CHAPTER 6

Stratigraphic and structural controls on the location of active methane seeps on Posolsky Bank, Lake Baikal

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Abstract

The distribution and origin of shallow gas seeps occurring at the crest of the Posolsky Bank in Lake Baikal have been studied based on the integration of detailed seismic, multibeam and hydro-acoustic water-column investigations. In total 65 acoustic flares, indicating gas-bubble release at the lake floor (seepage), have been detected within the 630 km^2 area of the Posolsky Bank. All seeps are located on the Posolsky Fault scarp near the crest of the Posolsky Bank or on similar locations in water depths of -43 m to -332 m. Lake Baikal is the only fresh-water basin in the world where gas hydrates have been inferred from BSRs on seismic data and have been sampled. Our seismic data also portray BSRs occurring up to water depths of -300 m, which is much shallower than the previously reported -500 m water depth. Calculations for hydrate stability, heat flow and topographic effect based on the BSR occurrence and multibeam bathymetry allowed the determination of a methane-ethane gas mixture and heat-flow values wherefore gas hydrates could be stable in the lake sediments at the given ambient conditions. None of the seeps associated with the Posolsky Bank have been detected within this newly established gas-hydrate stability zone. Our observations and data integration suggest that the seeps at the crest of Posolsky Bank occur where gas-bearing strata are cut off by the Posolsky Fault. These gas-bearing layers could be traced down the Posolsky Bank to below the base of the gas-hydrate stability zone (BGHSZ), suggesting that the detected seeps on the crest of the Posolsky Bank are mainly fed by gas coming from below the BGHSZ.

Keywords

Methane seeps; flares; seismic reflection data; multibeam; gas-hydrate stability; Posolsky Bank; Lake Baikal

6.1. Introduction

Active methane seeps occur worldwide in the marine environment especially at continental margins, and often in association with gas hydrates (Judd, 2003; Judd and Hovland, 2007). Scientific interest in the relationship between gas hydrates and methane seeps is mostly motivated by the understanding that gas hydrates can act either as: i) buffers, sealing off the upward migration of methane and preventing gas-bubble release in the water column (Naudts et al., 2006; Haacke et al., 2007); ii) sources for methane fluid flow within the sediment and seepage into the water column (Suess et al., 1999; Reeburgh et al., 2006) and iii) sinks for methane present in the gas-hydrate stability zone (GHSZ) (Henriet and Mienert, 1998). While gas hydrates are widespread in the marine environment, their presence has up to now been demonstrated in only one fresh-water lacustrine setting, i.e. Lake Baikal (Golmshtok et al., 2000). In this tectonically active rift lake, gas hydrates are present in the deeper subsurface and as near-bottom accumulations in mud-volcano-like structures (Klerkx et al., 2006). The gas hydrates in the deeper subsurface have been proposed as the main source of the methane that is being released at the mud volcano structures and that crosses the GHSZ along active faults (De Batist et al., 2002; Van Rensbergen et al., 2002; Vanneste et al., 2002). Apart from the methane release at the mud volcanoes in the deep parts of Lake Baikal (i.e. within the GHSZ), seepage also occurs outside of the GHSZ (Granin and Granina, 2002; Granin et al., in press). The sources and controls on these shallow seeps are, however, still poorly understood. This study focuses on one of these shallow seepage areas outside the GHSZ (i.e. on the Posolsky Bank) and tries to explain the source and distribution of shallow methane-bubble release.

6.2. Study area

Lake Baikal, located in South-Central Siberia, is the deepest lake in the world (1637 m) (Galaziy, 1993; Naudts et al., submitted) (Fig. 6.1.). It contains 20% of the worlds fresh liquid surface water (23000 km^3) (Galaziy, 1993). The lake occupies 3 basins within the Baikal Rift Zone (BRZ): the North Baikal Basin (NBB), the Central Baikal Basin (CBB) and the South Baikal Basin (SBB) (Fig. 6.1.). These three basins are separated by two structural highs: the Academician Ridge Accommodation Zone (ARAZ), between the NBB and the CBB, and the Selenga Delta Accommodation Zone (SDAZ) between the CBB and the SBB. Up to now, Lake Baikal is the only fresh-water basin in the world in which gas hydrates have been both inferred and sampled. Hydrates are present both as “deep hydrates” which occur in the subsurface at relatively large sediments depths, and as “shallow hydrates”, which occur near the lake floor. The presence of the deep hydrates was inferred based on the observation of distinct bottom-simulating reflections (BSRs) on multi-channel reflection seismic recordings (Hutchinson et al., 1991; Golmshtok et al., 1997) (Fig. 6.1.). BSRs have been observed in an area that exceeds 4000 km^2 covering the slope of the Selenga River Delta and adjacent CBB and SBB lake floors in water depths exceeding -500 m (Fig. 6.1.) (Golmshtok et al., 2000; Vanneste et al., 2001; De Batist et al., 2002). In the SBB, hydrates were retrieved at -121 and -161 m subbottom depth during the Baikal Drilling Project (BDP-97) (Williams et al., 2001) (Fig. 6.1.). Geochemical analyses showed that the gas hydrates consist of microbial methane ($\delta^{13}C_{CH_4}$ between -58 and -68 ‰) (Kuzmin et al., 1998; Kuzmin et al., 2000). Since 2000, shallow gas hydrates have been retrieved from several mud volcanoes in the SBB and CBB (Klerkx et al., 2003; Matveeva et al., 2003; Kalmychkov et al., 2006; Khlystov, 2006; Kida et al., 2006; Klerkx et al., 2006; Krylov et al., 2008a; Krylov et al., 2008b; Hachikubo et al., 2009; Poort et al., submitted) (Fig. 6.1.). The discovery of these gas-hydrate-bearing mud volcanoes was based on the observations of anomalous shallow BSRs which dome up towards the lake floor, instead of simulating the lake bottom (Vanneste et al., 2001; De Batist et al., 2002; Van Rensbergen et al., 2002; Vanneste et al., 2002). The mud volcanoes and shallow BSRs have been attributed to the destabilization of gas hydrates at the base of the gas hydrate stability zone

(BGHSZ) by tectonically driven geothermal fluid pulses near large faults (De Batist et al., 2002; Van Rensbergen et al., 2002; Vanneste et al., 2002; Klerkx et al., 2006). The shallow seeps, outside the GHSZ, occur typically in coastal areas and in the vicinity of river deltas and canyons. These shallow seeps were already described in historical records reporting on areas with absent ice cover in winter ('ice streamthroughs'), abundant dead fish and observation of bubbles at the lake surface (Granin and Granina, 2002). The two most prolific seep areas are offshore the town of Babushkhin on the southeastern shore of the SBB and around the crest of the

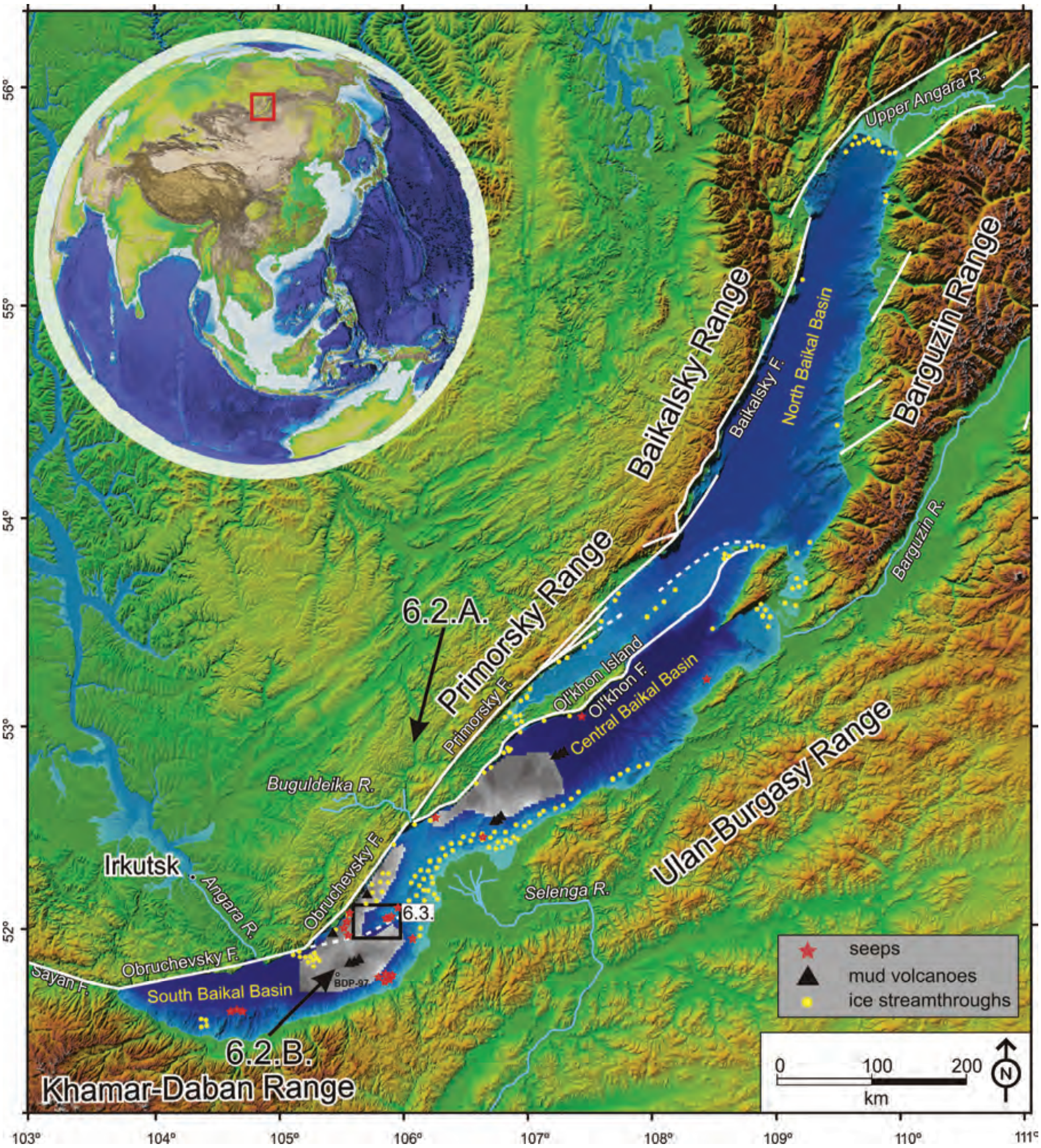

Figure 6.1. Location map of the study area in Lake Baikal with indications for regional faults, Baikal Basins, mountain ranges, rivers and area with observed bottom-simulating reflections (BSRs) (Golmshtok et al., 2000). The location of seeps (red stars), mud volcanoes (black triangles), ice streamthroughs (yellow dots) and the BDP-97 drill hole is also indicated (Granin and Granina, 2002; Klerkx et al., 2006; Schmid et al., 2007). The location on Planet Earth, the view directions for Figs. 6.2.A. & 6.2.B. and outline for Fig. 6.3. are also indicated. The map is constructed by compiling SRTM-derived topography data with bathymetry data from Lake Baikal (INTAS Project 99-1669 Team, 2002) and multibeam bathymetry data (Naudts et al., submitted).

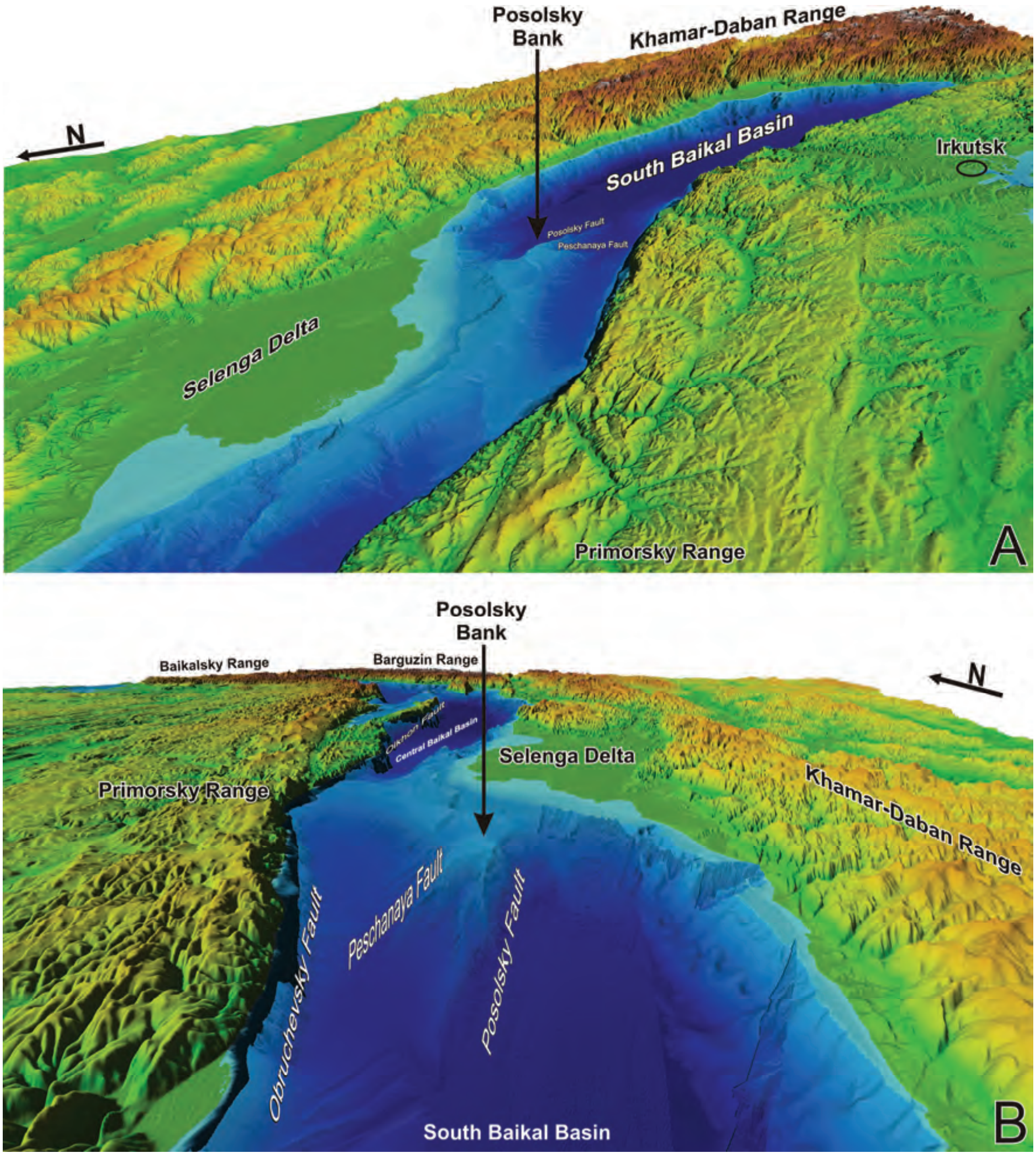

Figure 6.2. 3D views of Lake Baikal and Posolsky Bank with indication for the most prominent features. The view directions (A and B) are indicated on Fig. 6.1. The images are constructed by compiling SRTM-derived topography data with bathymetry data from Lake Baikal (INTAS Project 99-1669 Team, 2002) and multibeam bathymetry data (Naudts et al., submitted).

Posolsky Bank in the northeastern part of the SBB (Granin et al., in press). The distribution and source of the seeps on the crest of the Posolsky Bank are the focus of this paper. The Posolsky Bank is a tilted fault block within the Selenga Delta within the Selenga Delta Accommodation Zone (Figs. 6.1. and 6.2.) (Scholz and Hutchinson, 2000; Bezrukova et al., 2005; Charlet et al., 2005). The crest of the Posolsky Bank reaches water depths of less than -50 m (Naudts et al., submitted). The southern slope is very steep and coincides with the Posolsky border fault, i.e. the northern boundary fault of the SBB, while the northern slope is more gradually dipping (Figs. 6.2. and 6.3.). The sedimentary build-up of the Posolsky Bank mainly consists of fine hemipelagic sediments and spread sand lenses and laminae as shown by BDP-99 (Bezrukova et al., 2005).

6.3. Methods and data

6.3.1. Single-beam echosounding and seep detection

Due to the high impedance contrast between water and free gas, gas bubbles rising in the water column (seeps) can be acoustically detected by means of single-beam echosounder recordings. Rising bubbles show up as "acoustic flares" on echograms (Fig. 6.4.) (Greinert et al., 2006; Naudts et al., 2006; Artemov et al., 2007). Single-beam seep detection was performed from 2004 to 2008 with a FURUNO-1000 or a FURUNO-1100 echosounders (28 kHz) installed on R.V. Vereshchagin or R.V. Titov. The hydro-acoustic water-column data was continuously digitally recorded using a digitizing system developed in-house by the Limnological Institute in Irkutsk (LIN) (Granin et al., in press). During theses cruises, a total length of 666 km of echosounder tracks was recorded within the 630 km^2 Posolsky Bank area, which resulted in the detection of 65 active flare locations (Figs. 6.3., 6.4. and 6.5.). Since a flare can comprise one single bubble stream or can be a conjugation of different bubble streams or seeps within the footprint of the echosounder, the real amount of seeps, i.e. bubble-releasing locations on the lake floor is unknown.

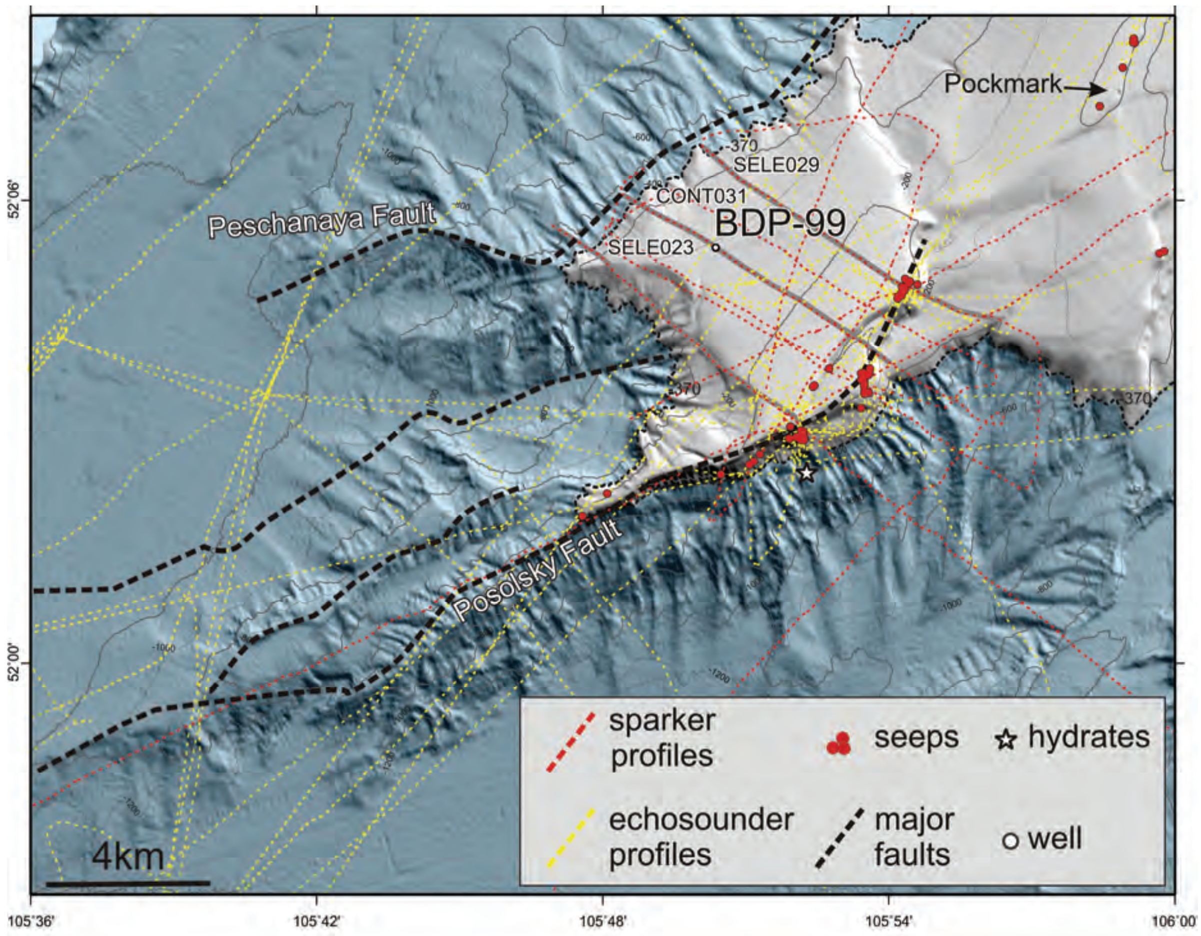

Figure 6.3. Multibeam bathymetry map of the Posolsky Bank overlain by bathymetric contours, detected seep locations (red dots), acquired sparker and echosounder profiles (respectively red and yellow dashed lines) and main faults (black dashed lines) (see Fig. 6.1. for location). Location of BDP-99 drill hole is also indicated together with depth contour of -370 m which forms the theoretical boundary of the GHSZ for pure methane hydrate (blue area) (Sloan, 1998).

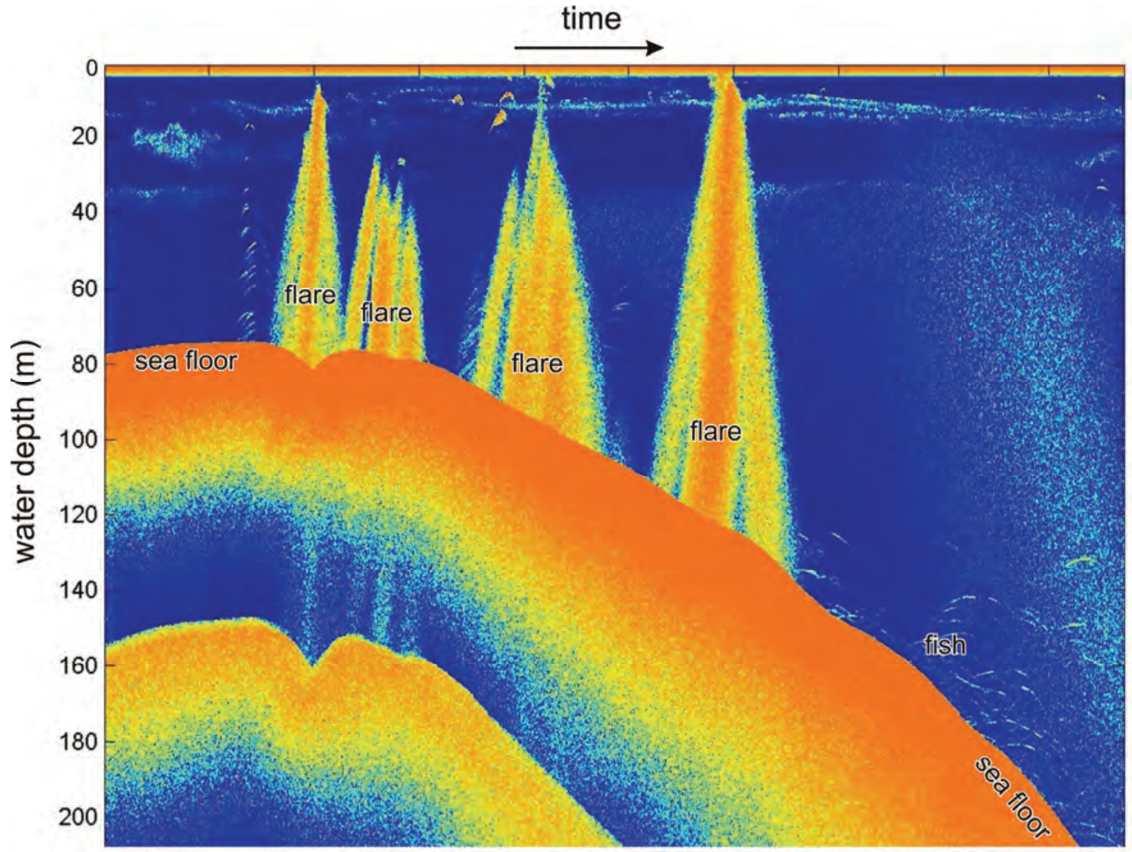

Figure 6.4. Echogram from the central seep area on the scarp of the Posolsky Bank (for location see Fig. 6.8.) where rising bubbles are hydro-acoustically detected as „flares“. The other backscatter signals in the water column probably correspond to fish.

6.3.2. Multibeam bathymetry

Multibeam swath bathymetry was acquired in the summer of 2009 with RCMG's mobile 50 kHz SeaBeam 1050 multibeam system during a two-month-long survey with R.V. Titov (Naudts et al., submitted). In total 12600 km of multibeam echosounder tracks were sailed covering 15000 km^2, including the Posolsky Bank area (Figs. 6.1.-6.3.). The system was operated with 120° swath, transmitting and receiving 108 beams of 3° by 3° beam angle and was motion-compensatend by an IXSEA OCTANS 3000 sensor from IFM-GEOMAR. Sound-velocity profiles were acquired via CTD casts and the sound velocity at the transducers was continuously measured by an online sound-velocity probe. Data acquisition was managed with Hydrostar Online and data-processing was carried out with HDPEdit and HDPPost software from L-3 ELAC Nautik GMBH. All grids shown in this paper have a cell size of 30 m.

6.3.3. Seismic subbottom data

The high-resolution seismic data were collected with RCMG's multi-electrode CENTIPEDE-sparker as a source (energy: 500 J) and a SIG single-channel streamer with 10 hydrophones as a receiver. The analog signal was bandpass-filtered (200-2000 Hz) and recorded on a Triton Elics Delph-2 system. The theoretical vertical resolution is 1 m and the maximum penetration is 200-300 ms two-way travel time (TWTT). Apart from the frequency filtering no other processing was carried out on the seismic data. Interpretation of the data was carried out with the Kingdom Suite software

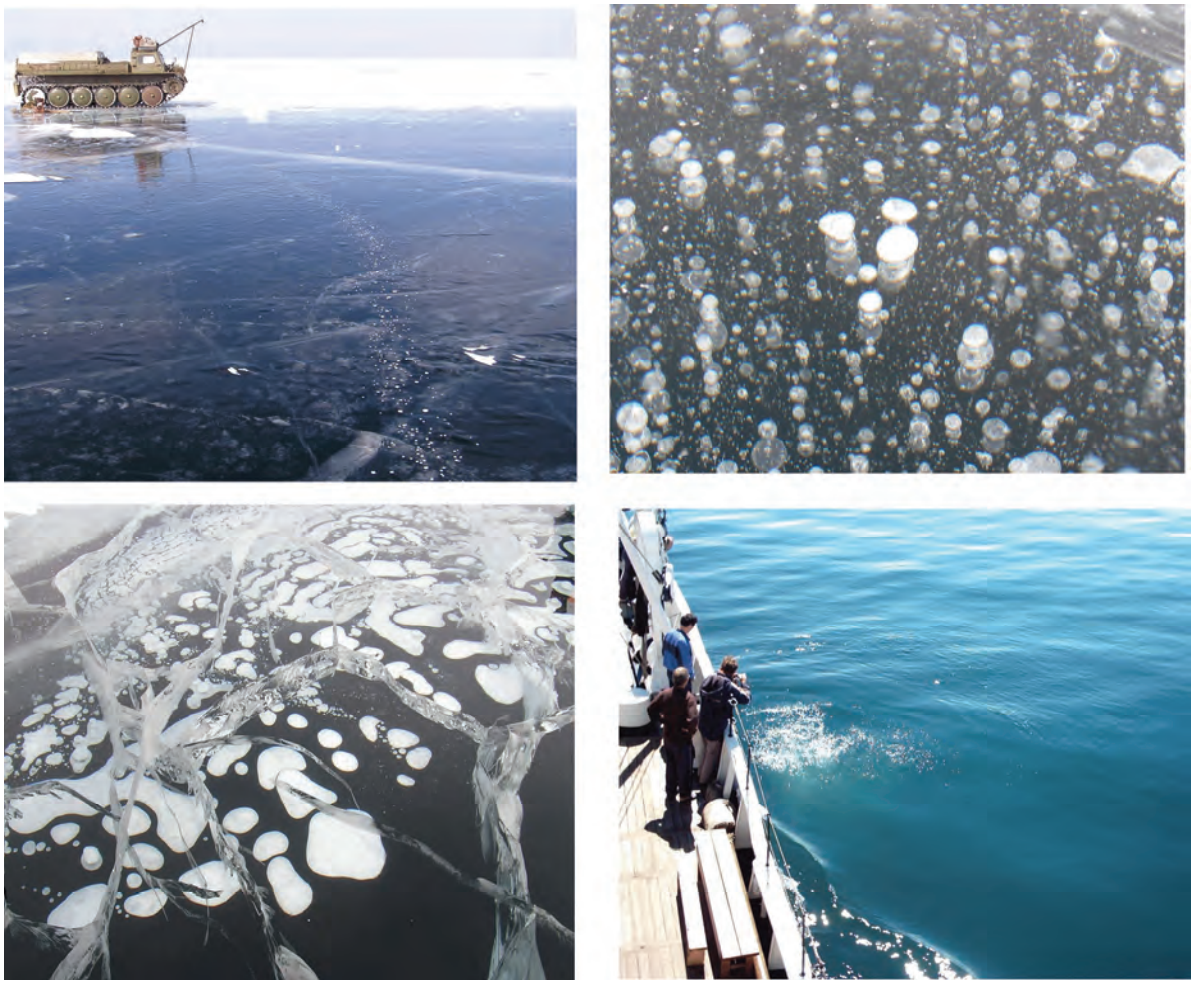

Figure 6.5. Pictures of gas bubbles being trapped underneath and within the frozen lake surface above seep sites at Posolsky Bank (pictures courtesy of N. Granin). The lower-right picture shows gas bubbles reaching the lake surface at a seep site close to the Selenga Delta (picture courtesy of V. Kapitanov).

package from SMT. During the 1997 (SELE-profiles) and 2000 (CONT-profiles) cruises, 175 km of sparker data were recorded in the Posolsky Bank area (Fig. 6.3.).

6.4. Observations and results

6.4.1. Lake-floor morphology

The Posolsky Bank, an uplifted basement block that is covered by a reduced sedimentary cover, can morphologically be seen as the southern extent of the Selenga Delta into the SBB (Figs. 6.1. and 6.2.). The Posolsky Bank is bounded by two major faults, the Peschanaya Fault in the north and the Posolsky Fault in the south, which strongly affect the lake-floor morphology (Figs. 6.2., 6.3. and 6.5.) (Scholz and Hutchinson, 2000). The top of the Posolsky Bank is flat and slopes gently to the NW (ca. 1° - 2°) from a minimum water depth of -36 m. At ca. -370 m water depth there is a strong change in slope to ca. 5°-15°; below this depth the lake bed is strongly incised. The incised morphology with ridges and gullies defining several canyon systems can also be seen on the steep western and southern slopes to water depths of -1100 to -1200 m (Figs. 6.3. and 6.5.). These incised flanks are often associated with scarps of small sublacustrine landslides (Fig. 6.3.). The northeastern side of the Posolsky Bank is not incised and forms, via a fault scarp, the transition to the Selenga Delta (Fig. 6.2. and 6.3.).

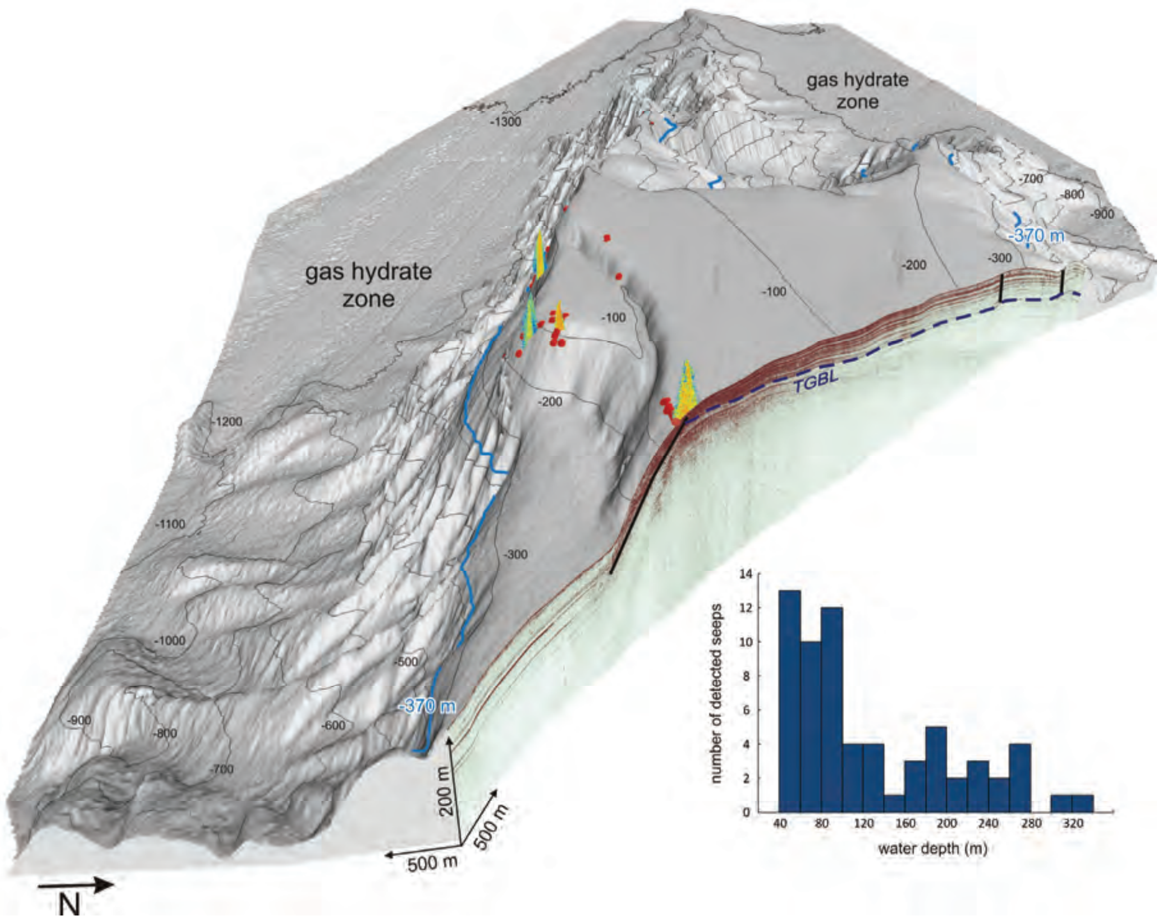

Figure 6.6. 3D view of multibeam bathymetry overlain by bathymetric contours and seep locations, plotted as red dots or shown as 3D flares in combination with sparker profile SELE029 (for location see Fig. 6.3.). Seeps occur at the crest of the Posolsky Bank upslope of the GHSZ, delineated by the -370 m blue contour line. No seeps have been detected near the Posolsky Bank within the GHSZ. On the seismic profile, strong acoustic attenuation in combination with dispersed enhanced reflections can be seen along one reflection. This reflection is interpreted as the TGBL. Seeps occur where the TGBL is cut off by the Posolsky Fault. The graph in the lower right corner shows the seep distribution versus depth with a clear seep cluster at -40 to -100 m water depth and no seeps in water depths greater than -340 m.

6.4.2. Stratigraphic framework

The sedimentary cover of the Posolsky Bank is well-stratified with a bedding that is generally parallel to the lake-floor morphology, except in the vicinity of faults (Figs. 6.6. and 6.7.) (Charlet et al., 2005). Seismic profiles SELE029 and CONT031 clearly show the presence of a well-stratified sediment package that thickens away from the crest of the Posolsky Bank towards the NW under the influence of the activity of the Posolsky Fault System. This set of continuous parallel high-amplitude reflections can be found throughout the Selenga area and represents the deposition of fine-grained hemipelagic muds which reaches a maximum thickness of ca. 100 m and represents 650 ka (Fig. 6.6. and 6.7.) (Colman et al., 2003; Bezrukova et al., 2005). Below this package with high-amplitude reflections, almost no reflections can be observed on SELE029 and CONT031. This sharp transition corresponds to a radical change in sedimentation environment with coarser sediments deposited during the glacial period preceding the quiet hemipelagic sedimentation of the last 650 ka (Colman et al., 2003; Bezrukova et al., 2005). This boundary and change in sedimentation environment corresponds to the start of increased subsidence in the SBB and Selenga area (Scholz and Hutchinson, 2000; Colman et al., 2003).

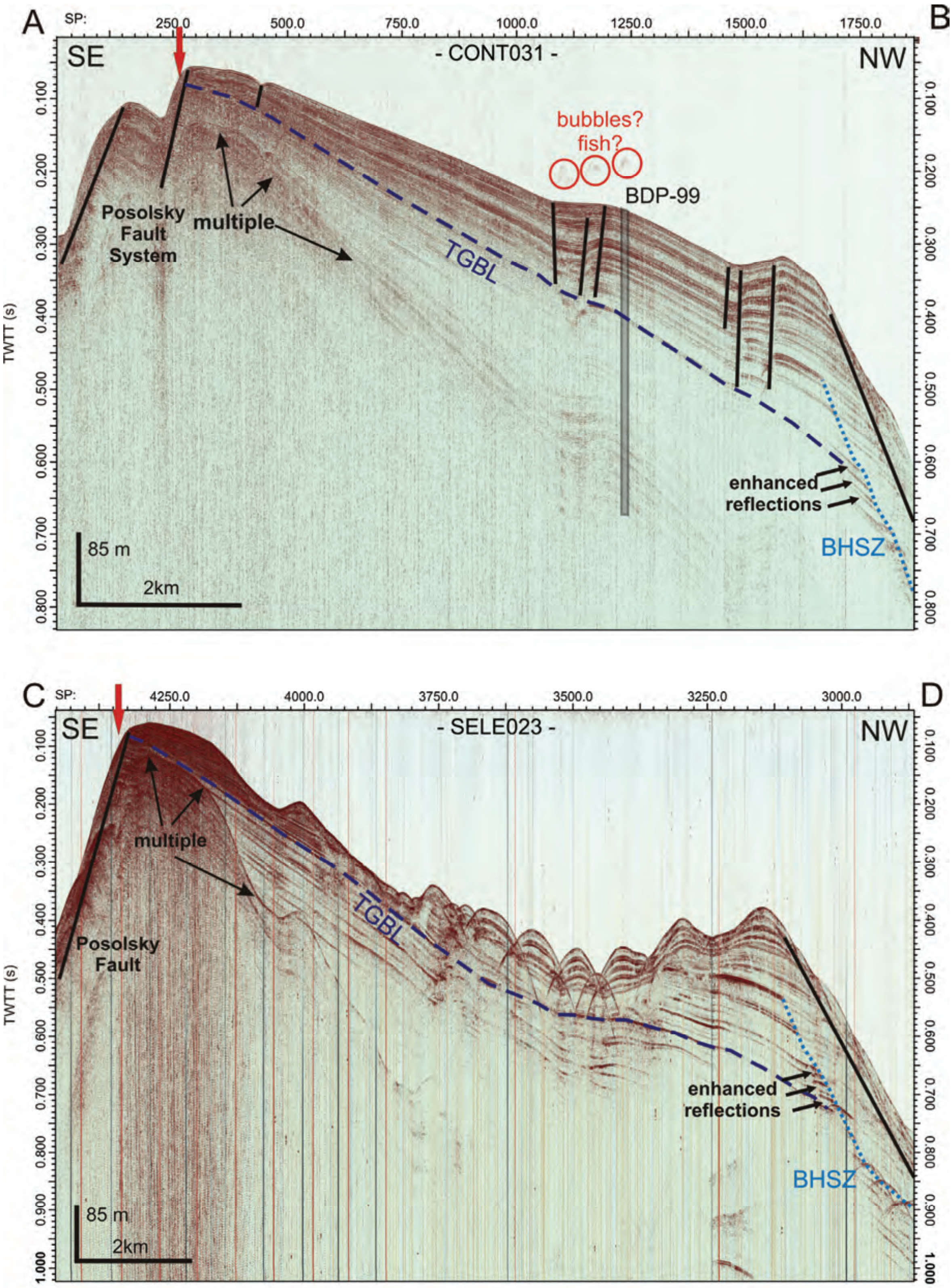

Figure 6.7. Seismic sparker profiles CONT031 (AB) and SELE023 (CD) where the TGBL can be traced from the seeps at the crest of the Posolsky Bank to below the BGHSZ. The BGHSZ shows up as a series of enhanced reflections. The location of BDP-99 well is also indicated. For locations of both profiles see Fig. 6.3.

6.4.3. Gas seep distribution

Up to 65 flares, each possibly consisting of several individual seeps, were hydro-acoustically detected within the 630 km^2 area around the Posolsky Bank in the NE part of the SBB. The seeps occur at -43 to -332 m water depth, with 54 % at water depths shallower than -100 m and 97 % at water depths shallower than -265 m (Fig. 6.6.). In many cases flares, visible on echograms, reached the lake surface; this was confirmed by the observations of bubbles at the lake surface (Figs. 6.4. and 6.5.). Integration of seep locations, multibeam bathymetry and seismic profiles shows that the majority of the seeps occur at the fault scarp in front of the crest of the Posolsky Bank where the sedimentary strata are cut off by the Posolsky Fault (Figs. 6.3., 6.6. and 6.7.). The seeps in the northeastern part of the study area are not directly related to the Posolsky Bank; they do, however, occur at similar locations, i.e. near a crest and at a fault scarp (Fig. 6.3.). Apart from the flares, an almost perfect circular pockmark, with a diameter of 160 m and a depth of 14 m can be observed in this area at -100 m water depth (Fig. 6.3.). The pockmark, indicative for fluid release at the lake floor, occurs at the conjunction of two fault scarps.

6.4.4. Indications for shallow gas and gas-hydrate occurrence

Apart from the release of free gas into the water column, as indicated by the hydro-acoustically detected flares, the presence of shallow gas and fluid-flow structures in the subsurface can also be inferred from seismic reflection data. Shallow gas strongly influences the mechanical and acoustic properties of the sediment (increased sound attenuation, acoustic energy scattering, affecting sound velocity, etc.). Therefore geo-acoustic methods, like reflection profiling, are significantly affected by the presence of shallow gas and are thus very well suited for the detection of free gas in the sediments. Even small concentrations of free gas present in the sediment pore space (0.5% gas by volume) already generate a variety of shallow-gas signatures (e.g. enhanced reflections, acoustic turbidity and acoustic blanking, etc) (Judd and Hovland, 2007; Naudts et al., 2009). Our sparker data demonstrate several types of enhanced and blanked reflections, which could or could not be indicative for the presence of shallow gas. Distinct alternations of high- and low-amplitude reflections in the upper well-stratified package are manifested on all profiles (Fig. 6.6. and 6.7.). This seismic response is, however, most likely not related to shallow gas but rather to temporal changes in the sedimentation environment and to variations in the physical properties of the associated sediments (Charlet et al., 2005). Possible gas-enhanced high-amplitude reflections associated with acoustic blanking occur near the crest of the Posolsky Bank and at the northwestern edge of the Posolsky Bank (Figs. 6.6. and 6.7.). At the crest of the Posolsky Bank, these enhanced reflections occur exclusively beneath the seep locations, indicating a clear relation with shallow gas. The enhanced reflections at the northwestern part of the Posolsky Bank generally occur over a short distance and are overlain by low-amplitude (blanked) reflections (Fig. 6.7.). This kind of seismic signature is well-known from a similar sparker dataset acquired in the deep part of the SBB. The transition line between both acoustic responses cross-cuts the stratigraphy and mimics the lake floor morphology and therefore is interpreted as a BSR (Vanneste et al., 2001; De Batist et al., 2002; Vanneste et al., 2002). This BSR is not a local feature but is present on all seismic profiles recorded at northwestern edge of the Posolsky Bank in water depths exceeding -290 m and at a subsurface depth of ca. 60 m (Fig. 6.7. and 6.8.). Generally it is assumed that the characteristic seismic signatures of BSRs are the result of relative dense hydrate-bearing layers with higher acoustic velocity overlying gassy sediments with low acoustic velocity. The presence of gas hydrates within the Posolsky Bank sediments is not only indirectly indicated by the geophysical data, hydrates have also been sampled at the lake floor at -500 m water depth, during a dive with the MIR-2 submersible at the Posolsky Fault scarp in the summer of 2009 (Oleg Khlystov, personal communication). Gas hydrates were retrieved at a small slide scarp 250 m below one of the major seep sites on the crest of the Posolsky Bank (Fig. 6.3.). The location with hydrates was also characterized by the presence of big bacterial mats indicating active fluid flow.

6.5. Discussion

6.5.1. Gas-hydrate stability, heat flow and topographic effect

The occurrence of BSRs from -290 m water depth at a subsurface depth of 60 m discussed in previous section does not correspond to earlier BSR observations in Lake Baikal starting at water depths of -500 to -580 m and at 50-100 m beneath the lake floor (Golmshtok et al., 2000; Vanneste et al., 2001).In most cases, the BSR corresponds to the lower, P-T controlled boundary of the GHSZ, also known as the BGHSZ. The stability limit for pure methane hydrates in Lake Baikal occurs at -370 m water depth (Sloan, 1998), when calculated using a present-day bottom water temperature of 3.5°C and a salinity of 0.76 ‰ (Golmshtok et al., 2000). So the newly observed BSRs occur well outside of the GHSZ for pure methane hydrate and occur in shallower water than the previously observed BSRs. This indicates that the inferred hydrates, assuming that the observed BSRs are indeed associated with hydrates, can only be stable if the local hydrate gas composition consist of a mixture of methane

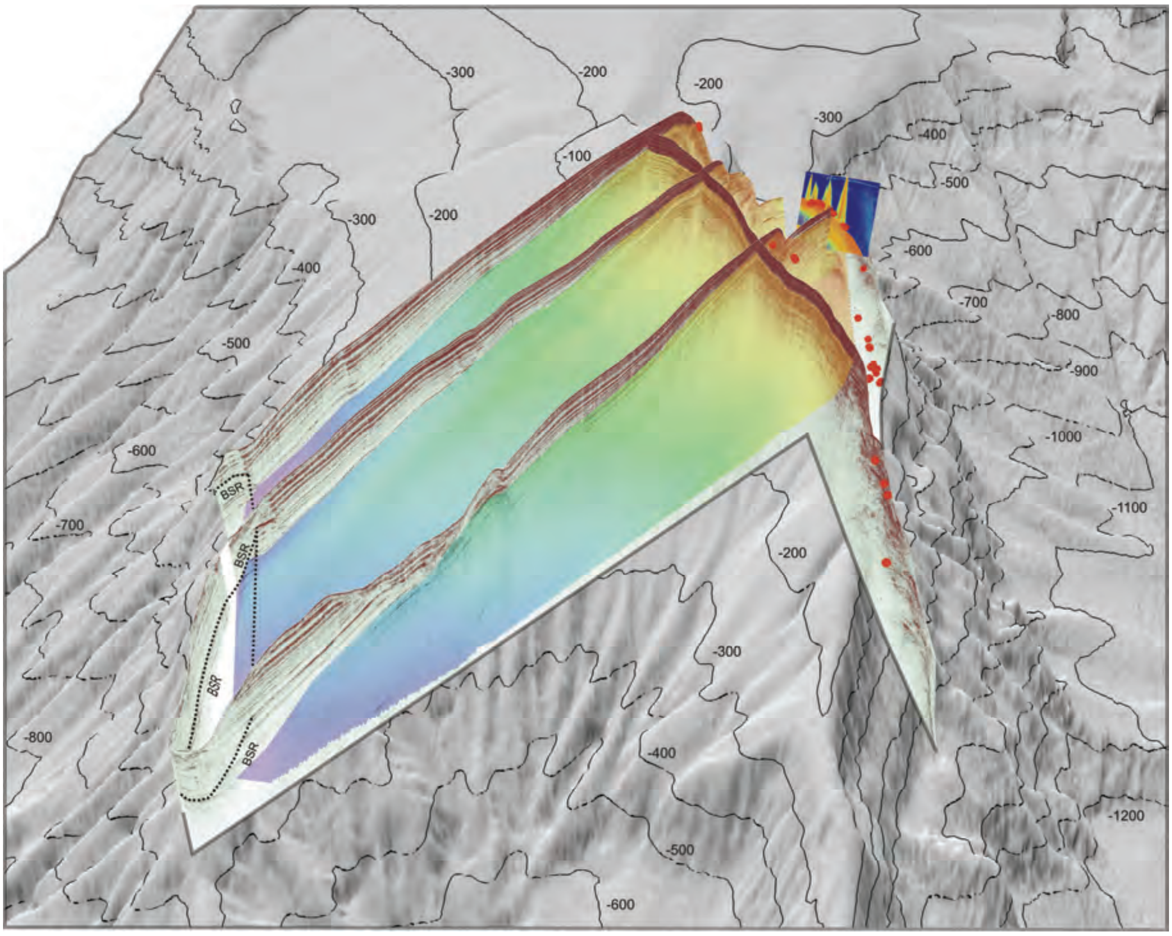

Figure 6.8. 3D view of multibeam bathymetry overlain with bathymetric contours and with seep locations plotted as red dots or shown on an echogram in combination with three sparker profiles. The top of the gas-bearing layer (TGBL) is shown as depth color-coded surface. This surface starts from or above the seeps positions at the scarp of the Posolsky Bank and can be traced down the Posolsky Bank to below the BSR or BGHSZ.

and higher hydrocarbons. Furthermore, the large subsurface depth of the observed BSRs at the limit of the GHSZ indicates that the local thermal conditions also strongly differ from the regional background values.

Based on hydrate stability calculations, a gas mixture of ca. 96 % methane and 4 % ethane would allow to shift the limit of the GHSZ to a water depth of -290 m (Sloan, 1998). There are several indications that such gas mixture indeed does occur at the Posolsky Bank. First of all, higher ethane concentrations have been measured in gas bubbles sampled from the Posolsky Bank gas seeps and at other gas seeps in Lake Baikal (Kalmychkov et al., 2006). Furthermore, the sharp depth limit of the seep distribution indicates that gas hydrates are probably present at the Posolsky Bank and that these hydrates act as a buffer preventing seepage in the GHSZ as was observed in other regions (Naudts et al., 2006; Westbrook et al., 2009). The depth limit for the majority of the seeps (97%) is -265 m water depth. When using the -265 m water depth as the limit of the GHSZ, a gas mixture of 94-95% methane and 5-6% ethane is needed to allow hydrates to be stable for the given ambient conditions. The latter is of course only an indirect indication that higher ethane concentrations probably do occur at the Posolsky Bank.

BSRs have never been observed to intersect the lake floor/seafloor at the limit of the GHSZ. This is partially related to the local geothermal gradient and associated heat flow. This is also the case for the BSRs observed at the Posolsky Bank, which occur at a subsurface depth of 60 m

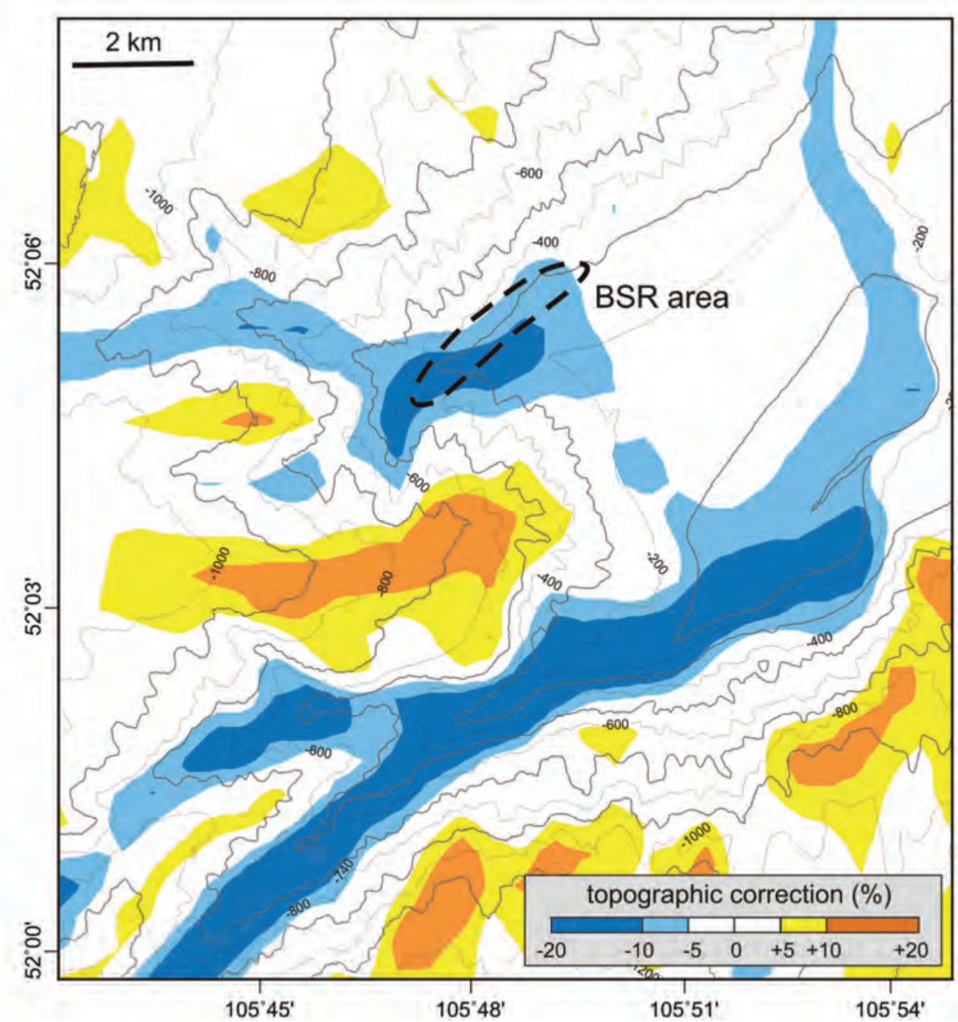

Figure 6.9. Bathymetric contour map of the Posolsky Bank area, showing the modeled topographic correction on background regional heat flow caused by the relief of the Posolsky Bank.

at the limit of the GHSZ (Figs. 6.7. and 6.8.). To obtain such a subsurface depth of the BSRs and thus the BGHSZ at the limit of the GHSZ, a local heat-flow value of 32-34 mW/m² is required. Heat-flow measurements for the Posolsky Bank are absent, but measured heat-flow values in Lake Baikal vary between 40 ± 6 and 195 ± 25 mW/m^2, with a mean value of 71 ± 21 mW/m^2 (Golubev et al., 1993; Vanneste et al., 2002; Poort and Klerkx, 2004). These heat flow values are clearly too high to allow a subsurface depth of 60 m for the observed BSRs at the limit of the GHSZ. However, local topographic variations can lead to changes in the conductive background heat flow (Poort et al., 2007). Topographic relief will attenuate heat flow in topographic highs and enhance it topographic lows. Therefore, the influence of the Posolsky Bank relief on the regional heat flow has been modeled using the procedure and code for topographic correction described in Balling et al (1981) and adjusted for digital terrain models by F. Lucazeau (personal communication). The model uses a background thermal gradient of 50 mKm^{-1} and a uniform thermal conductivity of 1.11 $Wm^{-1}K^{-1}$. For the upper meters of sediments, this model predicts a thermal gradient that differs up to 20 % in comparison with the background thermal gradient as a result of the topography of the Posolsky Bank (see Fig. 6.9.). When assuming a feasible background thermal gradient of 40 mKm^{-1} and considering the modeling results, the pronounced topographic relief of the Posolsky Bank can lead to a reduction of the local heat flow to the needed heat flow values of 32-34 mW/m².

These results indicate that the observed BSR probably does correspond to the BGHZS and that hydrates possibly do occur at the observed 60 m subbottom depth at -290 m water depth.

6.5.2. Fluid flow and seep distribution model

The observations and results discussed in the previous sections show that gas is being released at the Posolsky Fault scarp near the crest of the Posolsky Bank and that gas hydrates and shallow free gas are present in the subsurface of the NW edge of the Posolsky Bank (Figs. 6.6., 6.7. and 6.8.). In addition gas hydrates have been sampled at the fault scarp at a depth of -500 m (Oleg Khlystov, personal communication). The occurrence of seeps on the Posolsky Fault scarp could indicate that the fault system acts as a fluid conduit resulting in seepage. On the other hand, seismic data show that there is a stratigraphic connection between the seep locations and the free gas trapped underneath the BSRs indicating that fluid flow occurs along the tilted strata of the Posolsky Bank (Figs. 6.6. and 6.7.). Another alternative could be that the released gas comes from a shallow and local source near the seep locations. But this option is rather unlikely because of the presence of higher hydrocarbons in the released gas indicating at least an admixture of fluids from a deep source (Kalmychkov et al., 2006).

The first option with the fault acting as a fluid conduit for the seeps on the Posolsky Bank is also rather unlikely. Most compelling evidence is provided by the distribution of the gas seeps. The seeps occur only at the upper part of the Posolsky Fault scarp; the deepest seep is observed at -332 m water depth, whereas 97 % of the seeps occur in water depths shallower than -265 m and even 54 % of the seeps occur in water depths shallower than -100 m (Fig. 6.6.). Since the Posolsky Fault system is a combination of several faults forming a combined fault scarp of over 600 m, it is rather unlike that such an open system is able to act as a conduit for fluids that only allows the majority of the methane to be released at less than -100 m water depth (Figs. 6.6. and 6.7.). If the Posolsky Fault did act as a conduit, the seep distribution would have been completely different with seepage being more widespread over the fault scarp at all water depths. One could argue that gas hydrates act as a buffer and prevent gas release in the GHSZ as was already postulated in this study and by others (Naudts et al., 2006; Westbrook et al., 2009). But in this case, most of the methane migrating along the fault would be either trapped within the present gas hydrates or would be released just outside of the GHSZ, as was observed for the seeps in West Spitsbergen (Westbrook et al., 2009). In the case of the Posolsky Bank this would lead to a seep distribution with mainly seeps occurring at

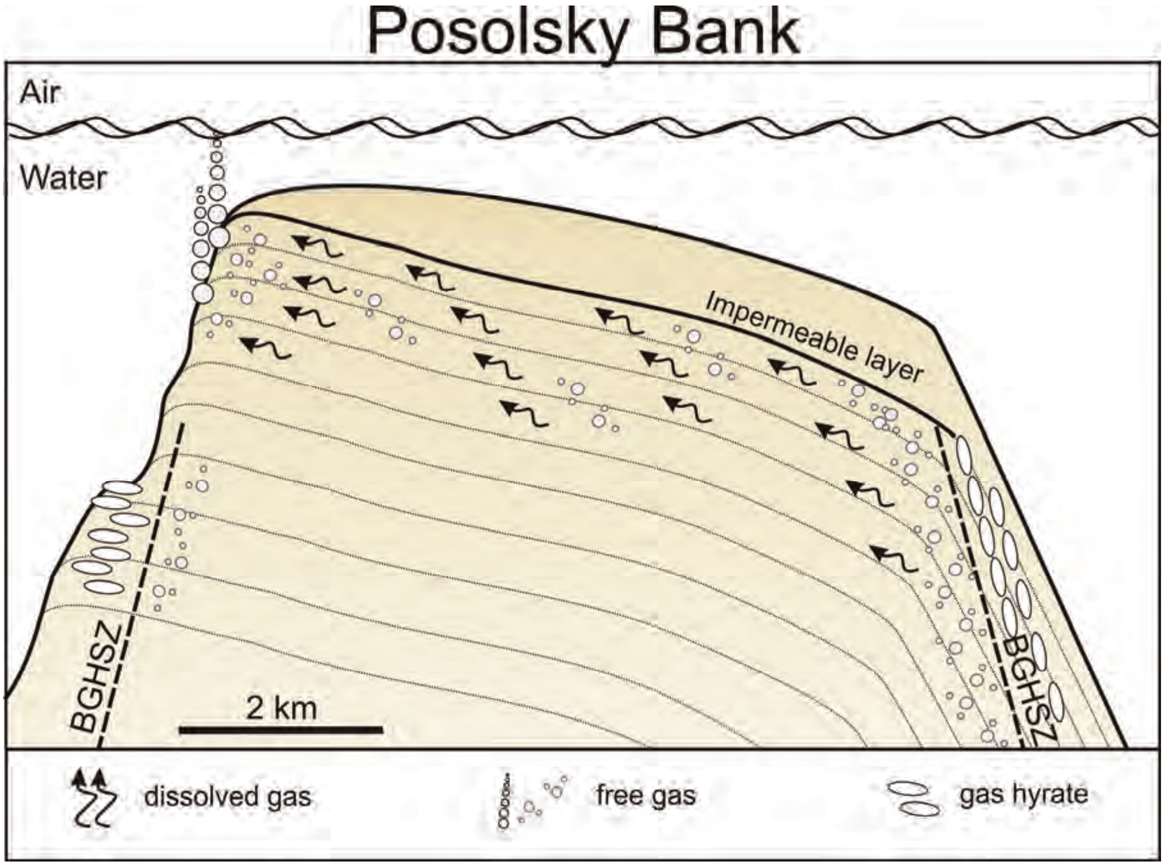

Figure 6.10. Proposed seep model for the Posolsky Bank gas seeps.

water depths of ca. 300-350 m, depending on the present gas composition and ambient conditions affecting gas-hydrate stability. However the observed seep distribution shown in figure 6.6. demonstrates the opposite with mainly seeps being released in water depths shallower than -100 m. So we can safely postulate that the fault system probably doesn't act as a fluid conduit for the seeps detected within the study area.

The second option wherein the seeps on the Posolsky Fault scarp are fed by fluid migration along the tilted strata of the Posolsky Bank can only be valid if the stratigraphic and sedimentary buildup of the Posolsky Bank allows such a migration pathway. The seismic data does indeed indicate the presence of such a possible migration pathway which connects the seeps at the scarp with the free gas present below the BSRs (Figs. 6.6., 6.7. and 6.8.). On the seismic data the top this possible gas-bearing layer (TGBL) shows up as the transition from the upper seismic unit consisting of continuous parallel high-amplitude reflections to the lower seismic unit with an almost transparent seismic facies (Figs. 6.6., 6.7. and 6.8.). Based on the eight sparker profiles available on the Posolsky Bank, the TGBL could be mapped as an almost continuous surface throughout the subsurface of the Posolsky Bank (Figs. 6.8.). The transition represented by the TGBL corresponds to a change in sedimentary characteristics with hemipelagic fine grained sediments overlaying coarser sediments (Colman et al., 2003; Bezrukova et al., 2005). The core data from the BDP-99 drill core provides some extra indication that the sediment layer underneath the TGBL is indeed suitable as a fluid conduit (BDP-99 locations is indicated on Figs. 6.3. and 6.7.) (Bezrukova et al., 2005). The core data shows that below the TGBL at a depth interval between 94-109 m there are much coarser sediments than in the overlying and underlying sediments as indicated by the clay and silt percentages and the gamma log (Bezrukova et al., 2005). This interval is also characterized by the widespread occurrence of granules and pebbles. The upper meter of this interval even consist of more than

50 % sand (Bezrukova et al., 2005). The grain size distribution in the sediment package below the TGBL, together with its confinement in between much fine finer sedimentary units, makes the sediment package below the TGBL extremely well-suited as a fluid migration pathway. This is also the first sedimentary unit in the BDP-99 core, starting from top, with plant and wood fragments indicating that this layer possibly also contributes as a source for the released methane (Bezrukova et al., 2005).

Based on the seismic stratigraphy and the BDP-99 well data we postulate that the seeps on the Posolsky Fault scarp near the crest of the Posolsky Bank are supplied by gas that migrated along relatively permeable sedimentary strata which are cut off by the Posolsky Fault system (Fig. 6.10.). This gas is partially sourced by the free gas present underneath the BSRs/BGHSZ at the NW edge of the Posolsky Bank. The seismic data show that the free gas present below the BGHSZ is not completely trapped by the gas hydrates; the geometry and permeability of the sedimentary build up of the Posolsky Bank enables the gas to migrate upwards along the sedimentary strata (Figs. 6.7., 6.8. and 6.10.).
Even the gas hydrates and seeps present at larger depths along the Posolsky Fault scarp are probably supplied by gas migration through the tilted sediment layers that make up the Posolsky Bank.

6.6. Conclusions

Integration of the seep distribution, the seismic stratigraphy, well data and gas-hydrate stability analysis suggest that the shallow gas seeps near the crest of the Posolsky Bank are partially supplied by gas from below the base of the gas-hydrate stability zone. Gas-hydrate-cemented strata act as a seal and together with the geometry and stratigraphy of the Posolsky Bank, gas is focused upwards via permeable stratigraphic pathways. Gas is eventually released in the water column, where these pathways are cut off by faults. This setting differs from the deep-water Baikal seeps and mud volcanoes, which are believed to be related to destabilizing gas hydrates under the influence of a tectonically-controlled geothermal fluid pulse along adjacent faults.

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Additional information

Lieven Naudts processed and interpreted most of the datasets, wrote the manuscript and made all figures. Lieven Naudts was chief scientist during the 9 weeks of the multibeam expedition on RV Titov and provided funds for this expedition via an FWO grant. Co-authors helped by reviewing the manuscript, by helping during the data acquisition and/or by providing the datasets. Corrections for topographic effect were made by Jeffrey Poort; who also assisted with the heatflow and gas-hydrate stability calculations.

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