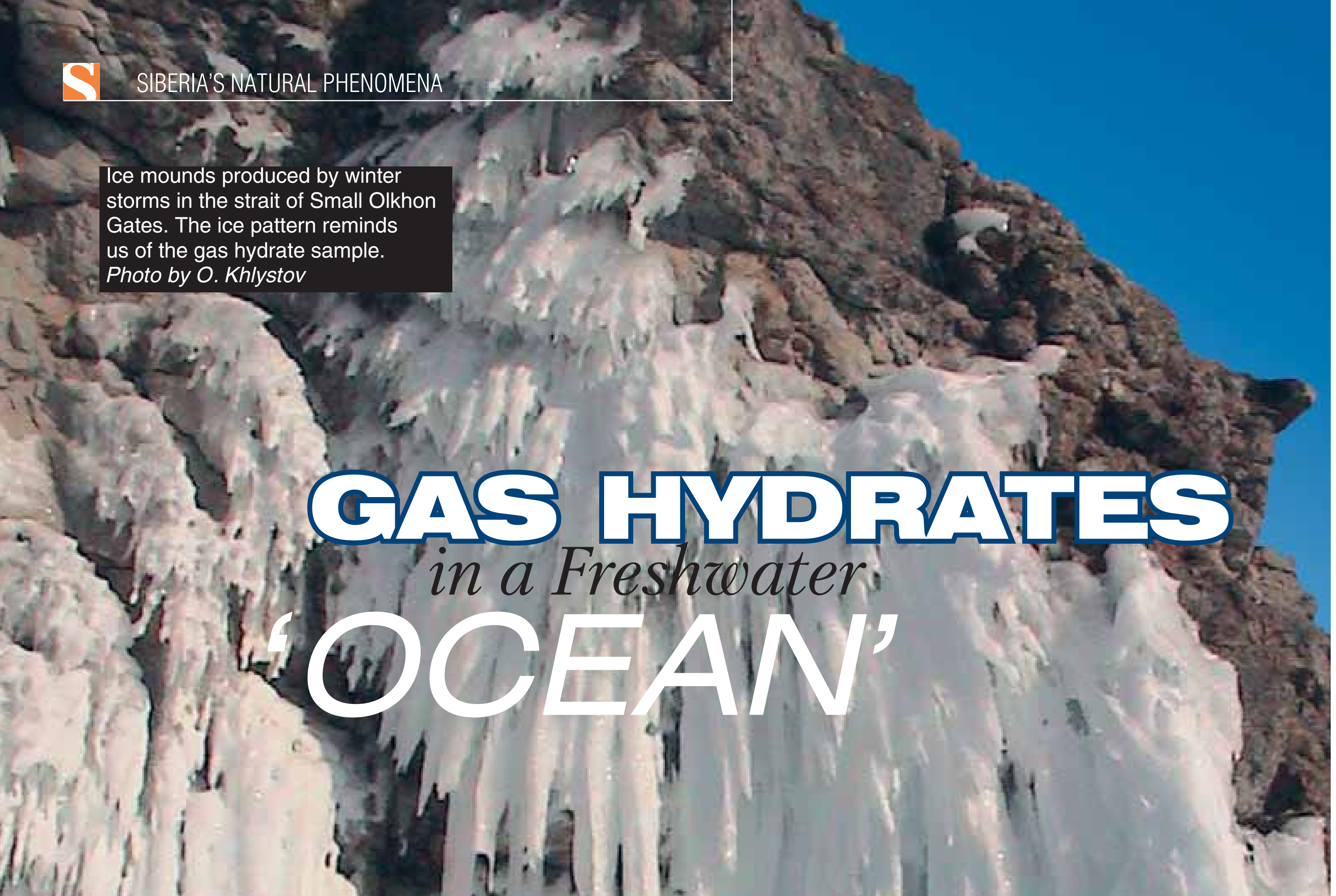

Ice mounds produced by winter storms in the strait of Small Olkhon Gates. The ice pattern reminds us of the gas hydrate sample.
Photo by O. Khlystov

GAS HYDRATES in a Freshwater 'OCEAN'

Gas hydrate crystals are ice-like mixtures consisting of gas molecules trapped within a framework of cages of water molecules.
Photo by O. Khlystov

Jan **KLERKX**, Marc **DE BATIST**, Nickolay **GRANIN**, Tamara **ZEMSKAYA**, Oleg **KHLYSTOV**

The reported results were obtained by the international team of scientists as part of the joint Belgian-Russian project supported by grants from INTAS, SB RAS, and RFBR (1998—2004).

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Jan KLERKX is corresponding member of the Royal Academy of Overseas Sciences of Belgium, he is Honorary Professor of the Siberian Branch of the Russian Academy of Sciences. Jan Klerkx has been involved in research activities on Lake Baikal since the early nineties. He has coordinated or has participated in projects related to methane escape in the lake or to the presence of gas hydrates, funded by the Belgian-Russian scientific collaboration or by INTAS

Lake Baikal is unique in many ways: it is the world deepest and one of the largest lakes, it is known for its pristine water, and it contains a unique endemic flora and fauna. But it is also the only place on Earth where gas hydrates occur in a freshwater environment.

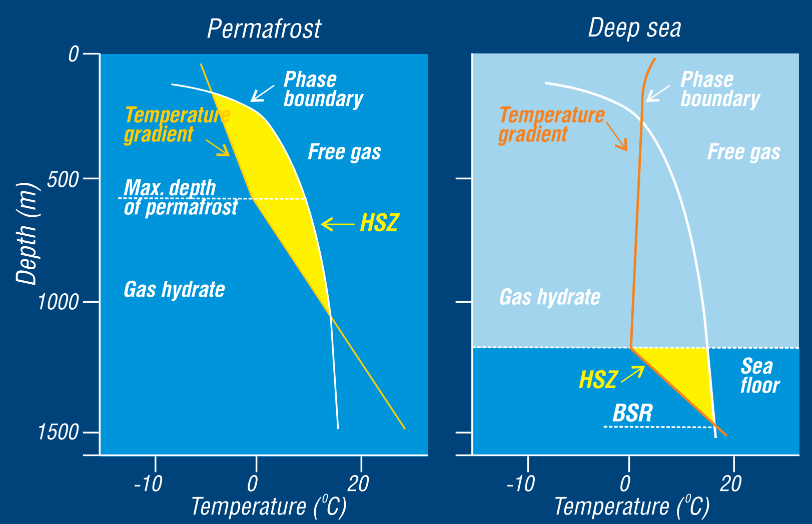
METHANE IN A 'CAGE'

Gas hydrates that might appear at first sight to be simply muddy pieces of ice actually are solid mixtures of gases and water, in which the gas molecules are trapped within a framework of cages of water molecules. Each volume of hydrate can contain as much as 150—180 volumes of gas!

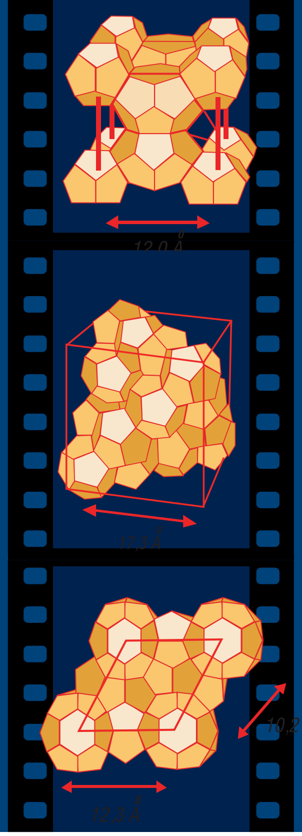
In nature, gas hydrates are formed in permafrost regions and in the marine environment. They consist mostly of hydrates of hydrocarbon gases, most often predominantly of methane. Permafrost associated gas hydrates are known and inferred from well-log data in many onshore and offshore regions in Asia, North America, and Europe, where the base of the permafrost occurs at a depth of more than 250 m. The overwhelming majority of direct observational data on gas hydrates pertains to deep-water subaquatic regions — continental slopes and rises, where they occur at high pressures and low temperatures.

Gas hydrates can exist within rocks and sediments in a zone where they are thermodynamically stable. This is the *Hydrate Stability Zone (HSZ)* that extends downwards from the cold seafloor in water depths greater than about 500 m in non-polar, open ocean conditions, and in permafrost regions from ~200 m to a depth that is determined locally by the rising temperature.

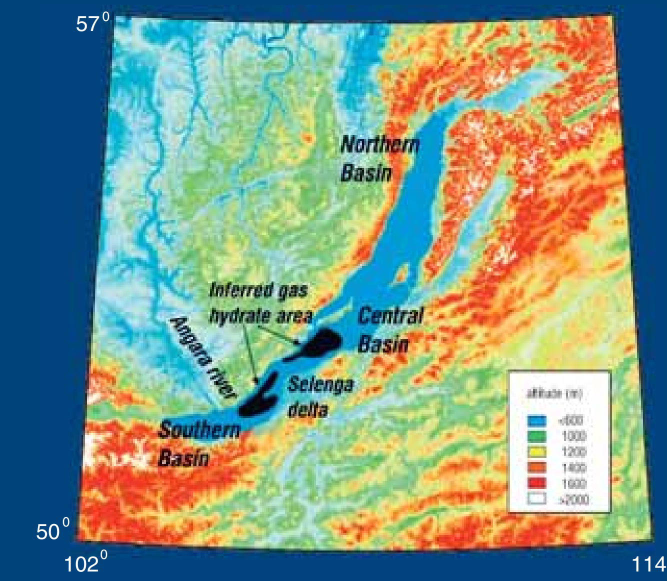
Permafrost methane hydrates are found in Alaska, Canada, and Russia in the conditions of low pressures and temperatures. They occur as part of a compound water-ice and hydrate permafrost. Water-ice is stable from the surface at about 0° C whereas the hydrate is stable from some depth below the surface (depending on average surface temperature, total pressure, and geothermal gradient) to some depth below the base of the water-ice stability zone.



PT conditions of the Hydrate Stability Zone (HSZ). Gas hydrates can exist within rocks and sediments in a zone where they are thermodynamically stable. This is the Hydrate Stability Zone



Every cloud has a silver lining. Being a carbon store, gas hydrates are a source of fossil fuel: The total amount of methane occurring in hydrated form is estimated to exceed 10^{19} g of methane carbon, which is more than the total amount of all other known sources of organic carbon. For this reason, gas hydrates are seriously considered as an alternative energy resource for the future, i. e. industrial exploitation of gas hydrate deposits in the oceans is expected in the coming decades.



Estimated thickness of sediments inferred to contain gas hydrates in Lake Baikal

THE EVIL OR THE GOOD?

Increased attention is paid nowadays to natural methane hydrates for environmental and economic reasons.

First, hydrates containing enormous amounts of methane store the so-called 'greenhouse' gas which can cause a global change of climate. Methane is 21 times more efficient as a greenhouse gas than carbon dioxide. Hydrates exist in nature at the limits of their phase stability, and even minor changes in temperature or pressure are sufficient for their irreversible decomposition. Voluminous methane release can result in acceleration of global rise of the Earth's temperature by 10 to 100 times, which would lead to further decomposition of natural hydrates. Arctic regions and adjoining areas, rich in gas hydrates deposits, are regions at great danger.

Yet this is not the only threat posed by gas hydrates. Their destabilization on continental margins, triggered by changes in bottom-water temperature or by a sealevel-induced decrease in hydrostatic pressure, may initiate submarine landslides, which in their turn may cause tsunamis and catastrophic flooding of the coastal areas. Gas hydrates are thus a submarine source of geohazard, though the process by which they generate underwater landslides remains little understood.

The overwhelming majority of direct observational data on gas hydrates pertains to deepwater subaquatic regions of land-locked and marginal seas where they exist at high pressures and low temperatures

Flares of sub-ice natural gas in the region of the Selenga Delta.
Photo by O. Khlystov

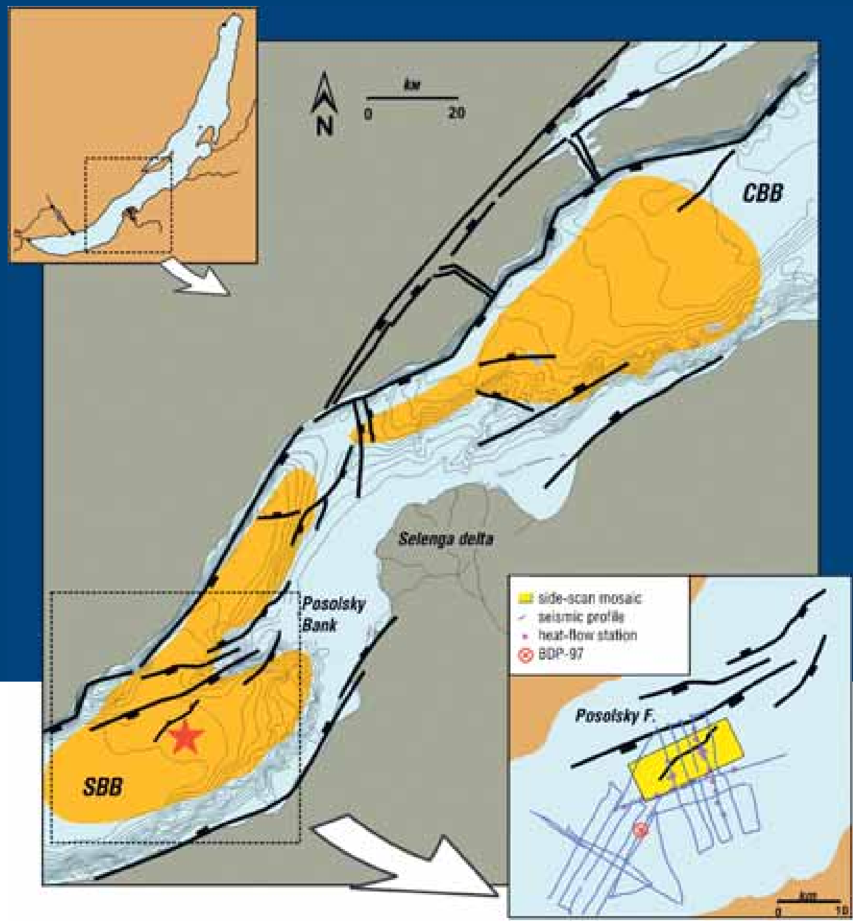
DISCOVERIES ON BAIKAL

During the last decades, occurrences of gas hydrates in the marine environment were found in many places in all oceans of the world, which attracted also the attention of geophysicists and geologists who were studying the bottom sediments of the freshwater ocean of Lake Baikal.

As already noted, gas hydrates can form in marine or lacustrine bottom sediments when several conditions are fulfilled: the sediments have to contain a sufficient amount of gas and water; they have to be submitted to relatively high pressure conditions and low temperatures, which means water depths of more than 500 or even 700 to 800 meters. These conditions exist in the deeper parts of Lake Baikal. A sufficient content in methane can be expected particularly where river input is important, such as around the Selenga delta. Rivers transport considerable amounts of organic matter that is deposited on the bottom and buried in the sediments to transform into methane.

Indirect evidence for the occurrence of gas hydrates in marine or lacustrine sediments can be obtained from the analysis of seismic reflection profiles. As a matter of fact, due to contrast in physical properties between the hydrate-bearing sediments and the underlying sediments containing gas without hydrates, a particular reflector appears on seismic profiles at the base of the gas hydrate stability zone, which is called *Bottom Simulating Reflector (BSR)*.

During a Russian-American seismic campaign for the intensive investigation of the bottom sediments of Lake Baikal, between 1989 and 1992, Alexander Golmshtok noticed the presence of such a Bottom Simulating Reflector over large areas north and south of the Selenga delta.



Estimated thickness of gas hydrate layer above BSR (yellow) observed in the area around the Selenga River delta at water depths exceeding 580 m, i.e. on the deeper delta slope and the generally flat basin floors of the adjacent sub-basins. Black lines delineate faults, asterisk marks the place where gas hydrates were recovered by gravity coring in 1997 (BDP-97).

The inset shows acoustic profiles of 1997 (violet) and the area of high-resolution deep-tow side-scan sonar sounding (light-yellow); violet points are heat flow stations

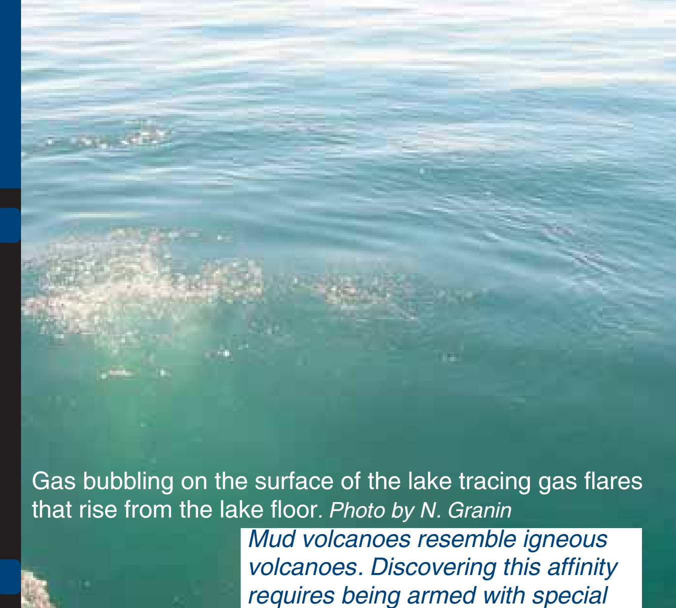
CBB — Central Baikal Basin
SBB — Southern Baikal Basin

It was the very first indication that gas hydrates could be present in Lake Baikal. In 1997, the first samples of gas hydrates were recovered during the Baikal Drilling Project deep drilling experiment under the leadership of Academician Mikhail Kuzmin, Director of the Institute of Geochemistry in Irkutsk. Layers of gas hydrates were sampled at the depths of 120 and 160 meters under the lake floor. By this discovery it was consequently confirmed that gas hydrates effectively exist within the lake sediments.

FROM BELGIUM AND ST. PETERSBURG OFF TO BAIKAL

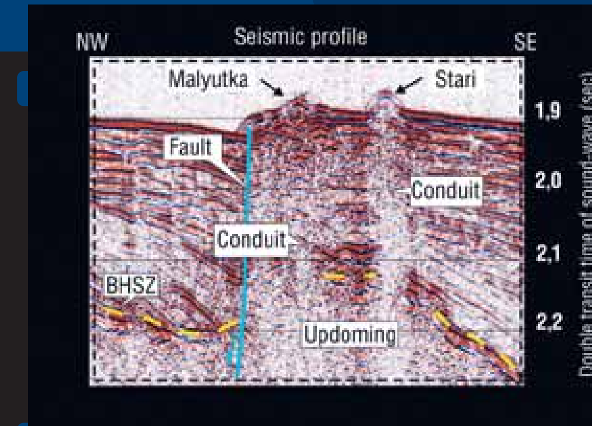
The curiosity of the scientists who were investigating the Baikal sediments was attracted by a particular feature of the BSR. Alexander Golmshtok already had noticed that the BSR on the seismic profiles, instead of having a regular pattern and mimicking the lake floor as it is usually the case, exhibited an irregular behaviour. It appeared disrupted along the faults, which made him suppose that the gas hydrate layer was locally discontinuous in places where gas hydrates were destabilized, resulting in methane eruption on the lake floor.

This was the reason to initiate a campaign of high-resolution seismic investigation of the bottom sediments, coupled with side-scan profiling, in order to image the morphology of the lake floor. This initiative was supported by a project of the Russian-Belgian scientific cooperation and by INTAS. An expedition, organised by the Limnological Institute in Irkutsk, under the leadership of Professor Marc De Batist of the University of Gent (Belgium), during the summer of 1999, defined all details of the BSR in the Southern Baikal Basin, south of the Selenga delta, and evidenced well-marked zones of disruption of the gas-hydrate layer along faults, and also vertical gas channels that developed along the faults and extend up to the lake floor. The side-scan sonar image of the lake floor recorded by the specialists of VNII Okeangeologia (St. Petersburg) revealed a series of gas venting structures on the lake floor, which resembled small mud volcanoes. These structures, with a width close to 2 km, are parallel to a fault zone, at a water depth of about 1350 metres.



Gas bubbling on the surface of the lake tracing gas flares that rise from the lake floor. *Photo by N. Granin*

Mud volcanoes resemble igneous volcanoes. Discovering this affinity requires being armed with special equipment or going down into water depths where liquid and gas plumes originate to rise as high as 25 m and to show up as bubbling on the water surface

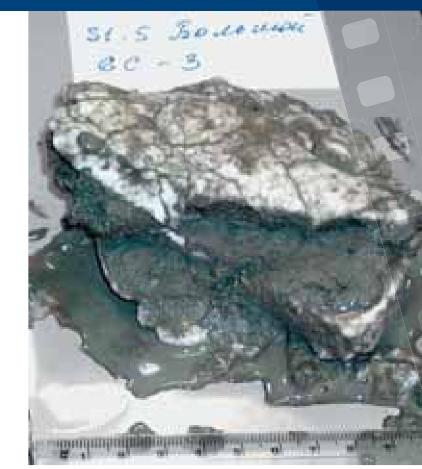


Seismic section across the Southern Baikal Basin showing irregularities of the BSR, its updoming and disruption. The section across the Stari and Malyutka venting sites is detailed (INTAS project, RSMG, Marc de Batist)

'FIZZY DRINK' OF VOLCANOES' MAKING

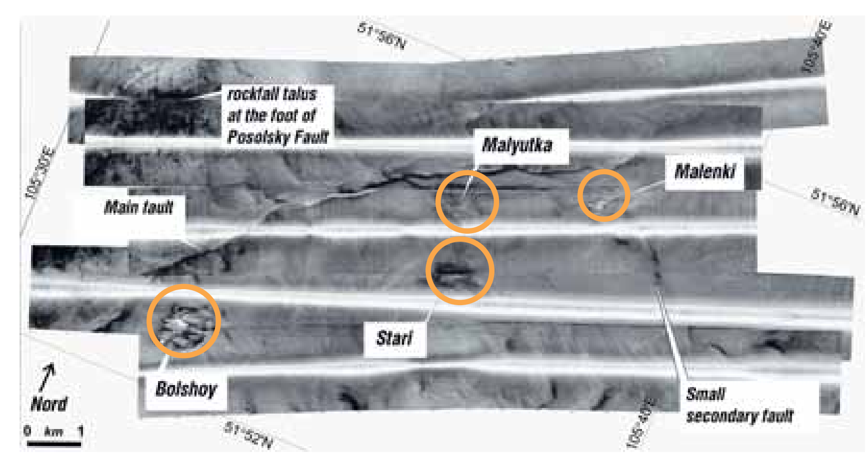
Mud volcanoes are morphological structures on the sea floor that resemble igneous volcanoes. They are formed by the expulsion on the sea floor of water, gas, and mud from the underlying sedimentary sequence, when pressure builds up at depth. During eruptive phases, and even during periods of quiescence, these mud volcanoes can release large amounts of fluids and gas. Often they occur in tectonically active zones but can also occur in zones where the sediment accumulation rates are high. Mud volcanoes are particularly abundant in and around the Black Sea and the Caspian Sea.

Surprisingly, echosounding records over mud volcanoes in Lake Baikal showed a plume of about 25 metres in the water, escaping from the venting sites. Chemistry analysis of water in these plumes indeed confirmed an increased content of methane. The discovery of the active venting structures on the lake floor allowed us to suppose that concentrations of near-bottom gas hydrates might be present within the mud volcanoes, as is the case in many mud volcanoes such as in the Black Sea.



Methane hydrate from the Southern basin of Lake Baikal. *Photo by A. Egorov*

A high-resolution deep-tow side-scan sonar mosaic shows four large morphological anomalies at the lake floor named Malenki, Bolshoy, Stari, and Malyutka.
Their bathymetry has been mapped in detail by single-beam echosounding. These anomalies, which correspond to mud volcanoes, are quite irregular in shape and measure up to 800 m across and 200 m high (INTAS project, engineering performance by Sonic group, VNII Okeanologiya, St. Petersburg)



The term 'near-bottom gas hydrates' refers to gas hydrates that deposit in the uppermost sedimentary layers. For a correct positioning exactly above the venting sites, shallow gravity sediment coring was performed from the ice in winter 2000 during an expedition organized by the Limnological Institute in Irkutsk, led by Jan Klerkx.

In one of the mud volcanoes, a gas hydrate layer about 10 cm thick, composed of large crystals with a size reaching 7 cm, was recovered from a depth of 15 to 40 cm under the lake floor. In many other places, the structure of the sediment, the high content in gases within the cores, and the thermal properties of the sediment led to assume the presence of fine-grained gas hydrates that unfortunately decomposed during the core recovery to the surface.

The sediments on the bottom of Lake Baikal consist typically of gray diatom-rich silts alternating with turbidites. In the vicinity of the mud volcanoes, the diatom-rich layer contains diatom species that lived about 3 m. y. BP and have been extinct for a long time. In the normal sedimentary succession of the Southern Baikal Basin, the horizon containing these diatoms should occur at a depth of approximately 300 meters. As it is common in mud volcanoes that the fluids originate deep in the sediments and carry material from that depth with them during eruptions, it is not unusual to find diatoms from a depth of 300 meters that have been transported to the surface along the feeding channels of the mud volcanoes.

The poetic term FLUID (fluidus in Latin means flowing) used by geologists refers to mobile liquid and gaseous components of magma or gas-saturated solutions that circulate deep in the Earth's subsurface

METHANE AND THE QUALITY OF BAIKAL WATER

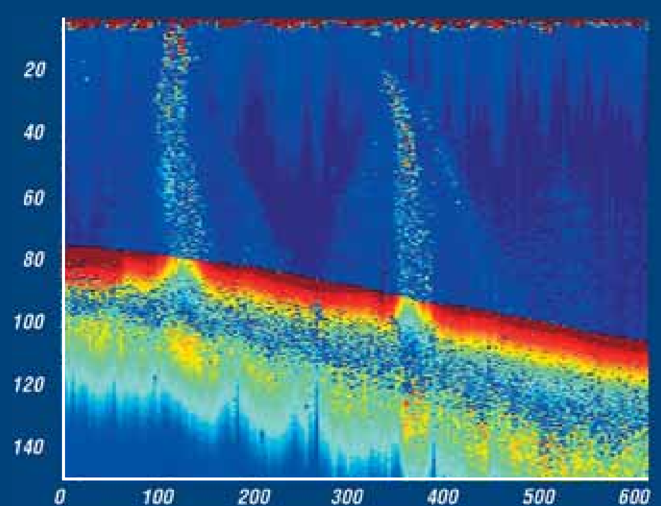
As it is evidenced that methane is introduced in the Baikal water from the bottom sediments in the venting sites, the question arises what is the effect of this methane on the quality and the structure of the Baikal water?

During recent years the methane content of the water has been intensely investigated. Near the bottom only a slight increase in methane content has been noticed in the vicinity of the seep areas. However, the highest methane content has been measured in the upper water layers (25—50 m). Also the geographical distribution of methane in the upper layers clearly relates the major methane input in the lake to inflowing rivers. From the chemical point of view, the methane originating from bottom seepages is clearly subordinated to methane from surface sources.

However, long-term records of the physical parameters of the water column clearly demonstrate the presence of an anomalous mixed deepwater layer in the Southern Baikal Basin, which is characterized by a temperature increase with depth. Water samples from this layer sometimes show elevated methane and — even more rarely — slightly lower oxygen concentrations. The layer is attributed to mixing caused by methane release on the lake floor. Consequently, although not consistently affecting the chemistry of the water column, the methane can affect its physical structure.

The ongoing studies on Lake Baikal, detailing the morphological features of the lake bottom and analysing the structure of the subbottom sediments by different remote techniques, confirm now that the venting structures that were discovered in 1999 in the Southern Baikal Basin are not unique. New sites of destabilisation of the gas-hydrate layer, new venting sites and new venting structures have also been discovered in the Central Baikal Basin. Thus, large areas of the Central and Southern Baikal Basins contain methane hydrates in the upper section of the sedimentary fill.

Acoustic image of methane gas flares in Lake Baikal ejected into the water from bottom sediments. *Echosounding record by N. G. Granin*



Shallow gravity sediment cores were retrieved from the ice above the venting sites during the winter trip of 2000 organized by the Limnological Institute in Irkutsk. *Photo by N. G. Granin*

BAIKAL IS UNIQUE IN ALL WAYS

One fundamental question however remains. Why does the gas-hydrate layer, which is stable in the major part of the oceanic environment, become unstable in Lake Baikal? And why does it result in methane release at the lake floor?

Several processes may be invoked for explaining the destabilisation of the gas-hydrate zone, the dissociation of gas hydrates and the upward channelling of fluids: high sediment accumulation rate, tectonic uplift, fluid flow, local extension or slumping.

When the sedimentary section is rapidly thickening by sedimentation, the base of the gas hydrate stability zone shifts upward whereby the lowermost gas hydrates become destabilized. The area around the Selenga delta is the site of major input

Information on gas escape in Lake Baikal has been collected for about one hundred and fifty years. The very first travellers who visited Lake Baikal already mentioned the existence of gas seepage in Lake Baikal. In 1868, a special expedition was organised to study this phenomenon. In the beginning of the 20th century, a more detailed description was given by Academician Vladimir Obruchev: "Long before the complete ice break, naked places appear, which are called 'ice steamthroughs' by the inhabitants; they are formed, in their opinion, due to the influence of warm underwater springs. Just after the freezing of the lake, when the ice is still very thin, large gas bubbles are gathering under the ice in the places where the ice steamthroughs will develop in the future.

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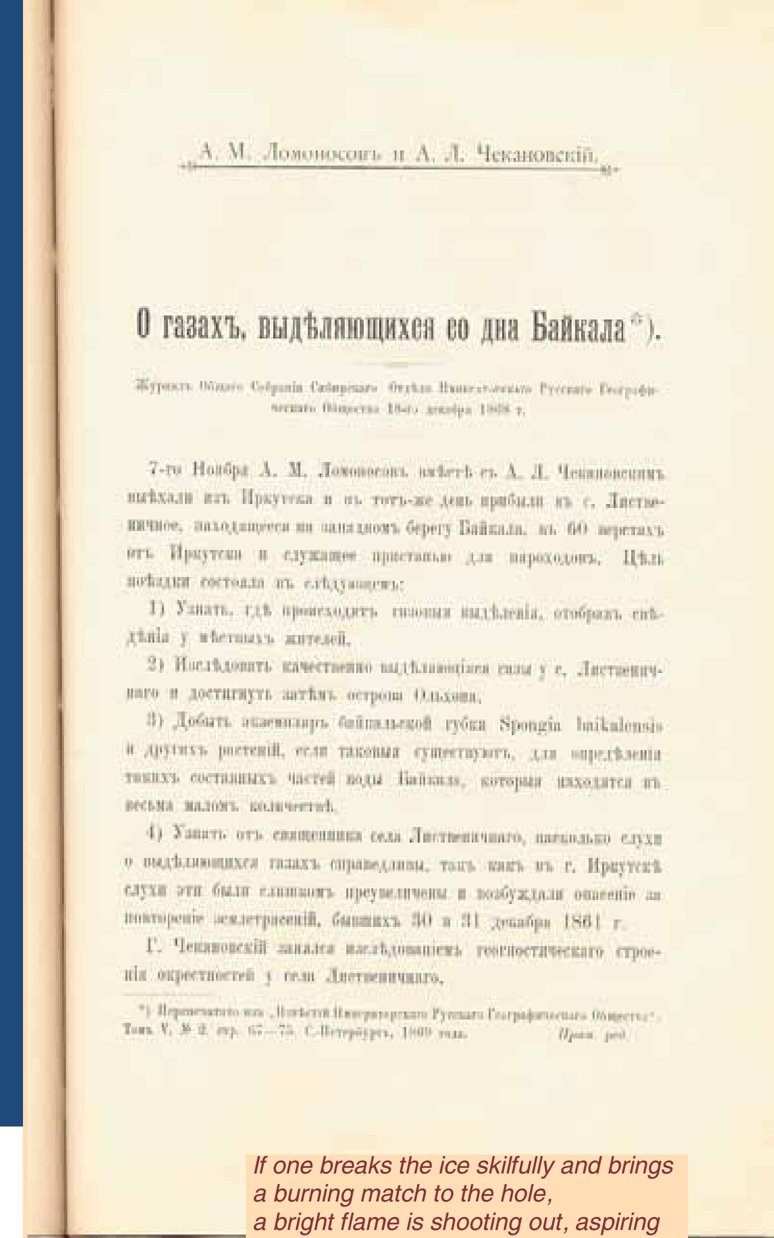
In winter gas bubbles above venting sites become frozen into the ice.
Photo by N. G. Granin

Methane stored in hydrated form threatens the human race with climatic and geological hazard, but is at the same time the potential energy resource for the future

Gas hydrates recovered by gravity coring appear as white opaque inclusions of two types: massive lumps enclosing thin fissures filled with sediment, and numerous inclusions in the sediments up to 2 cm in size, isometric and plate-like in shape. According to gas chromatography data, methane is the dominant component of the hydrated gas (up to 99 % of total hydrocarbons).
Photo by Jan Klerkx



А. М. Ломоносовъ и А. Л. Чекановскій.

О газахъ, выдѣляющихся со дна Байкала*).

Журналъ Общаго Собранія Сибирскаго Отдѣла Императорскаго Русскаго Географическаго Общества 18-го декабря 1868 г.

7-го Ноября А. М. Ломоносовъ вмѣстѣ съ А. Л. Чекановскимъ выѣхали изъ Иркутска и въ тотъ-же день прибыли въ с. Лиственичное, находящееся на западномъ берегу Байкала, въ 60 верстахъ отъ Иркутска и служащее пристанью для пароходовъ. Цѣль поѣздки состояла въ слѣдующемъ:

1) Узнать, гдѣ происходятъ газовыя выдѣленія, отобравъ свѣдѣнія у мѣстныхъ жителей.

2) Изслѣдовать качественно выдѣляющіеся газы у с. Лиственичнаго и достигнуть зимою острова Ольхона.

3) Добыть экземпляръ байкальской губки Spongia baikalensis и другихъ растеній, если таковыя существуютъ, для опредѣленія тѣхъ составныхъ частей воды Байкала, которыя находятся въ весьма маломъ количествѣ.

4) Узнать отъ священника села Лиственичнаго, насколько слухи о выдѣляющихся газахъ справедливы, такъ какъ въ г. Иркутскѣ слухи эти были слишкомъ преувеличены и возбуждали опасенія на повтореніе землетрясеній, бывшихъ 30 и 31 декабря 1861 г.

Г. Чекановскій занялся изслѣдованіемъ геогностическаго строенія окрестностей у села Лиственичнаго.

*) Перепечатано изъ „Извѣстій Императорскаго Русскаго Географическаго Общества". Томъ V, № 2, стр. 67—75. С.-Петербургъ, 1869 года. *Прим. ред.*

of sediments into the lake, which consequently results in rapid thickening of the sedimentary pile. When a fault reaching the base of the gas-hydrate zone is reactivated, it may tap the area where fluids and free gas from gas-hydrate dissociation accumulate underneath the BSR. This allows the fluids to discharge along the fault and to reach the lake floor. These fluids, being warmer than the surrounding sediments, destabilize gas hydrates and the base of HSZ is moving upward.

The presence of fluids moving along fault conduits is considered to play a role in the destabilization of gas hydrates, as well as directional fluid migration, mainly in a compressive environment. Although the overall conditions of the Baikal basin are extensional, there are indications of local shortening of the sedimentary layers, which can result in dewatering of the sediments and generation of a fluid flow.

It is postulated that the combined effects of rapid sedimentation in the area of the Selenga delta and fluid flow along the direction of minimal compression result in accumulation of fluids underneath the base of HSZ, thermal doming and upward movement of the BSR which will finally be disrupted. Methane-rich fluids will move upwards and erupt at the lake floor along the faults that are activated in the active tectonic environment of Lake Baikal.

This unusual succession of processes of methane accumulation in the form of hydrates and subsequent methane release from destabilising hydrates, and related methane venting and mud volcanism at the lake floor, make Lake Baikal a unique geotope. And the last but not least. Remember that hydrated methane in water environments is stable at low temperatures and high pressures. This makes difficult its investigation in warm deep seas where gas hydrates just never 'live' up to the surface. But they can be safely recovered in a very deep cold lake, such as Baikal, more so that the frozen winter lake is an advantageous working floor. The Baikal natural laboratory welcomes scientists from St. Petersburg and Japan, from small continental Belgium, and from the remote shores of the warm Indian ocean.

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If one breaks the ice skilfully and brings a burning match to the hole, a bright flame is shooting out, aspiring sometimes up to one sazhen (+- 2 m) high, depending on the bubble size". The greatest attention was paid to this phenomenon during the 1920s—1930s, since in that time Baikal was believed to be a promising oil-bearing region, as the escaping gases were shown to contain a significant amount of methane. According to historic accounts, gas escape from the lake was much more intense until the first half of the 20th century than it is at present.

The Editorial Board thanks Oleg Khlystov, chief reseacher of the group "Geology of Lake Baikal" (Limnological Istitute of SB RAS), for his assistance in preparation of the publication