Geology

Sublacustrine mud volcanoes and methane seeps caused by dissociation of gas hydrates in Lake Baikal

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Notes

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ABSTRACT

Four lake-floor seeps have been studied in the gas-hydrate area in Lake Baikal's South Basin by using side-scan sonar, detailed bathymetry, measurements of near-bottom water properties, heat-flow measurements, and selected seismic profiles in relation to results from geochemical pore-water analysis. The seeps at the lake floor are identified as methane seeps and occur in an area of high heat flow, where the base of the gas-hydrate layer shallows rapidly toward the vent sites from ~400 m to ~150 m below the lake floor. At the site of the seep, a vertical fluid conduit disrupts the sedimentary stratification from the base of the hydrate layer to the lake floor. The seeps are interpreted to result from local destabilization of gas-hydrate caused by a pulse of hydrothermal fluid flow along an active fault segment. This is the first time that methane seeps and/or mud volcanoes associated with gas-hydrate destabilization have been observed in a sublacustrine setting. The finding demonstrates the potential of tectonically controlled gas-hydrate destabilization to cause extreme pore-fluid overpressure and short-lived mud volcanism.

Keywords: gas hydrates, hydrothermal vents, Lake Baikal, methane, mud volcanoes, seepage.

INTRODUCTION

In the marine environment, gas hydrate below the seafloor is at places associated with methane seeps at the seafloor, marked by pockmarks, fluid vents, authigenic carbonate precipitation, and sometimes mud volcanism. The methane seeps are often interpreted to result from gas-hydrate destabilization, but it is difficult to differentiate the effect of gas-hydrate dissociation from other sources of fluid and gas. Whether hydrate formed out of upward methane-charged fluid flow or whether methane expulsion or mud volcanism results from decomposition of gas hydrates often remains a "chicken or the egg" problem.

In modern rift lakes (e.g., Lake Baikal, Lake Tanganyika), fluid seeps are most commonly hydrothermal in origin and occur along permeable, active faults in zones of elevated heat flow (Crane et al., 1991; Tanganydro Group, 1992). Hydrothermal seeps are in general not accompanied by mobilization and expulsion of subsurface sediment. More than 50 hot springs associated with large heat-flow anomalies have been mapped in the Baikal rift zone, essentially in the North and Central Basins (Golubev et al., 1993). At an offshore hydrothermal seep in Frolikha Bay, Baikal North

Basin, heat flow reaches 8600 mW/m^2 (Crane et al., 1991), and the flow of hydrothermal saline water from the seep can be traced within the freshwater basin (Kipfer et al., 1996). In the Baikal South Basin, heat flow varies between 50 and 100 mW/m^2 in a regular pattern without such large isolated anomalies (Golubev et al., 1993; Poort et al., 1998).

Lake Baikal is one of the world's largest rift lakes and the only freshwater basin with proven gas hydrates. Hydrates were found and sampled in a 225-m-long Baikal Drilling Project (BDP) core from the South Basin (Kuzmin et al., 1998). Gas from the hydrate samples consisted mainly of methane (99% of total hydrocarbons) of biogenic origin (carbon isotope composition $\delta^{13}C$ between $-58‰$ and $-68‰$; Kuzmin et al., 1998). In Lake Baikal there are no known sources of thermogenic gas, and the gas of the gas hydrate is probably derived from organic matter supplied by the Selenga River, the main source of terrigenous organic supply to the lake. The hydrates occur around the Selenga River delta (Fig. 1) at water depths of >580 m. The study area is located in a zone where multichannel seismic profiles show the base of the hydrate stability zone (BHSZ) to be irregular, not at all mimicking the lake floor as a bottom-simulating reflector (Golmshtok et al., 2000).

METHODS AND DATA

The data discussed are located in a study area of ~15 km × 16 km in the Baikal South Basin in a water depth of 1320–1440 m. In this study area, a side-scan sonar mosaic (Fig. 2) covers an area of ~90 km^2. The 30 kHz SONIC sonar imaged 0.8 km at each side of the track line, and the across-track footprint of the acoustic beam ranged from 0.75 m to 3.8 m. In addition, 9 single-channel airgun seismic reflection profiles (total length ~180 km) were obtained using a 3 L Impulse-1 airgun (frequency range of 45–330 Hz) with a penetration as deep as 700 ms two-way traveltime (~560 m) and a vertical resolution of ~3 m. Thermal-probe measurements (n ~ 30) were taken along two seismic profiles to calculate the lateral variation in heat flow (assuming purely conductive heat flow). The seeps were studied in detail by using conductivity-temperature-depth (CTD) casts (and measurements of light transmission and oxygen concentration) and a 12 kHz echo sounder. In the Malenki seep area, samples of hydrates in diatom-rich silts and silty clays were retrieved from shallow hydrate accumulations (~20 cm below the lake floor).

INTERPRETATION AND DISCUSSION OF THE DATA

Morphological Expression of Seeps at the Lake Floor

The four documented seeps are Bolshoy (large), Stari (old), Malyutka (very small), and Malenki (small). Malenki and Malyutka are low-relief craters, and Bolshoy and Stari are mud cones on the lake floor. The seeps occur south of a small fault antithetic to the Posolsky fault (downthrown side to the north).

Malenki is the largest of the low-relief craters, and occupies an irregular low area dissected by fault escarpments. The seep activity is visible on acoustic data as a reflective plume in the lake water. The seep area has a maximum depth of 8 m and a diameter of ~500 m. Malyutka is a low-relief seep area of ~200 m diameter with small parallel es-

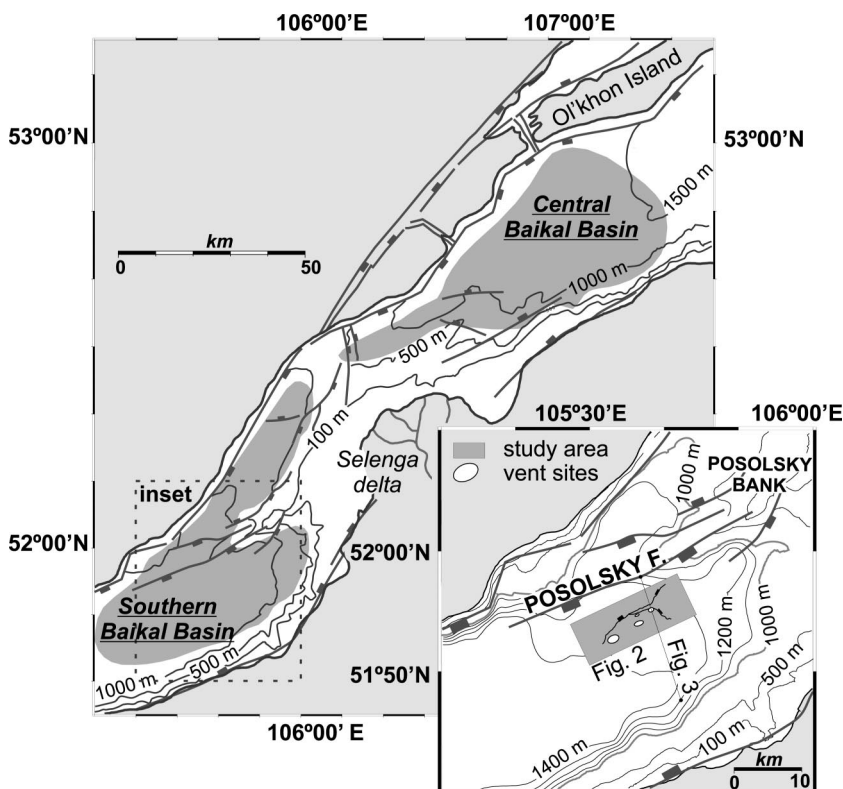*E-mail: pieter_vanrensbergen@yahoo.com.

Figure 1. Setting of study area and bathymetry within complex rift structure of Lake Baikal. Gas-hydrate accumulations (shaded regions) occur almost symmetrically around Selenga delta. Inset shows Posolsky fault and locations of Figures 2 and 3.

Relationship with Gas Hydrate and Heat Flow

The seismic reflection profiles show that the BHSZ in Lake Baikal is in general marked by a continuous high-amplitude bottom-simulating reflection (BSR) not affected by intrabasin faults or dipping stratigraphic reflections. In the study area, however, the BHSZ is irregular and strongly disrupted in the vicinity of the antithetic fault (Fig. 4A). Bright reflections, interpreted as free-gas pockets below the BHSZ (Vanneste et al., 2001), occur in patches that appear to be displaced along faults, although their apparent vertical displacement is at places much larger than the actual fault displacement. The distribution of bright reflections indicates that at places the BHSZ shallows to a subbottom depth of 150 m in the footwall block of the fault (as opposed to ~400 m in the surrounding areas). The fault segment along which this occurs is ~10 km long; adjacent segments of the same fault show no anomalies in the BHSZ morphology.

The actual seeps occur on top of narrow vertical zones of chaotic reflections—seismic chimneys—that disrupt continuous subsurface reflections on the seismic profiles (Fig. 4B). From the crest of the dome-shaped BHSZ to the lake floor, these seismic chimneys can be as high as 200 m. Such a seismic chimney is most commonly interpreted as a zone of vertical fluid conduction caused by hydraulic fracturing of the overburden by overpressured, often gas-charged, fluids (Van Rensbergen et al., 1999).

In the study area, heat-flow values from in situ thermal-probe measurements range between 55 and 110 mW/m^2, slightly higher than average heat-flow values for the Baikal South Basin (50–70 mW/m^2). The variations of the measured values correlate well with the observed changes in depth of the BHSZ. This finding indicates that the irregular morphology of the BHSZ is predominantly temperature controlled and directly related to the existence of a local anomaly of higher heat flow. At the Malenki seep, heat flow rises to 160 mW/m^2, much higher then the heat flow calculated from the depth of the BHSZ (Fig. 4A), indicating that hydrate is probably not stable at the observed depth.

At the Malenki seep, the volume of methane released by decomposition of hydrate is estimated as 3.9×10^9 m^3 (on the basis of the BHSZ morphology and according to Athy's law for porosity decrease with depth and a hydrate saturation of 10%, which was observed at the hydrate level in the BDP core). As this free gas rises, a large part of it will be fixed again in the form of gas hydrate. One example is a shallow hydrate accumulation encountered in the Malenki seep area.

carpments within the low area. The seep activity is seen on bathymetry data as well as on multichannel seismic data. The poor surface expression, lacking extrusive mudflows or well-developed craters, suggests that the Malenki and Malyutka seeps are young features.

Bolshoy is the largest of the four vents. It appears as an irregular cone 24 m high and 800 m in diameter (Fig. 3). Acoustic anomalies are present at the top of the cone. On side-scan sonar images the Bolshoy cone appears to be built from several smaller cones, giving a rough appearance to the slopes. Lake-floor

sediments accumulate against the northwest 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. The seismic data show possible lenses of extrusive mud just below the lake floor (maximum 40 m deep and as thick as 20 m) in the vicinity of the Bolshoy cone, but there is no seismic line through the center of the seep. The side-scan sonar data show no traces of mudflows at the lake floor. Stari is the farthest from the small antithetic fault. It is an ellipsoidal mound ~500 m long and 10 m high with an irregular surface.
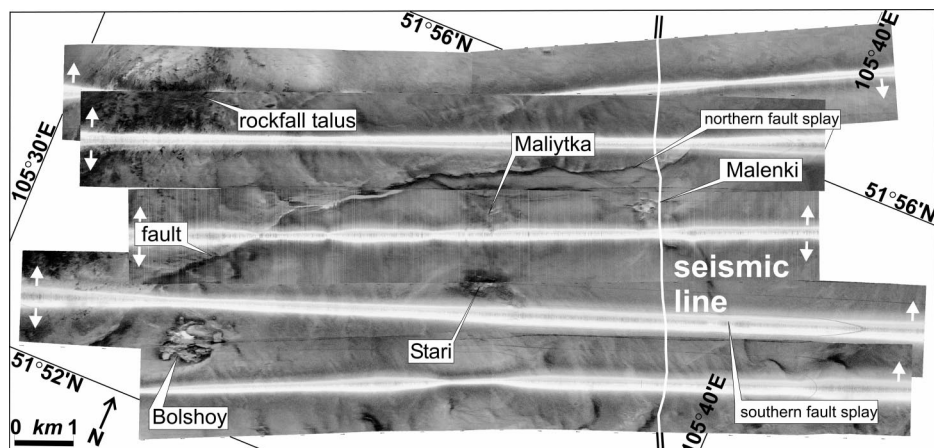

Figure 2. Side-scan sonar mosaic showing four methane seeps in their structural setting.
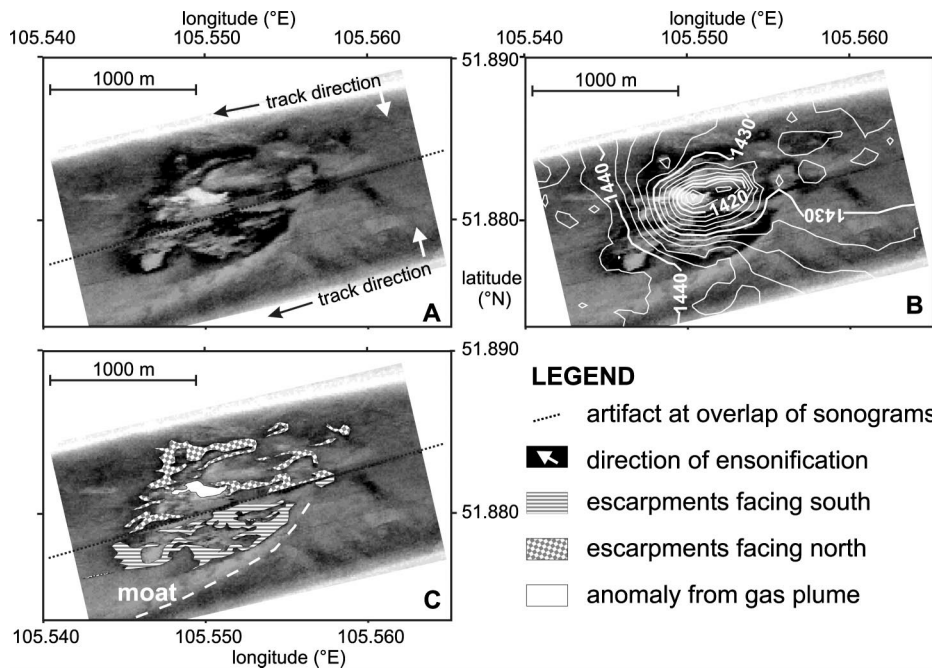
Figure 3. Detail of Bolshoy seep on side-scan sonar. Bolshoy seep is characterized by mud cone with irregular surface; its eastern flank is partly smoothed by lake-floor sediment. Low-backscatter anomaly in center represents gas cloud at apex of Bolshoy cone. A: Uninterpreted detail of side-scan sonar image. B: Side-scan sonar with superimposed bathymetry from echosounder survey. C: Interpretation highlighting irregular morphology of Bolshoy cone.

Geochemical Characterization of the Seeps

Nine vertical CTD casts are located at and around the Malenki crater. Figure 4C shows the results of a series of four CTD casts measured within a few hours time. The data show a small average positive temperature anomaly of 1.5 ± 0.7 mK and an average negative anomaly in oxygen concentration of ~0.087 $\pm$ 0.024 mgO$_2$/kg at station 04, but no significant variations in light transmissivity or conductivity. The temperature and oxygen anomalies occur in an interval of 60 m above the northwestern part of the crater (stations 09 and 07). To the northwest of the crater, this anomaly occurs in an interval between 70 m and 125 m above the lake floor (station 04). The anomalies of temperature and oxygen can be attributed to the oxidation of rising methane bubbles (R. Kipfer, 2001, personal commun.): the measured average oxygen deficiency corresponds to an oxidation of 1.36×10^{-6} mol/L of CH$_4$ in the free gas, which results in an estimated temperature increase of ~0.3 $\pm$ 0.1 mK. The estimated temperature increase is in agreement within a factor of two with the measured average temperature increase. These temperature and oxygen anomalies are transitory phenomena; CTD casts at almost the same locations measured a week earlier did not show any significant anomaly. These measurements confirm that gas is intermittently escaping at the Malenki crater. If fluids are also expelled at Malenki, they cannot be much different from the lake water in terms of temperature and salinity.

However, geochemical analysis of gas-hydrate–associated waters and subsurface pore waters in the Malenki seep area by Granina et al. (2000) showed that chloride concentrations in gas-hydrate–associated water (19.8 mg/L) and sediment pore water (11.8 mg/L) in the Malenki seep area are much higher than average concentrations in pore waters in Lake Baikal's South Basin (0.8 mg/L). An increase of chloride concentration in pore waters at the Malenki seep area is associated with an increase in sulfate concentration. The alkalinity of Baikal water is low (average HCO$_3^-$ concentration 66 mg/L; Falkner et al., 1991) and is even lower in the pore water sampled at the Malenki seep area (minimum HCO$_3^-$ concentration 12 mg/L; Granina et al., 2000), preventing carbonate precipitation. Lake Baikal is a freshwater basin with very low mineralization; hence the enrichment in chlorides and sulfates of the hydrate-associated waters and pore waters in the Malenki seep seems to suggest a deeper subsurface or onshore source. This conclusion is in agreement with the chemical and isotopic analysis of interstitial waters at the Malenki seep area by Matveeva et al. (2001). They also found an increase in mineral content in the gas-hydrate–associated waters interpreted as indications of subsurface injection of exotic fluids from deeper subsurface levels or from onshore sources along active rift faults.

Shanks and Callender (1992) explained similar geochemical signatures from hydrothermal vents in Frolikha Bay, northern Lake

Baikal, as meteoric water intrusion from on-shore mountain ranges along active rift faults and leaching of Cambrian evaporite rocks in the vicinity of Lake Baikal. The geochemical data at the Malenki seep may be interpreted similarly. Only in this case, venting of hydrothermal fluids at the lake floor is hindered by a low-permeability hydrate layer, and heat is advected from the warm hydrothermal fluids to the base of the hydrate layer.

CONCLUSIONS

The lake floor seeps in Lake Baikal's South Basin are methane seeps that occur where the base of the hydrate stability zone shallows in response to elevated heat flow. The heat-flow anomalies are most likely caused by hydrothermal activity along active fault segments in a way similar to that at hydrothermal vent sites in the Baikal North Basin. This study provides evidence that pore-fluid volume increase by localized dissociation of gas hydrate can cause an increase in pore pressure and hydrofracturing of the sedimentary overburden followed by vigorous expulsion of methane and water and extrusion of entrained mud.

The role of gas hydrates in the global carbon budget is still not fully understood. Since the discovery of submarine gas hydrates (Markl et al., 1970), the possibility of sudden destabilization and gas blowouts has been suggested with dramatic consequences for climate, sediment stability, and buoyancy of ships. These consequences have been downplayed (e.g., Kvenvolden, 2002). In fact, evidence is building that gas hydrates in seep areas accumulate as a consequence of a preexisting upward fluid flow (e.g., Makran accretionary wedge; Von Rad et al., 2000), rather than acting as a trigger for the flow. This is not the case in Lake Baikal, where methane is almost entirely of biogenic origin and where no deep sources of gas are known. Methane seeps and mud volcanoes in Lake Baikal are interpreted to be examples of vigorous gas and fluid expulsion caused by tectonically controlled gas-hydrate dissociation by an upward flow of fluids advecting heat to the BHSZ. The process is short-lived, being limited by the amount of hydrate, by the duration of the hydrothermal pulse, or by the time needed for a new equilibrium to be achieved.

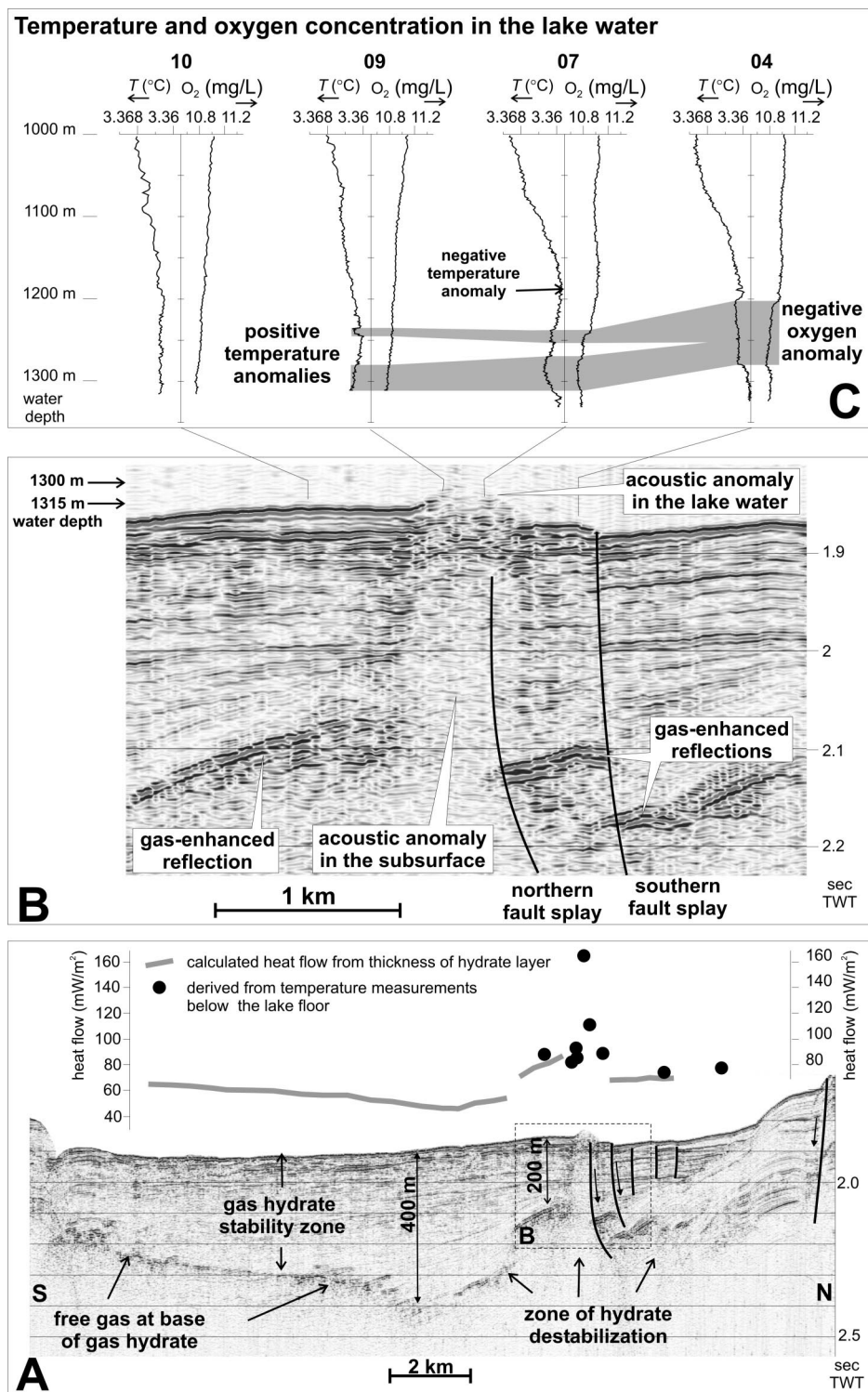## Temperature and oxygen concentration in the lake water

Figure 4. A: Seismic cross section showing localization of Malenki seep in its structural setting. Measured and calculated heat flow values are plotted along same profile. B: Detail of seismic section showing seismic chimney from crest of elevated base of gas-hydrate layer to lake floor at Malenki seep. Also shown is acoustic anomaly in near-bottom lake water. C: Near-bottom measurements of temperature and oxygen concentration indicate buoyant methane plume northwest of Malenki seep.

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