Multi-frequency seismic study of gas hydrate-bearing sediments in Lake Baikal, Siberia

M. Vanneste✉, M. De Batist, A. Golmshtok, A. Kremlev, W. Versteeg

Renard Centre of Marine Geology, University of Gent, Krijgslaan 281-S-8, B-9000 Gent, Belgium
P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, St.-Petersburg, Russia
Institute of Computational Mathematics and Mathematical Geophysics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia

Received 13 March 2000; accepted 6 October 2000

Abstract

In this paper we present and discuss the frequency-dependent behaviour of the acoustic characteristics of methane hydrate-bearing sediments in Lake Baikal, Siberia. Five different types of seismic sources (airgun-array, two types of single airguns, watergun and sparker) are used, encompassing a frequency bandwidth from 10 up to 1000 Hz. On low-frequency airgun-array data, the base of the hydrate stability zone (HSZ) is observed as a high-amplitude bottom-simulating reflection (BSR) with reversed polarity. The amplitude and continuity of the BSR decrease or even disappear on medium- to high-frequency data, a feature explained in terms of vertical and horizontal resolution. The increasing reflection amplitude of the BSR with increasing offset, the calculated reflection coefficient of the BSR and the occurrence of enhanced reflections below the BSR suggest the presence of free gas below the HSZ. The observation of some enhanced reflections extending above the BSR may be interpreted as an indication for free gas co-existing with hydrates within the HSZ. Amplitude blanking above the BSR is highly variable while the BSR itself appears to act as a low-pass frequency filter for medium- to high-frequency data.

New single-channel airgun profiles provide the first seismic information across the Baikal Drilling Project (BDP-97) deep drilling site, at which hydrate-bearing sediments were retrieved at about 200 m above the base of the local HSZ. At the drilling site there are no seismic characteristics indicative of the presence of hydrates. Combination of the drilling and seismic information has allowed us to make a rough estimation of the volume of hydrates and carbon stored in the sediments of Lake Baikal, which lead us to conclude that the Lake Baikal gas hydrate reservoirs do not form a prospective energy resource.

© 2001 Elsevier Science B.V. All rights reserved.

Keywords: Gas hydrates; Bottom-simulating reflector; Lake Baikal; Acoustic frequency spectrum; Fluid migration; Amplitude blanking

1. Introduction: gas hydrates in Lake Baikal

Gas hydrates are ice-like compounds of low-molecular weight gases (most often CH₄) enclosed within a hydrogen-bonded framework of water molecules. Hydrates occur naturally in the Earth’s shallow subsurface within pores of sedimentary rocks. Their stability is dictated by specific conditions of pressure (high), temperature (low), gas composition and pore water salinity (e.g. Kvenvolden, 1993; Sloan, 1998). The limiting factor is the presence or supply of sufficient amounts of gas molecules to stabilise the hydrate structure (Hyndman and Davis, 1992; Rempel and
Hydrate accumulations are mainly restricted to two areas: Arctic areas and continental margins (Kvenvolden, 1993). Their presence is usually inferred from the observation of a bottom-simulating reflection (BSR) on acoustic profiles. This is an anomalous, strong, single, polarity-reversed reflection that often crosscuts the stratigraphy (Hyndman and Spence, 1992; MacKay et al., 1994; Mienert et al., 1998; Posewang and Mienert, 1999). BSRs were initially interpreted to represent the basal limit of the hydrate-bearing sediments, being located at the sub-bottom depth at which the 3-phase equilibrium curve intersects with the temperature profile (Hyndman and Davis, 1992). Present-day insight, however, learns that the BSR is more likely to be generated at the top of a free-gas layer beneath the hydrate stability zone (HSZ) than at the base of partially hydrated sediments in the HSZ (e.g. Bangs et al., 1993; Holbrook et al., 1996; Wood and Ruppel, 2000). A gradual transition may exist between the hydrate accumulation zone and the top of the free gas zone (Xu and Ruppel, 1999). Hydrates appear to accumulate preferentially at the base of the HSZ (BHSZ) (Hyndman and Davis, 1992; Spence et al., 1995) but they are distributed at least throughout part of the stability zone (Booth et al., 1998). This might point towards a causal link of hydrate formation with upward fluid migration.

The occurrence of hydrates in Lake Baikal (Fig. 1) was first suggested by the presence of BSRs on multi-channel (MC) seismic reflection profiles acquired during a Russian survey in 1989 (Hutchinson et al., 1991). More details became available in 1992 during a joint Russian–American survey (Golmshtok et al., 1997). Clear indications for hydrate occurrences were found in the Southern (SBB) and Central Baikal Basins (CBB), in the area around the Selenga Delta (Fig. 1), while none at all were observed in the Northern Baikal Basin (NBB). The thickness of the HSZ, inferred from the seismic data, ranges between 35 and 450 m (Golmshtok et al., 1997). Confirmation was obtained in 1997 by deep drilling in the axial part of the SBB (BDP-97 borehole; position N 51°47.9'–E 105°29.25'; water depth 1428 m). Hydrate samples in coarse sandy turbidites were collected from 120 and 161 m sub-bottom depth (Kuzmin et al., 1998). No information from intermediate depths is available due to poor core recovery. The borehole did not penetrate the BHSZ. The hydrates sampled occupied approximately 10% of pore space (Golubev, pers. comm.). Geochemical analyses showed that the enclosed gas molecules were mainly methane of biogenic origin ($\delta^{13}C$ between $-58$ and $-68\%o$). Up to now, Lake Baikal represents the only confined fresh-water basin with both direct and indirect evidence of methane hydrates.

1.1. Objectives

In this paper, we focus on the analysis and interpretation of a series of different seismic data sets, and investigate the acoustic characteristics of the hydrate-bearing sediments in the SBB and CBB. More specifically, this paper aims to:

1. Present different seismic data sets (low-frequency airgun-array, medium-frequency single airgun, high-frequency watergun, very-high-frequency sparker) covering a broad spectrum of frequencies ranging from 10 to 1000 Hz.
2. Present and describe the frequency-dependent response of the BHSZ and its lateral continuity.
3. Discuss reflection-amplitude characteristics, such as reflection coefficients of the BSR, offset-dependence of the BSR’s reflection amplitude, amplitude effects in the hydrate-bearing section, and frequency filtering.
4. Better constrain the limits of the HSZ where no clear BSR is observed, by means of reflection amplitude variations.
5. Use the above observations and interpretations to provide a rough quantitative estimate of the hydrate distribution in Lake Baikal.

2. Study area: Lake Baikal

Lake Baikal (Fig. 1), located in the central part of
the tectonically active Baikal Rift Zone (South–Central Siberia), is the world’s deepest (1637 m) and most voluminous lake (23,000 km$^3$), containing approximately 20% of the world-wide reserve of fresh water (salinity 0.76‰) (Galaziy, 1993). Lake Baikal comprises three deep lake basins (SBB, CBB, NBB), separated by two structural highs: the Academician Ridge between the NBB and CBB and the Selenga Delta Saddle between the SBB and CBB. The basin-fill deposits may be as old as Late Cretaceous and up to 8 km thick (Zonenshain et al., 1992; Mats, 1993; Scholz et al., 1993). The upper hundreds of meters of these deposits consist of alternations of interglacial diatomaceous, hemipelagic muds with some thin turbidites and glacial clays interbedded with thicker and coarser turbidite layers (Nelson et al., 1998). Shallow structural highs, like the Academician Ridge, receive little clastic sediment and accumulate regular alternations of diatomaceous ooze and fine clay layers (Grachev et al., 1998). Sedimentation rates in Lake Baikal basins derived from core analyses vary from 16 cm/ka (NBB) to
74 cm/ka (SBB), with maximum values of 120 cm/ka measured in front of the Selenga Delta, where sediments are also enriched in organic matter (Edgington et al., 1991).

The Baikal Rift Basins are characterised by a complex pattern of active faults while heat-flow measurements vary between $40 \pm 6$ to $195 \pm 25$ mW/m$^2$ and show a general trend of decreasing in SSE–NNW direction (Poort et al., 1998). On smaller scale (order of km), strong heat-flow fluctuations with magnitude of $30$–$40$ mW/m$^2$ are reported to occur almost everywhere on the lake bed (Golubev, 1982; Poort et al., 1998). Locally, at intersections between the regional border fault and transverse faults, extreme high values of up to $8.6$ W/m$^2$ were measured (Golubev et al., 1993) and hydrothermal activity was observed at one location (Crane et al., 1991).

3. Seismic data acquisition and processing: technical aspects

In this paper, we present five seismic data sets from the SBB and CBB, in the area around the Selenga Delta. Location of the seismic profiles is shown in Fig. 2. Acoustic sources were airgun-array, Ship and Impuls airgun, watergun and sparker. They cover a frequency range between 10 up to 1000 Hz. Of these, only the airgun-array data were recorded in MC mode. Sources and receivers were all towed at or close to the surface. All data were specially processed or re-processed for this study. More details are given in Table 1.

The MC airgun-array data were collected in 1992 by a joint Russian–American team (Nichols et al., 1992; Klitgord et al., 1993; Scholz et al., 1993). For

---

Table 1
Overview of the acquisition and processing characteristics of the five seismic data sets used in this study

<table>
<thead>
<tr>
<th></th>
<th>Airguns</th>
<th>Impuls-1</th>
<th>Ship</th>
<th>Watergun</th>
<th>Sparker</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acquisition characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Property of:</td>
<td>Golmshtok</td>
<td>RCMG</td>
<td>RCMG</td>
<td>USGS</td>
<td>RCMG</td>
</tr>
<tr>
<td>Gun volume (l)</td>
<td>27.3</td>
<td>3</td>
<td>3</td>
<td>0.245</td>
<td>–</td>
</tr>
<tr>
<td>Source energy</td>
<td>140 bar</td>
<td>120 bar</td>
<td>120 bar</td>
<td>200 bar</td>
<td>400–500 J</td>
</tr>
<tr>
<td>Sampling interval (ms)</td>
<td>4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>Number of recording channels</td>
<td>96</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CDP fold</td>
<td>24</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Source-receiver offset (m)</td>
<td>495–2895</td>
<td>± 25</td>
<td>± 25</td>
<td>± 180</td>
<td>± 25</td>
</tr>
<tr>
<td>Angle of incidence</td>
<td>10–50°</td>
<td>&lt; 1°</td>
<td>&lt; 1°</td>
<td>&lt; 5°</td>
<td>&lt; 1°</td>
</tr>
<tr>
<td>Frequency range (Hz)</td>
<td>7–110</td>
<td>45–330</td>
<td>80–450</td>
<td>100–650</td>
<td>150–1000</td>
</tr>
<tr>
<td>Dominant frequency in water (Hz)</td>
<td>± 39</td>
<td>± 120</td>
<td>± 225</td>
<td>± 330</td>
<td>± 525</td>
</tr>
<tr>
<td>Dominant wave length in water (m)</td>
<td>± 37</td>
<td>± 20</td>
<td>± 6.4</td>
<td>± 4.4</td>
<td>± 2.8</td>
</tr>
<tr>
<td>Vertical resolution (m)</td>
<td>± 10</td>
<td>± 3</td>
<td>± 1.6</td>
<td>± 1.1</td>
<td>± 0.7</td>
</tr>
<tr>
<td>Lateral resolution (m)</td>
<td>300–465</td>
<td>± 170</td>
<td>± 125</td>
<td>± 100</td>
<td>± 80</td>
</tr>
<tr>
<td>Average penetration limits (m)</td>
<td>&gt; 3000</td>
<td>± 700</td>
<td>± 500</td>
<td>± 500</td>
<td>&lt; 400</td>
</tr>
<tr>
<td><strong>Processing characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDP-sorting</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity analysis</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMO-correction</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stacking</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correction for spherical divergence</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Minimum-phase predictive deconvolution</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Spectral analysis</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude analysis</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butterworth band-pass filter</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>FK-filter</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic gain control (AGC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In this study, we got access to the first 3000 ms of lines 92_01, 92_02, 92_03, 92_07 (Fig. 2).

Single-channel (SC) Ship and Impuls-type airgun profiles were acquired in 1999 during a joint Belgian–Russian expedition in selected areas in the SBB and CBB. Main objective was to investigate the specific characteristics of gas hydrate accumulations (Vanneste, 1999; De Batist et al., 1999). All 43 profiles were used in this study.

During two seismic surveys (1991–1992), an extensive grid of watergun profiles was acquired in different parts of the lake. These data are published as part of an USGS Open File Report (Colman et al., 1996). This study only makes use of line 91_04 of this data set.

In 1997 and 1998, a joint Belgian–Russian team collected dense grids of very-high-resolution seismic profiles in the Selenga Delta area (De Batist and Vanneste, 1997; Vanneste and De Batist, 1998). The data were shot using RCMG’s fresh-water multi-electrode sparker. Profiles SELE070 and SELE071 are presented here.

In the framework of this study, the available airgun-array data were completely re-processed, involving a.o. common-depth-point (CDP) sorting, velocity analysis, normal-move-out (NMO) correction and
stacking. The 3000 ms TWTT sections we had at our disposal did not allow detection of the BSR and underlying horizons in the far-offset recording channels, which hampered velocity analyses. All data were submitted to additional processing routines for resolution enhancement and true amplitude recovery. No automatic gain control (AGC) was applied. Details are provided in Table 1.

4. Data description: multi-frequency seismic imaging of the HSZ

4.1. Low- and medium-frequency imaging: airgun data

The BHSZ in Lake Baikal is, as in most oceanic hydrate provinces, expressed as a continuous
high-amplitude BSR on MC data. Such a BSR can clearly be seen on profile 92_01 (Fig. 3A), a stacked MC profile from the central part of the SBB. Vertical exaggeration of this profile is approximately 25:1. The BSR is roughly parallel to the flat lake floor and runs at approximately 340 ms TWTT sub-bottom depth. It can be traced along the whole profile. Within the first 13 km of the profile (NW side), the continuous BSR crosscuts the folded sedimentary units. A zoom taken from the central part of this profile (Fig. 3B) illustrates the reversed reflection polarity of the BSR, relative to the lake-floor reflection. This polarity reversal indicates a negative acoustic impedance contrast across the BSR, most probably due to a decrease in velocity.

The BSR is also imaged on more or less coincident SC airgun profiles GAHY020 (Impuls airgun, Fig. 3C) and GAHY008 (Ship airgun, Fig. 3D). On these higher-frequency profiles, several pseudo-vertical faults with small offsets are identified within the fold structure. The amplitude of the BSR on these profiles is highly variable and in general weaker than on the low-resolution MC data. The BSR only appears as a distinct reflection where it crosscuts the dipping sediment layers at the border of the fold structure. Within the folded sedimentary section itself, the BSR is very weak. Comparison with profile 92_01 (Fig. 3A) allows us to trace the BSR across the structure, where it lies on top of a package of higher-amplitude reflections (Fig. 3C). A few reflectors crossing the BSR...
at the border of the fold structure are characterised by high (enhanced) amplitudes just above the BSR, while the amplitudes of most other reflectors in this interval are weaker than average (“amplitude blanking”).

Another clear example of a crosscutting BSR on a medium-frequency Ship airgun profile is observed on line GAHY017 (Fig. 4), perpendicular to the above-described profiles (Fig. 3). The BSR, which does not perfectly mimic the lake floor along this profile, is very distinct in the central part of the section. Its continuity is affected neither by the dipping sediment layers nor by the small fault at SP 480. Some stratigraphic reflections are enhanced just below the BSR. Amplitude blanking above the BSR is variable along this line.

Similar BSR characteristics are observed on most low- to medium-frequency seismic profiles in the SBB and CBB.

4.2. High-frequency imaging: watergun data

A completely different image of the BHSZ is observed on higher-resolution seismic data. A good example is given on watergun profile 04_91 (Fig. 5A) from the SBB. This profile is characterised by a series of closely spaced, dipping, enhanced reflections or bright spots that all terminate up-dip at a sub-bottom depth of about 300 ms TWTT. The bright spots are part of individual continuous stratigraphic boundaries that can be traced on both sides of the enhanced parts. Polarity analysis of the enhanced reflections suggests that their polarity is reversed compared to the lake-floor reflection. The lateral extent and the amplitude of the bright spots vary. While sometimes no amplitude anomaly is observed, other enhanced parts extend over hundreds of meters. The vertical extent is limited to a zone of about

Fig. 5. Nearly coincident seismic profiles acquired with different acoustic sources and acquisition lay-outs. For location see Fig. 2. (A) High-resolution SC watergun profile 04_91 (Colman et al., 1996). The BHSZ is expressed as the up-dip termination of a series of enhanced reflection segments, suggesting the presence of free gas below the HSZ. In this case, the BHSZ does not form a continuous reflection. (B) Short- (495 m) and large-offset (2875 m) channels of low-resolution airgun-array profile 92_07, showing a distinct BSR.
50 ms TWTT. Amplitude blanking is present in the section above the enhanced reflections.

Fig. 5B shows the shortest-offset (above) and largest-offset (below) channels of the nearly coincident lower-frequency profile MC 92_07. Especially on the latter, a high-amplitude BSR with all typical characteristics can be seen. The BSR is still visible on the short-offset channel, although much weaker. It occurs at a sub-bottom depth of about 300 ms TWTT and forms the upper limit of a series of dipping, enhanced reflections. These observations indicate that the acoustic features observed on water-gun profile 04_91 (Fig. 5A) represent the high-frequency response of the BHSZ along this section. This interface still follows the lake-floor topography, but it does not appear as a distinct and continuous BSR as it does on lower-frequency data.

4.3. Very-high-frequency imaging: sparker data

The very-high-resolution sparker profiles SELE071 (Fig. 6A) and SELE070 (Fig. 6) show yet another image. The profiles are characterised by the presence of high-amplitude reflections jumping from one stratigraphic horizon to another at an average sub-bottom depth of about 300–320 ms TWTT (Fig. 6). On nearby MC profiles the BSR is clearly visible and occurs at about the same sub-bottom depth. The enhanced reflections
Fig. 6. Very-high-resolution SC sparker profiles SELE071 (A) and SELE070 (B), showing the presence of enhanced reflections and the characteristic acoustic-basement effect at the inferred BHSZ. For location see Fig. 2.

seem to act as a kind of acoustic basement: they completely block all acoustic energy and no reflections from below are detected. It should be noted, however, that the maximum sub-bottom penetration of the sparker signal in other deep-water areas of Lake Baikal is also in the order of 350–400 ms TWTT. Several other sparker profiles that cross MCS lines do not have sufficient penetration to reach the BSR. It is therefore very difficult to use
solely these very-high-frequency acoustic characteristics to unambiguously determine the position of the BHSZ, without any additional lower-frequency seismic data.

4.4. Seismic imaging of the HSZ at the BDP-97 site

A number of Ship airgun profiles were shot across the BDP-97 site: profile GAHY005/006 (Fig. 7A) and profile GAHY010 (Fig. 7B). On line GAHY005/006 the drilling site is located at SP 370; on line GAHY010 near SP 150-160. On these profiles, only a very faint BSR can be discerned in some parts of the sections. The BSR is visible to the NE and to the SW of the BDP drilling site, but not over a distance of several kilometres in the vicinity of the site. Where present, the BSR is continuous and regular and

Fig. 7. Medium-resolution SC airgun profiles GAHY005/006 (A) and GAHY010 (B) across the BDP-97 hydrate drilling site. Only a very faint BSR can be observed along part of these profiles. No BSR can be observed at the drill site. The sub-bottom depths from which hydrates were recovered lie well above the BHSZ. For location see Fig. 2.
crosscuts stratigraphic boundaries under a small angle at sub-bottom depths of 350–390 ms TWTT (Fig. 7).

Some stratigraphic reflections below the BSR are slightly enhanced, and reflection amplitudes above the BSR are locally suppressed. Sub-bottom depths of hydrate recovery (120 and 161 m) were converted into ms TWTT using the Golmshtok velocity model (Golmshtok et al., 1997). No specific seismic features indicative for the presence of hydrates can be observed at the drilling site.

5. Discussion: acoustic characteristics of the HSZ

5.1. Amplitude blanking above the BHSZ

Amplitude blanking, or reduction in acoustic reflection amplitude, is a common effect that has been described on seismic records from several well-studied gas hydrate provinces (e.g. Shipley et al., 1979; Lee et al., 1993; Dillon et al., 1994; Hovland et al., 1997; Wood and Ruppel, 2000). It is usually observed in the section just above the BSR. The effect is often attributed to the presence of hydrates in the pore spaces of the sediments that act as cement and reduce the velocity and density contrasts between the individual strata hereby damping the reflection amplitudes in that particular sedimentary section. It has therefore been argued that amplitude blanking can be used to estimate the amount of in situ hydrates in sediments (Lee et al., 1993). Results from ODP Leg 164, however, show that the low reflectance above the BSR can readily be explained as the naturally low background reflectance of a uniform medium (Holbrook et al., 1996] although other factors might be important as well (Wood and Ruppel, 2000).

Amplitude blanking is also observed on seismic records from Lake Baikal. In most cases blanking occurs in a limited zone just above the BSR and fades out upwards. The intensity of the blanking effect varies laterally. It is the least evident on the low-frequency MC airgun-array profiles. On profile 92_07 (Fig. 5B) some blanking can be observed on the shortest-offset channel (above). In contrast, medium-frequency SC airgun data show more distinct blanking effects, such as on profiles GAHY008 (Fig. 3C), GAHY020 (Fig. 3D) and GAHY017 (Fig. 4). The same applies to the SC watergun profile 04_91 (Fig. 5A).

Comparison of the drilling results with seismic profiles through the BDP site where hydrates were retrieved from about 200 m above their stability limit (Fig. 7), illustrates that significant amounts of hydrates (10% of porous volume) can be present in sedimentary sections that are not characterised by amplitude blanking or any other acoustic anomaly. This leads us to conclude that hydrate inclusion cannot be directly and unambiguously related to amplitude blanking.

5.2. Enhanced reflectors below and above the BHSZ

Another common feature on seismic records from gas hydrate provinces is the presence of enhanced reflector segments or high-amplitude reflections below the BSR (Andreassen, 1995; Bouriak et al., 2000; Taylor et al., 2000; Wood and Ruppel, 2000). High-amplitude reflections are caused by strong acoustic impedance contrasts due to changes in physical and lithological properties across the interface. Under normal conditions, properties vary in such a way as to create positive-polarity reflections. In the case that free gas occurs beneath the interface, negative-polarity reflections or “bright spots” will be generated. Even small amounts of free gas in the pore spaces may cause a strong decrease in compressional wave velocity and thus in acoustic impedance (Domenico, 1974; in Sheriff and Geldart, 1995). The existence of free gas accumulations below BSRs has been confirmed at several locations by drilling (Bangs et al., 1993; MacKay et al., 1994; Holbrook et al., 1996; Wood and Ruppel, 2000). Free gas may be trapped beneath partially hydrate saturated sediment due to the reduced effective porosity and permeability above (Ecker et al., 1998).

Enhanced reflections or bright spots are characteristic for nearly all seismic records from Lake Baikal. They occur on some MC profiles (Fig. 5B), and are very common on SC airgun profiles (Figs. 3C, D and 4) and on the SC watergun profile (Fig. 5A) and even on some SC sparker lines (Fig. 6A and B). In most of these examples, they occur — as described above — just below the BSR. Polarity analysis of the enhanced reflections shows that they are reversed in polarity relative to the lake-floor reflection, and they are interpreted to indicate the presence of free gas accumulations.
The enhanced reflector segments on Fig. 5 follow normal stratigraphic boundaries that are inclined with respect to the BHSZ. The up-dip terminations of the bright spots line up regularly at what we infer to be the base of the overlying hydrate-enriched sediment section that effectively seals the gas-bearing strata. The down-dip terminations are much less regular. These observations suggest a distinct stratigraphic and lithological control on the accumulation of the free gas below the BHSZ (preferentially in higher-porosity layers ?), and also on the migration of pore fluids within the sedimentary section.

On Figs. 3C, D and 4, some negative-polarity enhanced reflections extend to a certain height above the BSR, while the amplitude of the other reflectors in this interval is generally suppressed. This suggests that in some places gases may locally migrate or seep into the HSZ. Migration pathways again appear to be primarily stratigraphically controlled. These observations provide an indirect evidence for the existence of a meta-stable situation in which hydrates and free gases are present within the regional HSZ. This could be attributed to transient pulses of pore fluids with a slightly higher than background temperature causing a very localised and temporary shift in the hydrate stability field. Alternatively, stratigraphically controlled capillary effects which may also cause shifts in the hydrate stability field in the order of several meters or tens of meters (Clennell et al., 1999; Henry et al., 1999) cannot be ruled out. Such features are, however, not commonly observed.

5.3. Acoustic frequency-filtering at the BHSZ

Using our multi-frequency data set, we have also investigated qualitatively attenuation (absorption, scattering) and acoustic filtering effects. Higher frequencies are preferentially attenuated and attenuation increases substantially when the sediment is partially gas-saturated (e.g. Sheriff and Geldart, 1995; Castagna et al., 1993).

On the very-high-frequency sparker data (Fig. 6), the enhanced reflectors occurring close to the
estimated depth of the HSZ (in this case 300–320 ms TWTT) appear to act as acoustic basement. No reflection arrivals could be recorded from below this level. Although the penetration limit of the very-high-frequency and relatively low-energy sparker signals in other areas of Lake Baikal is generally not much higher than 350–400 ms TWTT (De Batist and Vanneste, 1997; Vanneste and De Batist, 1998; Back et al., 1999), the sudden and complete attenuation below the enhanced reflectors is quite striking as normally the amplitude of the signal tends to decrease gradually with depth.

We don’t observe a similar sudden attenuation effect on the low- to high-frequency data. Detailed visual frequency analysis using colour-encoded displays of the acoustic instantaneous and response frequencies of SC airgun records GAHY008, GAHY020 and GAHY017, and of SC watergun profile 04_91 reveal a shift to lower instantaneous frequency across the BHSZ. The effect is more pronounced on sections with a distinct BSR and/or enhanced reflections beneath the BSR. We interpret it as attenuation due to the partial filling of pore spaces with free gas. This effect is not observed on the MC airgun-array lines 92_01 and 92_03, neither on the individual recordings nor on the stacked section.

These observations confirm that the BHSZ behaves more effectively as a low-pass frequency filter for higher acquisition frequencies (single-airgun, water-gun, sparker).

5.4. BSR amplitude versus offset analysis

The variation of reflection amplitude as a function of offset or angle of incidence depends on the properties of the reflecting interface, i.e. on the difference in elastic properties between the two media separated by that interface. Increasing negative reflection amplitudes with increasing offset point towards partial occupation of pore spaces just below that reflector with free gases (Sheriff and Geldart, 1995; Ecker et al., 1998; Yuan et al., 1999).

Displaying different channels of the low-resolution airgun-array data from Lake Baikal clearly demonstrates that the reflection amplitude of the BSR depends on offset/angle of incidence. A reflectivity gather plot of the traces composing CDP 380 of line 92_03 clearly shows that the BSR amplitude is higher at larger offsets (Fig. 8). Reflection strength plots of individual recording channels illustrate that this effect is not restricted to some CDPs but is characteristic for the entire profile. This is the case for all MCS profiles used. These observations provide an additional argument confirming the presence of free gas below the BHSZ. Unfortunately, we cannot relate the observed offset-dependent amplitude characteristics to absolute values of free gas content, because we lack sufficiently detailed sub-bottom compressional and shear-wave velocity information and density profiles from the area.

In a way, this offset-dependent behaviour was already illustrated on Fig. 5B, which shows the difference in appearance (reflection strength, continuity, etc.) of the BSR between the short-offset channel display (above) and the large-offset channel display (below) of line MC92_07. On the large-offset display, the BSR occurs as a distinct and continuous high-amplitude reflection, while on the short-offset display it is more diffuse, less continuous and has lower amplitude. The reflection amplitude appears smaller along this profile compared to other MC lines, most probably due to its near-margin location in a different sedimentary and tectonic environment.

The observation of increasing reflection amplitude with offset on all MCS data also explains why the BSR is generally much better expressed (higher-amplitude, more continuous) on stacked MCS profiles than on SC data obtained in the same frequency bandwidth. The stacked data will have a significant contribution of the larger-offset arrivals that will lead to a strong increase in the BSR amplitude.

5.5. Reflection coefficients

We also quantitatively estimated reflection coefficients (a measure for the difference in elastic properties across the interface between two media) of the lake-floor reflection and of the BSR using the multiple quotient method (Warner, 1990). In this method, the amplitude of the lake-floor reflection is assumed to be proportional to the lake floor’s reflection coefficient and to an unknown factor describing the source and receiver geometry. The amplitude is also inversely proportional to the travel path length of the acoustic wave. The unknown factor can easily be eliminated by comparing the primary lake-floor reflection with the
first lake-floor multiple and by taking into account the difference in path length between them. Thus, the reflection coefficient of the lake floor can be calculated. Reflection coefficients of the BSR can be calculated in the same way.

We applied this method to a segment of the shortest-offset channel (offset 495 m) of MC airgun-array profile 92_01, characterised by a regular and continuous lake floor and BSR (Fig. 3A). Because the reflections between the lake floor and the BSR are characterised by weaker amplitudes, they were not taken into account in the calculation. Physically, this means that the sedimentary section between the lake floor and the BSR is considered to transmit the acoustic energy perfectly, i.e. without transmission loss due to reflections, scattering or absorption. For the sake of simplicity, we also assumed that the angle of incidence was nearly vertical (in fact, it was close to 10°). The error induced by this approximation is minimal at low angles (Castagna, 1993). Receiver directivity for these angles of incidence is also of minor importance (Vanneste, 2000).

The amplitudes of the primary lake-floor reflection and its first multiple were picked for the first 450 shot points. Travel path length of the acoustic waves below the lake floor was calculated using the Golmshток velocity model (Golmshток et al., 1997). The lateral variability of both reflection coefficients along the selected profile segment is shown in Fig. 9. Average values for the reflection coefficients are 0.197 for the lake floor and −0.085 (−43%) for the BSR. Comparable values were reported from BSR analyses in several oceanic settings (Hyndman and Spence, 1992; Minshull et al., 1994; Andreassen et al., 1995; Kremlev et al., 1997). Fluctuations in the BSR reflection coefficient are significant, and show an inverse trend compared with the much smaller fluctuations of the lake-floor reflection coefficient. Around SP 275-370, scattering is less significant. Average values along that segment are 0.145 for the lake floor, and −0.063 (−43%) for the BSR. These results indicate that the BSR originates at an interface characterised by a strong decrease in acoustic impedance, but they bring no conclusive evidence for the presence of free gas below the BSR. In combination with all above-described observations, however, we interpret these data as a confirmation for the presence of free gas beneath the BSR. Unfortunately, these results do not allow us yet to really quantify the amount of gas present in the sedimentary section beneath the BSR.

The same method was then applied to the medium-resolution Impuls airgun line GAHY020 (Fig. 3C) that more or less coincides with MC line 92_01. Only that part of the section where the BSR appears as a clear crosscutting reflection (SP 220-300) was considered. Average values are 0.139 for the lake floor and −0.049 (−34%) for the BSR.
5.6. BSR characteristics and continuity: influence of acoustic frequency

The use of different acquisition frequencies off Vancouver Island (MC airgun-array, single airguns) already revealed a decreasing reflection continuity of the BSR with increasing source frequency (Spence et al., 1995). On high-frequency deep-tow data, the BSR is rarely evident (Gettrust et al., 1999). Our seismic data from Lake Baikal also clearly illustrate that the BHSZ produces a distinctly different seismic image depending on the frequency of the acoustic signal and on the acquisition layout. On low-frequency stacked MC airgun array the BHSZ is represented by a classic BSR, i.e. a continuous high-amplitude reflection with reversed polarity. On SC data in the same frequency bandwidth it appears still as a BSR but with smaller amplitude. As discussed above, the difference in amplitude is easily explained by a contribution of the high-amplitude responses recorded in the larger-offset channels of the MCS data. On medium-frequency zero-offset SC airgun data, the amplitude and continuity of the BSR decrease even more and the BSR locally disappears. On higher-frequency data (SC watergun), the BHSZ is no longer expressed as a single reflection, but it is characterised by a series of separate enhanced reflections that most probably mark the top of the free gas zone below the hydrate-bearing sediments.

An explanation for the observed variability of reflection amplitude has to be found in differences in frequency-controlled horizontal (Fresnel zone) and vertical resolution. At lower source frequencies, a larger volume of sub-surface is sampled than at higher frequencies, and also the physical properties that contribute to the strength of the reflection are averaged out over this larger volume. For higher-frequency data, smaller volumes are sampled while also small-scale lateral variations or inhomogeneities become more important (energy scattering, absorption) once their dimensions are smaller than the resolution. This will result in reduced reflectivity and possible a decreasing signal/noise ratio. The fact that on higher-frequency data the BSR is weaker (or not present) indicates that the BHSZ is most probably not a regular interface, or not even an interface at all but rather a discreet interval with gradually changing properties.

6. Extent of the hydrate accumulation zone: constraints for volume estimations

6.1. Vertical extent of the hydrate accumulation zone: seismic data versus BDP results and implications for formation mechanism

Medium-resolution SC airgun profiles GAHY005/006 (Fig. 7A) and GAHY010 (Fig. 7B) were shot across the BDP-97 borehole site. A BSR is observed on parts of the profile, but not in the immediate vicinity of the borehole. The lake floor is virtually flat along the entire profile, no faulting is observed and we do not suspect the stratigraphy to be responsible for strong lateral variations in heat flow and pressure. It is therefore reasonable to assume that the BHSZ occurs at a more or less constant depth along the entire profile, i.e. at 350–390 ms TWT. Using the Golmsh tok velocity model (Golmsh tok et al., 1997), this equals a sub-bottom depth of 320–355 m. In the BDP-97 borehole, gas hydrates were retrieved from 120 and 161 m sub-bottom depth (i.e. 2170 ms and 2215 ms TWTT), thus well above the BHSZ. This indicates that the vertical extent of the hydrate accumulation zone reaches to at least 200 m above the BHSZ. Unfortunately, no results from intermediate depths are available due to poor core recovery. Also, the borehole did not penetrate to the BHSZ.

These observations indicate that sufficient amounts of stabilising gas molecules must have been present in
situ for the formation of hydrates throughout the entire accumulation zone, or that gas must have been supplied via fluid migration from below the HSZ. It is questionable if the organic matter content of the basin-floor turbidite sands and silts is high enough for in situ microbial generation of methane filling up to 10% of porous volume. We propose a process of methane enrichment by means of fluid migration along structural (e.g. through faults, which are very common in the Baikal rift basins) or stratigraphic pathways as an alternative and more plausible scenario for hydrate formation.

6.2. Lateral extent of the hydrate accumulation zone: estimates of quantities

The grid of medium-resolution SC airgun profiles around the BDP hydrate drilling site (SBB, see Fig. 2), was used to estimate the amount of methane or carbon stored as hydrates in the shallow subsurface of the area. The depth of the lake floor and of the BSR was picked at more than 800 points over an area of 700 km² and converted to sub-bottom depths. The estimate is based on the mean sub-bottom depth of the BSR of 306 m. At this depth, the porosity according to Athy’s law (see also Golmshtok et al. (1997) is approximately 56%. In the studied area a volume of 206.69 × 10⁹ m³ of sediments is calculated to fall within the HSZ. We can further assume that:

(1) hydrates occur to at least 200 m above the BSR in the entire area;
(2) the partial hydrate saturation is about 10% of porous volume (maximum).

The total amount of hydrates in the studied area can thus be calculated to be 7.58 × 10⁹ m³. Taking into account a hydrate gas expansion factor of 164 (Kvenvolden, 1998), a maximum volume of 1.24 × 10¹² m³ of methane at STP conditions is contained in the hydrated sediment layer.

Golmshtok et al. (1997), using the entire set of MC airgun-array profiles, mapped two zones of inferred hydrate accumulations, one northeast and one west–southwest of the Selenga Delta (Fig. 1) with a total area of roughly four to six times the size of our study area. Extrapolating our values over the entire area, the total amount of methane stored under the form of gas hydrates in the shallow subsurface of Lake Baikal will not exceed 9 × 10¹² m³ at STP (or 4.6 Gton carbon). This is four orders of magnitude less than the estimated worldwide reserves of clathrated methane in submarine sediments (10,000 Gton) (Kvenvolden, 1998). Furthermore, it is only about 13% of the estimated amount of carbon stored in the hydrate-rich sediments of Blake Ridge, on the Atlantic margin (35 Gton, Dickens et al., 1996).

Unfortunately, the BDP borehole had a very poor recovery and did not penetrate the BSR. Hence, no details are available about the distribution of hydrates in the vicinity of the BHSZ, and about variations in hydrate saturation with depth. It is very likely that hydrate concentrations will increase towards the BHSZ, but due to insufficient information we did not take this into account in our calculations. We also did not take into account the presence of free gas below the HSZ for our volume estimations.

7. Conclusions

- Lake Baikal is the only confined freshwater basin with direct (drilling) and indirect (seismic) evidence for the presence of gas hydrates. Hydrates occur in the deeper-water areas (>580 m of water depth) almost symmetrical to the Selenga Delta, which is one of the main sources of organic matter for the lake.
- The BHSZ is generally represented on MCS profiles by a distinct polarity-reversed BSR that cross-cuts other stratigraphic reflections and mimics the lake floor. Enhanced reflections occur commonly below the BSR, and amplitude blanking can be observed above the BSR, but the effect fades out upwards and its intensity varies laterally.
- The seismic expression of the BHSZ strongly depends on the frequency of the seismic signal and on the acquisition lay-out. Low-frequency MC airgun-array profiles (40 Hz) show all of the typical BSR characteristics. On medium-frequency SC airgun profiles (120 Hz), the amplitude and continuity of the BSR is much less explicit. The higher amplitude of the BSR on MC data can partially be explained by the acquisition lay-out which results in recording high-amplitude arrivals in the long-offset channels as a result of the AVO-effect at the top of the
free-gas layer below the BHSZ. On higher-frequency records, such as the SC watergun profiles (225–330 Hz), the BHSZ is no longer expressed as a single reflection, but rather as a facies change between high-amplitude (enhanced) reflections below and low-amplitude (blanked) reflections above. The very-high-frequency SC sparker data (525 Hz) are characterised by the sudden and complete absorption of acoustic energy beneath enhanced reflections. These sparker data cannot be used to unambiguously determine the BHSZ without additional lower-frequency seismic control.

- The presence of enhanced, polarity-reversed reflections below the BSR (on most data), increasing reflection amplitudes of the BSR with increasing offset, and average BSR reflection coefficients of $-0.063$ to $-0.085$ ($-43\%$ of the lake-floor reflection coefficient) are interpreted as indirect evidences for the presence of free gas below the HSZ. Furthermore, the BSR is seen to act as a low-pass filter (i.e. sudden attenuation of higher frequencies) for the SC medium- to high-frequency data sets.

- Free gas accumulates within specific strata beneath the HSZ, indicating that stratigraphy and lithology are major factors controlling the migration of fluids and the accumulation of free gas in the sedimentary sections. The presence of some inverse-polarity enhanced reflections above the BSR suggests that in some places gases may locally migrate into the HSZ along stratigraphically controlled pathways. Such features are not commonly observed but are interpreted as indirect evidence for the co-existence of free gases and hydrates within the regional HSZ.

- The BSR reflection amplitude depends on both vertical and horizontal (Fresnel zone) resolution, which determine the size of the sub-bottom volume that gives rise to an acoustic reflection. The higher the acquisition frequency, the smaller this volume and the more sensible the acoustic response is to small-scale lateral changes. In this way, alternating series of gas-containing and gas-free strata beneath the HSZ do not necessarily result in a coherent BSR on higher-frequency profiles.

- Significant amounts of hydrates (10% of porous volume) can be present in the sub-surface without any apparent expression on seismic profiles. On SC airgun profiles, no BSR can be observed in the vicinity of the BDP-97 drilling site, and there is no acoustic blanking in the section from which the hydrate samples were collected. This indicates that the absence of the seismic characteristics indicative for the presence of hydrates (i.e. BSR, amplitude blanking) does not necessarily mean that hydrates are not present.

- The extent of the hydrate accumulations and the total estimates of the amounts of methane or carbon stored as hydrates in the lake (4.6 Gton) show that the Baikal gas hydrates do not have any future economic potential.

Acknowledgements

This study was supported by the Belgian OSTC (Project IN/RU/005) and by INTAS (Project 96-1915). The Geophysical Survey (Novosibirsk, Russia) provided the compressor and airguns during the expedition in 1999. We thank M. Grachev, O. Khlystov and A. Duchkov for logistic support, and the captains and crews of R.V. Titov and Vereshchagin for their craftsmanship. S. Guidard is acknowledged for assistance with data processing and helpful discussions and K. De Meersman for assistance with the seismic data interpretation. Thanks are also addressed to J.P. Henriet for introducing gas-hydrate research at RCMG, and to J. Klerkx for making everything possible. Thanks to K. De Rycker and W. Cresens for technical assistance during the expeditions. Dr K. Andreassen and an anonymous referee are acknowledged for thoughtful comments and suggestions that greatly improved the manuscript. M. Vanneste acknowledges a Flemish IWT-fellowship during his PhD research. M. De Batist was Research Associate of the FWO-Flanders.

References


Quaternary depositional systems in Northern Lake Baikal, Siberia. J. Geol. 107, 1–12.


