mobilizing and extruding subsurface sediments.

Conclusions

In this paper, we investigated in detail the nature, morphology and structure of lake floor seeps that occur in Lake Baikal. These are the first gas seeps and mud volcanoes associated with gas hydrate discovered outside the marine environment. The seeps were encountered in the South Baikal Basin in an area with peculiar anomalies in thickness of the hydrate-bearing sediment layer. Measurements of near-bottom water properties, surface data (side-scan sonar and bathymetry) and subsurface data (high-resolution seismic profiles, heat flow data, and geochemical studies) are combined into an integrated study of the seeps and associated mud mobilization features.

The seeps are gas seeps without much, if any, expulsion of associated fluids. The gas seeps occur as low-relief craters or mud cones. Mud cones appear to be older than craters and have a different structural setting. Mud cones occur at the crest of rollover structures, in the footwall of a secondary normal fault. The craters occur at fault splays and are dissected by numerous escarpments parallel to the main fault direction. The gas seeps are located in areas of elevated heat flow where the base of the hydrate stability zone (BHSZ) moves upwards from about 350 m to about 150 m below the lake floor. At the Malenki site, the surface seep is directly connected with the base of the hydrate stability zone through a vertical 'seismic chimney', interpreted as a feeder pipe. A shallow accumulation of gas hydrate was found in short cores in the Malenki seep area.

Active gas seeps in a hydrate provinces are most often the result of a gas flow from deep subsurface hydrocarbon systems and hydrates are often only a side product of this gas flow. In this case however, it is interpreted that the seeps are caused by an ongoing process of focused hydrate decomposition and associated massive methane escape. This rare example of focused gas flow from hydrate decomposition, at this moment in geological time, may be due to the combination of thick hydrate accumulations in an active rift characterized by numerous heat flow anomalies. A heat flow anomaly at one of the active seeps is interpreted to be a young feature, probably due to a recent influx of thermal fluids in the subsurface and probably caused focused destabilization at the base of the hydrate accumulation zone. The expulsion of large quantities of methane creates craters at the lake floor but also seems capable of extruding mud, most likely without much sediment fluidization.

Our interpretation of the Baikal gas seeps suggests that gas hydrate destabilization can create large pore fluid overpressures in the shallow subsurface (<500 m subsurface) and cause mud extrusion at the sediment surface.

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