

Oil in the Lake of World Heritage

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Lake Baikal is the oldest and deepest lake in the world. It contains approximately 20% ($23 \cdot 10^3 \text{ km}^3$) of the world's surface reserves. Since the community of diverse endemic organisms of the lake has not suffered from human impact at its recent stage of development [1], it is included into the UNESCO world heritage list. Unique features of Lake Baikal include natural oil seeps in its shelf zone, which have been known since the 18th century [2]. At oil shows in the middle and south sections of Lake Baikal, oil occurs as bitumen in shore cliffs or rises from the lake bottom as floating spherules of viscous hydrocarbons that make up spills (up to 1.5 m across) in an area of approximately 1 km² in summer. In winter, the floating oil is accumulated under ice as bituminous films and inclusions in narrow fissures. The oil composition corresponds to the biodegraded type. Its origin and age were debatable until recently [3].

In 2005, a new natural oil occurrence was discovered in deep-water settings of Lake Baikal that differs from the previously known ones. The discovery poses a problem concerning the role of natural oil occurrences in the ecosystem of the unique basin and its petroleum potential. The new oil occurrence was discovered in Middle Baikal (Cape Gorevoi Utes) owing to satellite observations of a dark spot (~1 km across) on the lake surface in the spring of 2003. Observations of 2004 and 2005 showed that such a spot appears in this area every spring. In July 2005, numerous oil spots (up to 1 m in diameter) were recorded on the lake surface in an area

of approximately 1 km². Echo sounding revealed an underwater acoustic anomaly in the form of a gas flare ~500 m high.

The oil sampled from the lake surface was studied using the gas chromatography/mass spectrometry method (Fig. 1). The samples contained *n*-alkanes, acyclic isoprenoids, and polycyclic aromatic hydrocarbons. Based on the database including characteristics of molecular indicators for 76 genetically different oil fields [4], the ratios of molecular indicators (pristane/phytane 6.7; dibenzothiophene/phenanthrene <0/1), and the low sulfur content (<0.08%), we concluded that the samples correspond to oils formed in sediments of deep freshwater basins during the Oligocene–Early Miocene. This age estimate obtained for the Baikal oil based on molecular indicators is consistent with one hypothesis, according to which the Baikal oil is not older than the Cretaceous and it originates from organic matter buried in a freshwater basin [5].

The bottom sediments were sampled at the center of the gas flare and at its periphery (at a distance of 200 m). The core taken in the central part (0–40 cm) is composed of dark gray reduced massive clayey–silty sediment. The Holocene diatomaceous ooze layer typical of Baikal is missing at the surface. The sediment was mixed with oil and saturated with gas. The oil content exceeds 10% of the dry sediment. The second core demonstrates distinct bedding along its entire length. According to biostratigraphic data (*Cyclotella minuta*, *Aulacoseira baicalensis*, and others), the sediment represents the Holocene diatomaceous ooze. The surface sediment (upper 4 cm with a brown color) is oxidized, while the remainder of the core is reduced (gray in color). The interval of 10–40 cm hosts lenses and interbeds of silt and fine- to medium-grained sand with small brown oil droplets (up to 3 mm across) fringed by small gas bubbles. The oil content in this core interval is approximately 1% of dry sediment.

The difference between two sampled cores in terms of oil-and-gas occurrence and lithology is probably explained by different intensities of their influx. The central part of the gas flare is characterized by permanent fluxes of gas, oil, and groundwater, which provide

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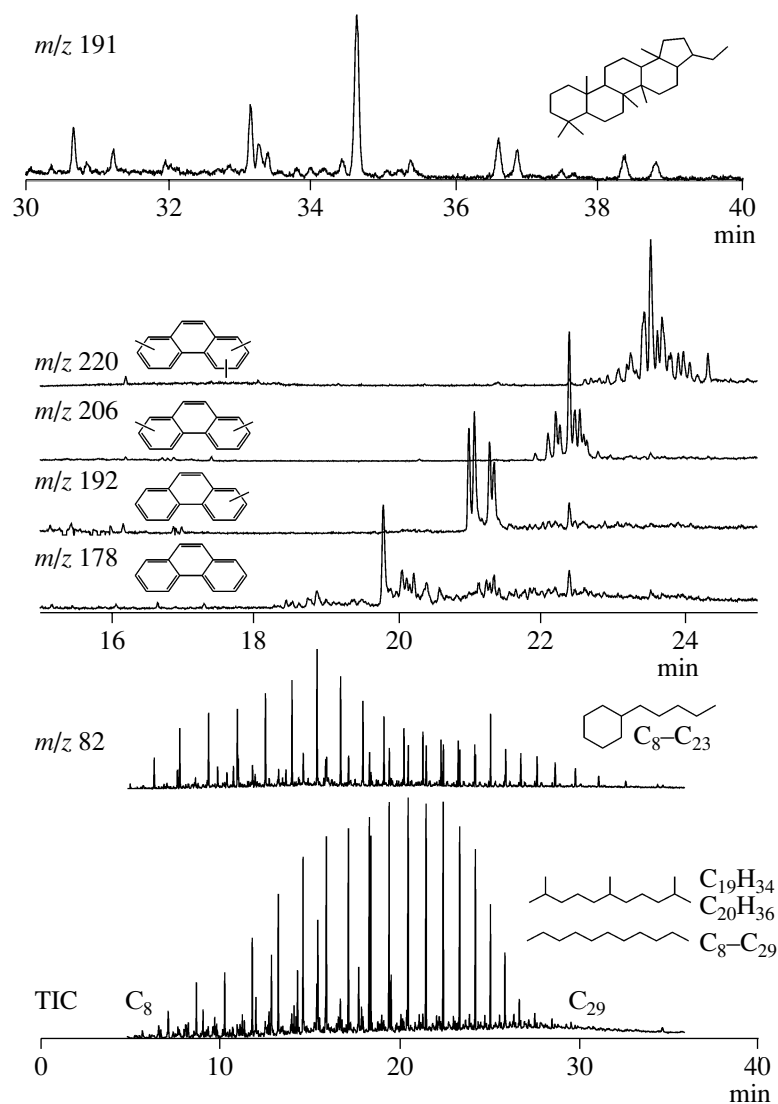


Fig. 1. Chromatogram of oil solution (1%) in chloride methylene. Oil sample was taken from the water surface of Lake Baikal in the Cape Gorevoy Utes area in July 2005. (TIC) homological succession of *n*-alkanes with C₈ to C₂₀ and acyclic isoprenides (pristane and phytane); (*m/z* 82) *n*-alkylcyclohexanes with C₈ to C₂₃; (*m/z* 178) phenanthrene; (*m/z* 192) methylphenanthrenes (methylanthracenes); (*m/z* 206) dimethylphenanthrenes (dimethylanthracenes); (*m/z* 220) trimethylphenanthrenes (trimethylanthracenes); (*m/z* 191) hopane series.

mixing of clayey sediments and removal of the upper Holocene diatomaceous layer. In this area, the oil–gas mixture enters the water as gas bubbles with an oil film. These bubbles are reflected in the echo-sounding record as the gas flare. As the bubbles ascend, gas is dissolved and oil films merge into small spheres, which float to the surface autonomously to form oil spots at the lake surface. In the peripheral part of the gas flare, where vertical permeable zones are lacking, gas and oil mainly spread along horizontal silty–sandy interbeds and accumulated therein. However, their primary bedding is not distorted.

Gases from sediment cores were studied in the onboard laboratory. They are composed of hydrocarbon gases with an insignificant admixture of CO₂ (up to

0.2%). Hydrocarbon gases are largely represented by methane (99%) and its homologues (approximately 1%). Such a high content of methane homologues is atypical of recent Baikal sediments. The component composition of homologues is also atypical: a very high share of propane as compared with that of ethane and a high proportion of butanes, with isobutane substantially prevailing over normal butane. The hydrocarbon gases also contain admixtures of pentane, hexane, and heavier homologues. We conducted isotopic analysis of carbon in methane and ethane to determine the origin of hydrocarbon gases in the oil seep area. The $\delta^{13}\text{C}(\text{CH}_4)$ value varied from -44.3 to -43.74% , and $\delta^{13}\text{C}(\text{C}_2\text{H}_6)$ is -23.35% . These parameters indicate the thermogenic nature of the gases [6] associated with the oil.

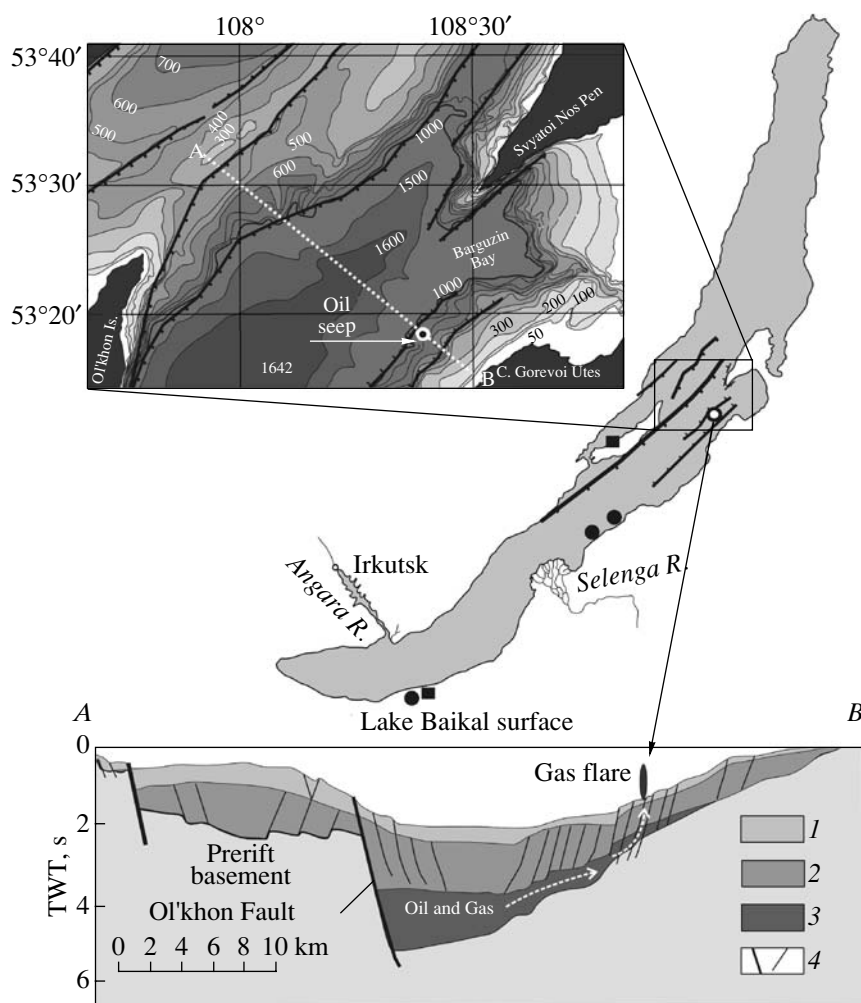


Fig. 2. Map of Lake Baikal with natural oil seeps along with bitumen (black circles) and coal (black box) outcrops. The inset shows the bathymetric chart of the new oil show area. The schematic cross section (A–B) and recent active faults are based on CMP materials [7–9]. (1) middle Pleistocene–Holocene; (2) Pliocene–lower Pleistocene; (3) Oligocene–Miocene; (4) faults.

Taking into consideration the geological structure of the Middle Baikal Basin, we may assume that Cenozoic sediments in the lake can serve as a source for oil. Indeed, multichannel seismic profiling by the CMP method revealed that the sedimentary cover of the basin in the studied area is composed of three seismostratigraphic sequences (Fig. 2). In the northwestern area with the thickest sediments (7.5 km), they are bordered by the scarp of the main (Ol'khon) fault. The lower acoustically transparent (i.e., lacking reflecting horizons) seismostratigraphic sequence (maximal thickness 4.5 km) corresponds to sediments accumulated in the Oligocene–Miocene, since the sequence began to accumulate during the first stage of Baikal rifting in the Oligocene. The upper boundary corresponds to the Miocene/Pliocene transition from slow rifting to fast rifting. The sediments of the upper part of this seismostratigraphic sequence correlate with Miocene coal-bearing sediments of the Tankhoi and Khalagai forma-

tions on the eastern coast of the Baikal South Basin and western coast of Ol'khon Island [7–9].

Along the eastern coast of the lake, the sedimentary cover is crosscut down to the basement by the currently active normal faults. It is clear that oil spills discovered at the lake surface are discharged into the water along permeable zones of these tectonic fractures. The oil is probably generated not in sediments of the oil seep area but in sediments of the lower (transparent) seismostratigraphic sequence developed in the middle part of the lake, where thermobaric conditions are most favorable for oil and gas generation. Here, the lake is more than 1.5 km deep, the seismostratigraphic sequence is more than 4 km thick, and the overlying sequence is 3 km thick. Pressure in sediments of the lower seismostratigraphic sequence increased with deepening of the basin and accumulation of overlying sediments. At present, the pressure exceeds 700 atm and the temperature is estimated at $>200^{\circ}\text{C}$. Oil and gas generated from the

dispersed organic matter under elevated thermobaric conditions probably migrate toward the eastern coast of the basin along reservoirs of the lower seismostratigraphic sequence to the permeable zone of the faults and ascend to the lake bottom. Saturation of sediments of this seismostratigraphic sequence with oil and gas is probably responsible for its acoustic transparency.

Despite constant generation of oil spots at the water surface, the area covered by them (1 km²) remains unchanged. According to our estimates, approximately 4 t of oil is discharged in this area every year. The constancy of the size of the polluted area indicates that oil is rapidly transformed. The microbiological community plays an important role in this process. The results obtained show that the community is dominated by oil-oxidizing bacteria. The ratio between them and heterotrophic bacteria in the maximal oil accumulation area reaches 120. In water samples taken away from the oil spots, the population of oil-oxidizing bacteria substantially decreases and the ratio between oil-oxidizing and heterotrophic varieties falls to ~6. In Baikal areas located beyond natural oil occurrences, this ratio ranges from 0.02 to 0.10. Thus, we have revealed that the Baikal ecosystem copes with its natural pollution by hydrocarbons primarily due to its microbial community.

It should be noted, however, that the natural gradual oil discharge (4 t/yr) is incomparable with catastrophic man-caused oil spills due to mismanagement of industrial activity in Baikal, a world heritage lake.

Bottom sediments were recovered by a piston corer, and oil samples were taken from the lake surface in the area with the following coordinates: 53°18'24" W, 108°23'20" N. The chromatographic analysis of oil samples (1% solution in methylene chloride) was conducted with an Agilent (GC 6890, MSD 5973) chro-

matographic mass spectrometer with separation of gases in a 50-m ULTRA-2 column ($d = 0.32$ mm). The composition of hydrocarbon gases was determined with a KhPM-2 portable chromatograph equipped with a flame ionization detector. The carbon isotope composition of methane was determined with a VG OPTIMA (ISOTECH, FISIONS Company) mass spectrometer equipped with a device for the preliminary chromatographic separation of gas samples.

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