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ORIGINAL ARTICLE

Holocene and Late Glacial sedimentation near steep slopes in southern Lake Baikal

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ABSTRACT

We here present new data on sedimentation at and near the steep north-slopes of southern Lake Baikal. Short sediment cores were taken at 550 m and at 1366 m water depth, within 3600 m offshore Cape Ivanovskii at the station of the Baikal Deep Underwater NEUTRINO Telescope*. The sediments within 3600 m off the northern coast of Southern Lake Baikal are dominated by pelagic deposition. Our data reveal surprisingly little influence from terrigenous material from adjacent coastal areas, tributaries and their catchment. At the shallow-water site (at 550 m water depth, 700 m off shore) just 27 cm thick homogenous sediments have accumulated during the Holocene on top of Pleistocene deposits resulting in Holocene sedimentation rates of 0.003 cm* a^{-1}*. The very low rates are caused by long-term persistent winnowing of fine particles caused by week contour currents along the slope. The uppermost sediments are oxidized down to 22 cm. Very low concentrations of* C_{org}*,* Si_{bio} *and* N_{tot} *in Pleistocene sediments increase dramatically within the Holocene. The heavy mineral fraction of the shallow-water sediments contains up to 33.6% olivine and up to 2.4% spinel. These rare minerals originate from white marbles of the nearby coastal outcrop* Belaya Vyemka *of the Early Precambrian* Sharyzalgaiskaya Series*. At the deep-water site (at 1366 m water depth, 3600 m off shore) Holocene sedimentation rates are 10-times higher (0.036 cm* a^{-1}*). Sediment oxidation occurs just within the uppermost 2 cm. Of the two rare type minerals of the* Sharyzalgaiskaya Series *spinel does not occur at all and olivine is represented by very diminished concentrations. This indicates insignificant influx of terrestrial material from the nearby shore to the deep-water site. Distal turbidites of far-off sources are intercalated to pelagic sediments at the deep-water site. Breakdown events of deltas at the SE- and S-coast of the basin are suggested to be responsible for the formation of the turbidites. They contain terrestrial (deltaic) material, low amounts of biological material (diatoms, spiculae, chrysophyte cysts), low concentrations of* Si_{bio}*,* C_{org} *and* N_{tot} *and occur at approximate recurrence rates of 300 years.*

Key words: Lake Baikal; near-shore sedimentation; winnowing; sedimentation rates; turbidites, diatom stratigraphy; spinel; olivine.

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INTRODUCTION

Lake Baikal is the world's oldest lake and has accumulated up to 8 km of sedimentary deposits. It is also the world's deepest lake, holding 20% of the world's surface freshwater reserves and the world largest amount of endemic species. In order to extensively assess environmental impacts on Lake Baikal, their recent and their longer-term history, and their potential influence into the future, it is important to have comprehensive knowledge on the forcing mechanisms and processes, which are responsible for these changes. Research papers of different scientific disciplines have contributed background knowledge on the formation of Lake Baikal and the dynamics of its vast water mass (Goldyrev, 1982; Bezrukova *et al*., 1991; Shimaraev *et al*., 1993; Khozhova and Izmest'eva, 1998). It has been shown that biological, physical and geochemical processes all influence biological and geochemical variability in the lake (Mackay *et al*., 1998; Flower, 1998; Müller *et al*., 2005; Granina and Callender, 2007; Schmid *et al*., 2008). Detailed studies of the lake bottom morphology and of composition and age of sediments in the different basins have been used, to further our understanding of processes of sediment formation and accumulation in Lake Baikal (Potrik'eva, 1959; Karabanov *et al*., 1984; Appleby *et al*., 1998; De Batist *et al*., 2002; Colman *et al*., 2003; Vologina and Sturm, 2009) and to studying past environmental and climate changes (Kuzmin *et al*., 2000; Bangs *et al*., 2000; Grachev *et al*., 2002; Fietz *et al*., 2005; Mackay, 2007). Formation and deposition of turbidities within the deep basins of Lake Baikal have been investigated and described within the conceptual principles of turbidity current formation in freshwater basins (Sturm and Matter, 1978). Within Lake Baikal they are triggered by earthquakes, catastrophic floods in the catchment and by methane gas eruptions (Lees *et al*., 1998; Nelson *et al*., 1999; Back *et al*., 1999; De Batist *et al*., 2002; Vologina *et al*., 2003; Vologina *et al*., 2012).

In this paper we present new data, which demonstrate the marginal influence of terrigenous coastal material on near-shore sites at steep slopes of Lake Baikal, which as yet has been poorly studied. The data have been gathered during several expeditions (between 2000 to 2010) to the station of the NEUTRINO NT200 Telescope (Belolaptikov *et al*., 1998) near Cape Ivanovskii at the north-shore of the South Basin. Our paper explores the source of coastal/terrestrial material, its limited near-shore deposition and its little influence on deep-water sedimentation within regions less than 3600 m off a steep coastal slope of a lake.

Geological characteristics

Early Precambrian rocks of the *Sharyzalgaiskaya Series* form most of the N-coast of the south basin of Lake Baikal (Fig. 1). They consist of biotite, biotite-garnet, hyperstene, granitic gneisses, crystalline slates, pyroxene-magnetite quartzites, amphibolite spinel-forsterite marbles and calciphyres (Khrenov, 1983; Salnikova *et al*., 2007; Melnikov, 2011). A prominent 1.5 km long outcrop, *Belaya Vyemka*, of the *Sharyzalgaiskaya Series* is exposed to the east of the NEUTRINO Telescope Station (Fig. 2); it is characterized by white marbles and calciphyres (Melnikov, 2011) and contain the very rare type-minerals olivine $(MgFe)_2SiO_4$) and spinel ($MgAl_2O_4$). The outcrop was generated during the construction of the Trans-Siberian Railway tracks along the shores of Lake Baikal (*Krugobaikalskaya*) at the beginning of the 20th century (Marks, 1991).

The lake morphology near this site comprises a very steep, cliff-like slope, which descends down to the >1300 m deep, flat basin plain within less than 2 km from the shore. This abrupt morphology is caused by the main, W-E striking Cenozoic Obruchevskii fault (Khrenov, 1983). The drainage area along the N-coast is very small with only small stream-like tributaries, transporting minor amounts of runoff particles into the lake.

METHODS

A total of four sediment cores were collected during winter months in 2000, 2008 and 2010 from the ice-covered lake at two sites offshore of the NEUTRINO telescope station (Tab. 1). Two cores were taken 700 m offshore at 550 m water depth (*shallow-water site*), situated on a small morphological platform at the steep slope. This platform was discovered in 1986, during a detailed bathymetric survey for the NEUTRINO Telescope Station by V.A. Fialkov and E.B. Karabanov, Limnological Institute, Irkutsk. Two cores were taken 3600 m offshore on the flat basin plain at 1366 m water depth (*deep-water site*) (Fig. 1). All coring stations were exactly relocated using GPS from the ice. Water depths were measured by counting meters of wire released by motorised winches.

Two types of gravity corer were used to collect short cores (UWITEC-63 and EAWAG-63/S), and transparent PVC-tubes of 63 mm Ø were used with both corers to ensure complete, undisturbed core recovery (including the delicate water/sediment interface). After recovery the cores were cut longitudinally, photographed and analysed for detailed lithology, using smear slides under a light microscope SK14 with a magnification of 100x. Additionally, sediments of five streams near Cape Ivanovskii were sampled for the characterization of tributary material: i) Polovinnaya; ii) Bolshaya Ponomaryvka; iii) Ivanovka; iv) Stream; and v) Shumiha (Fig. 1). All stream samples were analysed for grain size and mineral composition, as described below.

The lithological description of the cores included the characterization of biogenic material and the assessment of grain sizes and terrigenous particles. One half of each core was sampled continuously in intervals of 0.5 cm from 0-10 cm, and in intervals of 1 cm for the rest of core for detailed analyses of C_{tot}, N_{tot}, Si_{bio}, grain size and diatom determination. C_{tot} and N_{tot} were determined by a gas chromatograph (HEKATECH Euro AE® Elemental Analyser). C_{org} was calculated by subtraction of C_{inorg} (determined by a CO_2-COULOMETER) from C_{tot}. The analysis of Si_{bio} followed the method of Ohlendorf and Sturm (2008). Non-pretreated, freeze-dried samples were leached by 1M NaOH under ultrasonic treatment in Teflon® autoclaves at 100°C without stirring. Complete leaching was checked by SEM examination for the absence of scales of diatoms, chrysophytes, spicules, *etc*. Concentrations of Si, Al and Na were determined by ICP-OES. Al and Na were used to correct for the amount of potentially leached minerals. Diatom analyses of cores BAIK08-2 (42 samples) and BAIK10-4 (82 samples) with sampling intervals of 1 cm were performed according to Grachev *et al*., 1997. A MALVERN-MASTERSIZER® Hydro 2000S was used to measure grain-sizes of core BAIK00-1. To reduce the effect of diatoms, chrysophyte cysts and spiculae of sponges on the interpretation of grain size distributions, grain size analyses were performed on both, bulk samples and samples without Si_{bio}. Light and heavy minerals of cores BAIK08-1 and BAIK08-2 were separated by bromoform (2.7 g cm^{-3}) and determined under oil immersion with a MIN-8 microscope using the fraction 50-250 µm. The amounts of sand (>50 µm) and silt (5-50 µm) fractions were determined by sieving. The clay fraction (<5 µm) was separated by elutriation (grain size classification by Rukhin 1969).

The chronology of recent sediments was determined by radiometric dating, using measurements of ^{210}Pb (half-life: 23.3 years) and ^{32}Si (half-life: 144 years). ^{210}Pb activities were measured by γ-counting of freeze-dried sediment samples (at intervals of 0.5 cm) for 24 h in a calibrated CANBERRA Ge(Li) borehole detector. Sedimentation rates were calculated using the CRS (Constant Rate of Supply) model. Ages of the uppermost turbidites of core BAIK00-1 were taken from Morgenstern *et al*., 2013, who used radioactive ^{32}Si (half-life: 144 years) to determine the sedimentation rates of deep-water sediments during the last millennium. AMS-^{14}C was not used in our study to date older sediments, because of ambiguous results reported for Lake Baikal sediments by Watanabe *et al*., 2009.

RESULTS

Lithology of sediments

The uppermost sediments of the shallow-water cores BAIK08-1 and BAIK10-4 (Fig. 1, Tab. 1) consist of dark greenish-grey, homogenous silty clay with admixtures of sand. Smear-slide analyses show abundant pelagic diatoms and spiculae of sponges. The uppermost part of the sediments is oxidized, represented by a zone of dark to light brown, yellowish colours, which is underlain by lay-

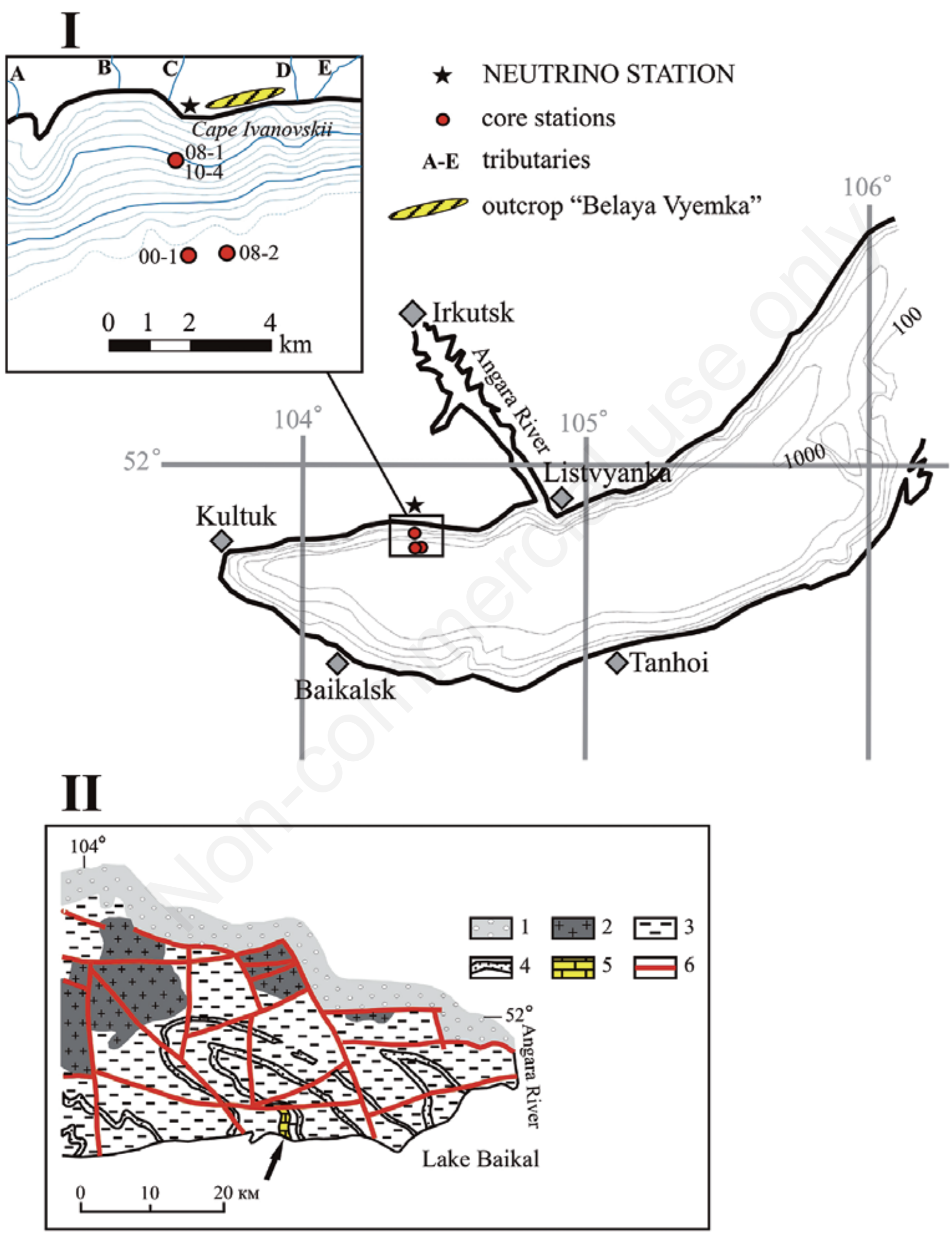

Fig. 1. Bathymetry of southern Lake Baikal. I) Core locations at shallow-water (BAIK08-1, BAIK10-4) and at deep-water (BAIK00-1, BAIK08-2); also shown are the outcrop *Belaya Vyemka* and the position of five tributaries, sampled near the NEUTRINO-telescope station at Cape Ivanovskii; A, Polovinnaya; B, Bolshaya Ponomaryvka; C, Ivanovka; D, Stream; E Shumiha. II) Geological sketch map of the area (after Melnikov, 2011), depicting rocks of the *Sharyzalgaiskaya Series* and the outcrop *Belaya Vyemka* (black arrow); Legend of geological map: 1, Neoproterozoic-Early Paleozoic cover of the Sibirian Craton; 2, Paleoproterozoic granites of the Sayanskyi Complex; 3, Archean granitic gneisses; 4, Archean biotite-garnet gneisses, 5, Archean forsterite marbles and calciphyres of *Belaya Vyemka*, containing the rare minerals olivine and spinel; 6, fault lines.

ers of dark brown to black Fe/Mn-crusts. The total thickness of the oxidized zone is 20.0 cm in core BAIK08-1 and 21.5 cm in core BAIK10-4. The lower parts of the cores are formed of lighter grey, homogenous clayey silt with abundant admixtures of terrigenous particles. Turbidites (graded beds) and sand layers do not occur in the shallow-water cores. Sediments of deep-water cores BAIK00-1 and BAIK08-2 (Fig. 1, Tab. 1) consist also of dark, greenish-grey, homogenous, silty-clayey sediments but with smaller amounts of sand. Planktonic diatoms, chrysophyte cysts and spiculae of sponges form up to 40%, organic material up to 10% and fine terrigenous particles <30% of these deposits (Ohlendorf and Sturm, 2008). Just the uppermost 2 cm (BAIK00-1) and 2.8 cm (BAIK08-2) are oxidized, showing a zone of light to dark brown colours. Older, olive-brown to dark brown oxidized layers appear at 6.0 cm (BAIK00-1) and 8.0 cm of BAIK00-1 and at 7 cm to 7.5 cm of BAIK08-2.

The pelagic deep-water sediments are intercalated occasionally by turbidites (graded beds), which are clearly distinguishable by their darker colour, by upward grading from sand to silt and clay and by the higher amount of terrestrial plant remains. In core BAIK00-1 four turbidites could be observed with a thickness between 3 cm and 29.5 cm (14.5-19.0 cm, 32.5-35.5 cm, 48.8-57.5 cm, 79.0-108.5 cm). The two uppermost turbidites (14.5-19.0 cm and 32.5-35.5 cm) could be correlated to turbidites of the shorter parallel core BAIK08-2 at 15-18 cm and 27.9-31.6 cm (Figs. 3 and 4).

Results of diatom analysis

In shallow-water sediments (BAIK10-4) numbers of diatoms, vary widely and are dominated by planktonic diatoms (Fig. 2). Within 0-27 cm they show a first maximum of 1.2-104×10^6 valves g^{-1} (benthic diatoms: 0.05-1.19×10^6 valves g^{-1}, chrysophyte cysts: 0.26-23.4×10^6 specimens g^{-1}, spiculae: 10-110×10^3 specimens g^{-1}). The most common diatom species are *Cyclotella minuta* (Skvortzow) Antipova (6.7-96.3%), *Aulacoseira baicalensis* (K. Meyer) Simonsen (0.6-62.1%), *Aulacoseira skvortzowii* Edlund, Stoermer et Taylor + spores (0.2-57.2%), *Cyclotella baicalensis* Skvortzow (0.6-6%), *Cyclostephanos dubius* (Früke) Round (0.01-5.3%), *Synedra acus* Kützing (0.01-

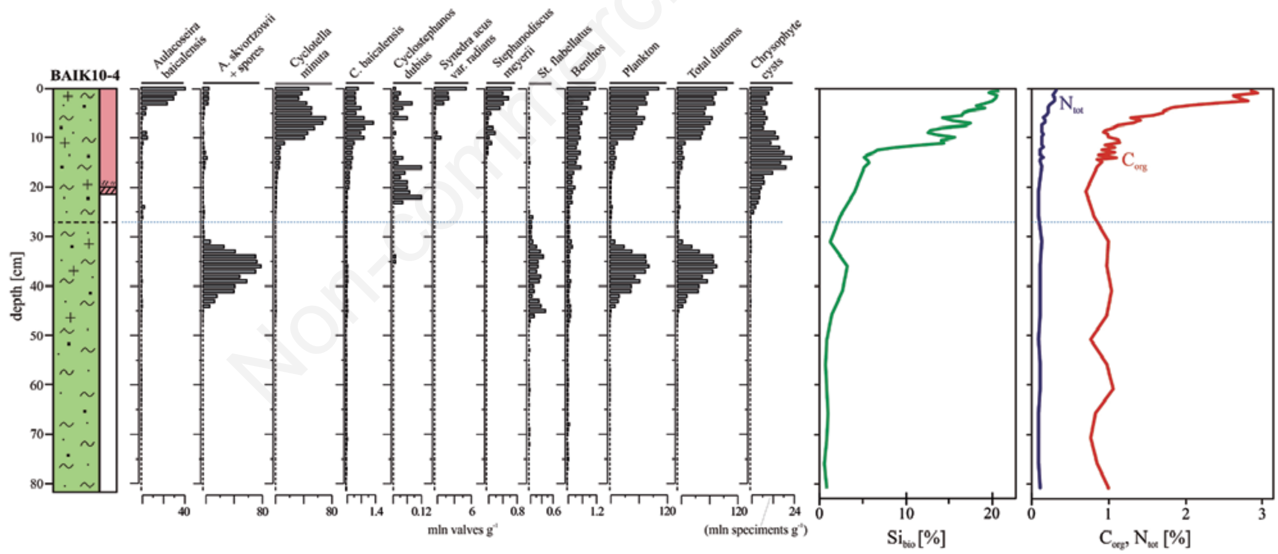

Fig. 2. Lithology, distribution of diatom assemblages and content of Si_{bio} and C_{org}, N_{tot} of shallow-water core BAIK10-4. The dotted line indicates the Holocene/Pleistocene boundary. For the legend of lithology see Fig. 3.

Tab. 1. List of sediment cores taken near Cape Ivanovskii with coordinates, distance from shore, water depth and length.

Names of cores	Coordinates	Distance from shore (m)	Water depth (m)	Core length (cm)
BAIK00-1	51°46.065 N 104°24’983 E	3600	1366	108.5
BAIK08-1	51°47.386’ N 104°24.893’ E	700	550	76.0
BAIK08-2	51°46.077’ N 104°25.871’ E	3600	1366	41.9
BAIK10-4	51°47.386’ N 104°24.893’ E	700	550	82.0

5.3%) and *Stephanodiscus meyerii* Genkal et Popovskaya (0.04-0.9%). Very few specimens have been observed of *Aulacoseira granulata* (Ehrenberg) Simonsen, *Aulacoseira subarctica* (O. Müller) Haworth. There are just 0.01-2.6% redeposited diatom species of Pliocene-Pleistocene age: *Cyclotella iris* Brun et Héribaud, *Cyclotella comptaeformica* Khursevich, *Cyclotella tempereiformica* Khursevich, *Cyclotella distincta* Khursevich, *Cyclotella gracilis* Nikiteeva et Likhoshway, *Stephanodiscus asteroides* var. *baicalensis* Khursevich et Fedenya *and Stephanodiscus grandis* Khursevich et Loginova.

Another planktonic diatom maximum occurs between 27-48 cm (0.31-83.4$\times10^6$ valves g^{-1}). Here the dominating species are represented by *Aulacoseira skvortzowii* + spores (20.3-98.6%) and *Stephanodiscus flabellatus* Khursevich et Loginova (0.3-17.1%). The number of planktonic diatoms decreases markedly in the interval 49 to 81 cm, showing values of only 0.04-0.56$\times10^6$ valves g^{-1} (Fig. 2). Planktonic diatoms dominate diatom assemblages of deep-water sediments (BAIK08-2) with concentrations of 16-263$\times10^6$ valves g^{-1} (benthic diatoms: 0.15-1.27$\times10^6$ valves g^{-1} (Fig. 3). They contain higher numbers of chrysophyte cysts (6-56$\times10^6$ specimens g^{-1}) and spiculae (0.5-1.7$\times10^5$ specimens g^{-1}). *Cyclotella minuta* (up to 99%), *Aulacoseira baicalensis* (up to 42%), *A. skvortzowii* + spores (up to 19%) and *Synedra acus* (up to 13.2%) constitute the main diatom species. Minor quantities are represented by *Cyclotella baicalensis* (up to 2.6$\times10^6$ valves g^{-1}), *Stephanodiscus meyerii* (up to 4.5$\times10^6$ valves g^{-1}), *Crateriportula inconspicua* Flower et Håkansson (up to 0.14$\times10^6$ valves g^{-1}), *Cyclostephanos dubius* (up to 0.3$\times10^6$ valves g^{-1}) and *Synedra ulna* var. *danica* (Kützing) Grunow (up to 0.34$\times10^6$ valves g^{-1}). Small amounts (<0.14%) of reworked diatom species of Pliocene-Pleistocene age have been identified: *Stephanopsis costatus* Khursevich et Fedenya, *Tertiarius baicalensis* Khursevich et Fedenya, *Cyclotella*

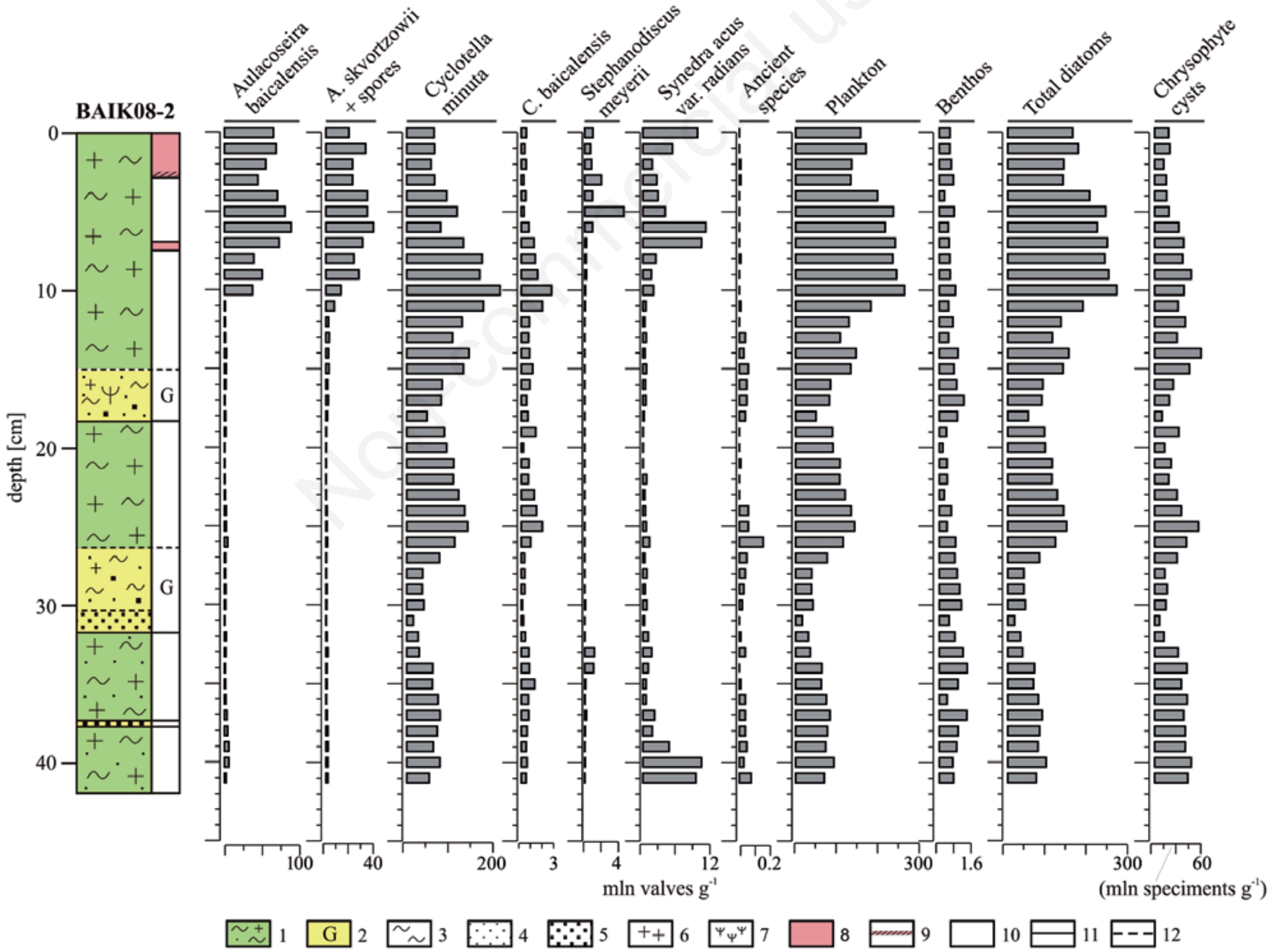

Fig. 3. Lithology and distribution of diatom assemblages of deep-water core BAIK08-2. Legend of lithology: 1, pelagic mud; 2 G, turbidite (graded layer); 3, clay, 4, silt; 5, sand, 6, diatoms; 7, land plant remains; 8, oxidized sediment; 9, Fe/Mn crust; 10, O_2-reduced sediment; 11, distinct boundaries between layers, 12, indistinct boundaries between layers.

tempereiformica, C. comptaeformica et var., *Stephanodiscus williamsii* Khursevich, *Stephanodiscus baicalensis* var. *concinnis* Pomazkina et Likhoshway, *Stephanodiscus carconeiformis* Khursevich et Loginova, *Stephanodiscus formosus* Khursevich et Loginova, *Stephanodiscus grandis* and *Stephanodiscus flabellatus* (Fig. 3).

Within turbidites of BAIK08-2, at 15 cm to 18.3 cm and 26.3 cm to 31.7 cm, numbers of planktonic diatoms, chrysophytes and spiculae are markedly reduced, whereas the numbers of benthic and ancient diatoms are slightly higher (Fig. 3).

Contents of biogenic silica (Si_{bio}), organic carbon (C_{org}) and total nitrogen(N_{tot})

Within sediments of shallow-water core BAIK10-4 highest concentrations of Si_{bio} (20.93%), C_{org} (2.92%) and N_{tot} (0.30%) are observed at the top of the core. Concentrations decrease down-core within 25 cm to minimal values of 0.7% (Si_{bio},), 0.7% (C_{org}) and 0.08% (N_{tot}) and stay low until the base of the core (Fig. 2). A similar pattern is observed in the pelagic deposits of deep-water core BAIK00-1 (Fig. 4). Highest values of Si_{bio} (25.5%), C_{org} (3.9%) and N_{tot} (0.4%) occur at the top of the core and decrease to 2.0% (Si_{bio},), 1.1% (C_{org}) and 0.1% (N_{tot}) towards the base of the core. Concentrations within turbidites (graded beds) are distinctly lower compared to pelagic muds. Values of Si_{bio} vary between 1.3-14.1%, of C_{org} between 0.6-2.3% and of N_{tot} between 0.4-0.1%.

Results of grain size analysis

Shallow-water sediments (BAIK08-1) contain 48-58% clay, 16-26% silt and 23-31% sand. The fraction 50-250 µm contains up to 0.4% terrestrial plant remains. Deep-water sediments (BAIK08-2) are characterized by 57-68% clay, 25-30% silt and only sometimes contain small amounts of sand (<12%). The fraction 50-250 µm contains up to 42% diatoms and spiculae, but no terrestrial plant remains. Turbidites, which are intercalated to the pelagic deposits, contain up to 62% sand. The fraction 50-250 µm of turbidites includes up to 8% diatoms and spiculae, and up to 2.8% terrestrial plant remains

Interpretation of grain sizes of pelagic sediments of Lake Baikal may be erroneous if analyses performed on bulk sediment samples, because high amounts of siliceous diatoms, chrysophytes and spiculae generally have a coarsening effect on the grain size distribution. Median grain sizes of Si_{bio}-free samples (Fig. 4, black line) are up to 15 µm smaller than those of bulk sediment samples, which include biogenic siliceous microfossils (Fig. 4, grey line). Siliciclastic material of turbidites shows a different behaviour, as the median of samples without Si_{bio} is up to 33 µm coarser than the median of bulk sediment samples. These results show a clear distinction between pelagic sediments and turbidites (Fig. 4).

Of the four turbidites in the deep-water core BAIK00-1 the uppermost turbidite shows an inverse grading. The next two turbidites show at their base maximum grain sizes of 57 µm and 52 µm, respectively (Fig. 4, black line). Grain sizes of 73 µm at the base of the lowermost turbidite become finer (2.6 µm) towards the clayey top and include a recurrence of coarser fraction in its upper part (Fig. 4, black line).

Mineral composition

The light mineral fraction of both shallow- and deep-

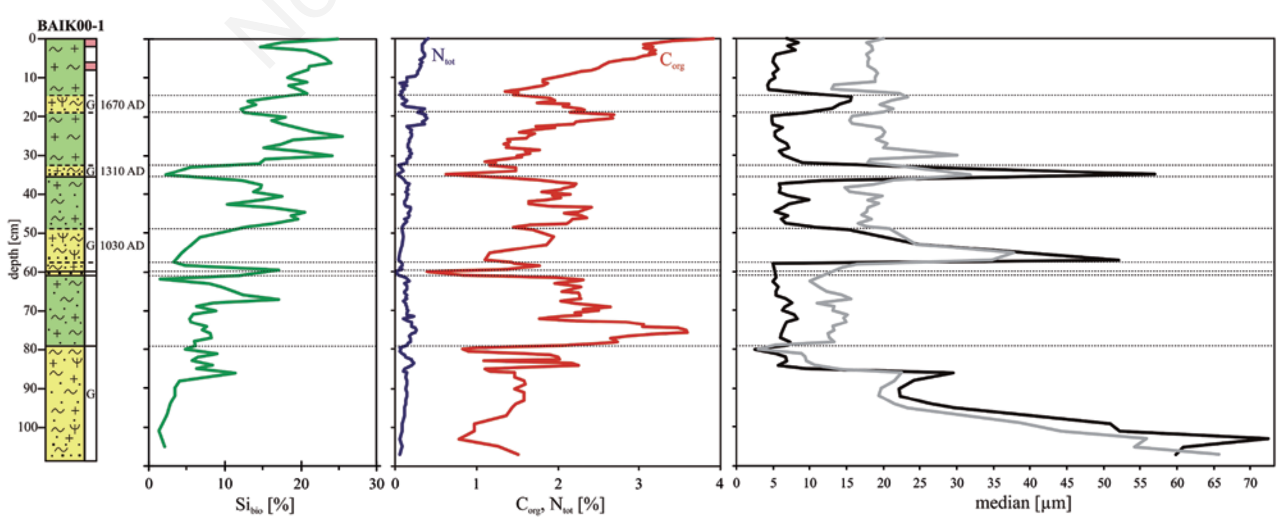

Fig. 4. Lithology content of Si_{bio}, N_{tot}, C_{org}, and median grain size distribution of deep-water core BAIK00-1. The black line of the grain size distribution shows results without Si_{bio}. The grey line shows grain size results including Si_{bio}. For the legend of lithology see Fig. 3.

water sediments, is dominated by quartz, plagioclase, K-feldspar, biotite (5-32%), muscovite (0.4-1%), chlorite, graphite (<1%) and aggregates (up to 2.4% in shallow-water and up to 39% in deep-water sediments). Turbidites of the deep-water cores contain up to 56% biotite, up to 3% muscovite and 4% aggregates. The main minerals in the light fraction of the turbidites are quartz and plagioclase.

Remarkably, the shallow-water sediments of core BAIK08-1 contain up to 33.6% olivine [$(MgFe)_2SiO_4$] and up to 2.4% spinel [$MgAl_2O_4$] (Tab. 2). These two rare type-minerals characterize rocks of the *Sharyzalgaiskaya Series* (Early Precambrian) that are beautifully exposed at the famous outcrop of *Belaya Vyemka* (Melnikov, 2011), which is situated nearby to the shallow-water coring site. Besides these two specific minerals, the heavy mineral fraction of the shallow-water sediments contains amphiboles (mainly hornblende), pyroxenes (hyperstene and diopside), ilmenite, garnet, magnetite, apatite and epidote (Tab. 2). The heavy mineral fraction of the deep-water sediments (BAIK08-2) additionally contains sillimanite, pyrite, sphene, and zircon (Tab. 2). Heavy mineral assemblages of turbidites show clear differences to the pelagic sediments. They contain up to 40% hornblende (<19.2% in pelagic sediments), up to 14.6% sillimanite (<2.4% in pelagic pelagic sediments) and up to 12.6% epidote (<2.8% in pelagic sediments). Concentrations of <6% hyperstene (up to 38.2% in pelagic sediments), and <8% diopside (up to 10.8% in pelagic sediments) are distinctly lower in turbidites.

Of the rare type-minerals of the Sharyzalgaiskaya Series, spinel is absent within all deep-water sediments. Just 0.4-3.4% of olivine have been observed in pelagic muds and 0.4-1% in turbidites.

Mineral composition of the tributaries near Cape Ivanovskii

The light mineral fraction of sediments from the tributaries near Cape Ivanovskii (Fig. 1) contains mainly feldspars (mainly plagioclase), quartz and mica (mainly biotite). The heavy mineral assemblages are dominated by amphiboles (mainly hornblende), pyroxenes (diopside and hyperstene), ilmenite, magnetite, garnet, goethite, epidote, apatite and zircon (Tab. 3). Samples of Stream, near the outcrop of *Belaya Vyemka* contain small amounts of olivine (1.6%) and spinel (0.2%), Ivanovka Stream just olivine (0.6%) (Fig. 1, Tab. 3).

DISCUSSION

Although the two coring sites are less than 3000 m apart, the sedimentary record of the shallow-water cores (BAIK08-1, BAIK10-4) at 550 m differs distinctly from the deep-water cores (BAIK00-1, BAIK08-2) at 1366 m.

The uppermost 27 cm, dark-greenish sediments of the shallow-water cores contain the diatom species *Aulacoseira baicalensis, Cyclotella minuta, Cyclotella baicalensis, Cyclostephanus dubius, Stephanodiscus meyerii* and

Tab. 2. Mineral composition and content (%) of heavy minerals of fraction 0.05-0.25 mm of shallow-water sediments (BAIK08-1) and of deep-water sediments (BAIK08-2).

Minerals*	BAIK08-1 shallow-water			BAIK08-2 deep-water					
	5-10 cm	30-35 cm	60-65 cm	0-10 cm	15-18 cm turbidite	18-25 cm	28-30 cm turbidite	30-31.6 cm turbidite	33-40 cm
Olivine	33.6	21.0	28.8	-	0.4	3.4	few	1.0	0.4
Spinel	2.4	0.4	-	-	-	-	-	-	-
Hornblende	17.0	22.0	26.0	16.4	22.0	10.0	27.2	40	19.2
Hyperstene	13.6	20.0	12.8	38.2	5.0	37.4	5.0	6.0	21.4
Diopside	14.8	18.0	13.8	10.8	7.4	9.6	8.0	7.4	10.8
Ilmenite	5.4	5.4	5.2	12	10.8	17.0	10.4	4.0	7.6
Garnet	2.8	4.8	2.8	10	19.6	8.8	24.2	9.4	24
Epidote	2.8	1.6	2.2	4	5.6	2.4	4.0	5.6	2.4
Apatite	1.4	2.0	3.0	2.6	2.4	3.0	4.2	4.0	4.0
Magnetite	3.6	3.0	4.0	3.6	2.0	3.0	1.6	1.2	2.0
Zircon	0.4	0.6	0.6	1.0	1.4	1.0	0.4	0.2	1.2
Sphene	0.2	0.4	few	1	4.4	1.0	2.0	1.4	2.0
Pyrite	-	-	-	-	8.8	6.8	1.0	0.4	1.0
Sillimanite	-	-	-	few	0.8	0.2	10.2	14.6	2.4

**The contents of the minerals tremolite, goethite, rutile, leucoxene, tourmaline, chloritoide, staurolite, biotite, distene are <1% and are not shown in the table.*

Synedra acus (Fig. 2) that clearly represent Holocene diatom assemblages (Mackay *et al*. 1998; Edlund and Stoermer 2000). Down-core, the onset of *Stephanodiscus flabellatus* and the disappearance of the Holocene diatoms mark the transition to Pleistocene sediments (Bradbury *et al*., 1994; Grachev *et al*., 2002; Kuzmin *et al*., 2009) (Fig. 3). Correspondingly, high concentrations of Si_{bio} (20.9%), C_{org} (2.9%) and N_{tot} (0.3%) in Holocene sediments decrease rapidly to minimum concentrations (Si_{bio} 0.7%, C_{org} 0.7%, N_{tot} 0.1%) during Pleistocene deposition of light grey, terrigenous clayey silts. This transition reflects the dramatic change from depleted lake productivity during the Pleistocene to higher lake productivity during the Holocene (Fig. 2; Qiu *et al*., 1993; Moore *et al*., 2011).

Cores at shallow-water sites near Cape Ivanovskii exhibit very low Holocene sedimentation rates of <0.003 cm a^{-1}. They are comparable to low sedimentation rates on ridges and banks, which have been observed on Academician Ridge and other elevated parts of the lake (Edlund and Stoermer, 2000; Vologina *et al*., 2009). There, weak SW-NE currents across the ridge (Hohmann *et al*., 1997) cause long-term scavenging of fine-grained pelagic particles and prevent a regular pelagic accumulation of sediments. Likewise, near Cape Ivanovskii, persistent contour currents of 0.02-0.15 m s^{-1}, measured along the slope (Schmid *et al*., 2008) are responsible for winnowing of fine particles and cause the reduction of the Holocene sediment record.

Similar to sediments at Academician Ridge (Vologina *et al*., 2003), a thick oxidized zone (up to 21.5 cm) is developed at the top of sediments at the shallow-water site (Fig. 2) that confirms very low rates of sedimentation. Oxidized zones and rates of sedimentation are directly linked to quantity and quality of sedimentary organic matter, as low sedimentation rates allow deeper diffusion of oxygen into sediment pore-water, whereas high sedimentation rates prevent deep oxygen penetration (Mizandrontsev, 1982). Measurements of nutrient fluxes across the sediment/water-interface proved these assumptions with a quantitative interface model of nutrient cycling (Müller *et al*., 2005) and demonstrated that the thickness of the oxidized zone is time-dependent (Och *et al*., 2012). Thin oxidized zones atop deep-water cores BAIK00-1 and BAIK08-2 (Figs. 3 and 4) indicate higher sedimentation rates of deposits within deep basin plains of Lake Baikal (Vologina and Sturm, 2009).

Sedimentation at the deep-water site at 1366 m water depth occurs under normally undisturbed depositional *background conditions*. Sediments consist of fine-grained, homogenous pelagic mud of autochthonous biogenic material (diatoms, chrysophyte cysts, spiculae of sponges) and minor admixtures of allochthonous, terrigenous particles. These sediments represent continuous, calm, nonturbulent depositional conditions and they are characteristic for the sedimentation of the deep basin plains of Lake Baikal. Diatom assemblages of the sediments (Fig. 3) are characteristic of the Holocene (Mackay *et al*., 1998). Dating of deep-water core BAIK00-1 by ^{210}Pb and ^{32}Si revealed sedimentation rates of 0.036 cm a^{-}

Tab. 3. Mineral composition and content (%) of heavy minerals of the fraction 0.25-0.05 mm of sediments from tributaries in the area of Cape Ivanovskii.

Minerals			Tributaries*		
	Polovinnaya	Bolshaya	Ivanovka	Stream	Shumiha
Olivine	-	Few	0.6	1.6	-
Spinel	-	-	-	0.2	Few
Hornblende	24.0	30.8	33.6	24.6	22.4
Hyperstene	5.4	19.0	14.2	14.8	16.0
Diopside	24.0	20.8	25.4	33.4	33.2
Ilmenite	14.8	12.2	10.4	8.4	11.2
Garnet	5.0	3.0	3.6	6.6	4.0
Epidote	0.8	3.2	5.2	2.8	0.8
Apatite	1.4	3.2	2.0	1.2	1.2
Magnetite	12.0	2.0	2.0	4.0	10.0
Zircon	1.6	1.0	0.6	0.6	0.2
Sphene	0.4	0.8	0.6	Few	Few
Goethite	10.0	2.2	0.8	0.2	0.4
Actinolite, Tremolite	-	0.8	Few	1.2	0.4
Anatase	-	-	Few	-	-
Leucoxene	0.6	1.0	1.0	0.4	0.2

**For the location of tributaries see Fig. 1.*

^{1} (Morgenstern *et al*., 2013). The pelagic muds of the basin plains are occasionally, interstratified by turbidites (Vologina and Sturm, 2009). Turbidites contain high amounts of terrigenous, sandy material, small amounts of diatoms, chrysophytes and spiculae and show distinctly lower concentrations of Si_{bio}, $C_{org}$and N_{tot} than the homogenous pelagic muds (Figs. 3 and 4).

Turbidites represent deposits of turbulent, high-energy conditions, triggered by catastrophic events: breakdowns of delta slopes, voluminous mud flows and excessive floods in the catchment (Sturm and Matter, 1978; Girardclos *et al*., 2007). Alterations of pelagic mud and turbidites indicate that normally calm sedimentation conditions within the deep basins of Lake Baikal are interrupted occasionally by high-energy turbidity currents and by rapid re-deposition of older material from far distance sources (Nelson *et al*., 1999; Colman *et al*., 2003; Vologina *et al*., 2003). Analogical, we suggest distant sources for the turbidites of the deep-water cores BAIK00-1 and BAIK08-2 (Fig. 4) near Ivanovskii Cape. All the more, as the cliff-like N-shore of the basin does not contain any large deltas. The turbidites contain diatoms, which are characteristic for Pliocene/Pleistocene. These diatoms do not appear within the normally deposited pelagic muds but are common in deep-water turbidites of other sites (Vologina *et al*., 2007). Their sources are Pliocene/Pleistocene sediments, which are widespread along the South- and SE-coast of Southern Baikal and are not exposed at the North coast of this basin (Mats, 1985; Imetkhenov, 1987; Atlas of Baikal, 1993; Mats *et al*., 2001). Therefore, we assume that the turbidites, intercalated to the deep-water pelagic muds at the site of our investigation at the N-coast near Ivanovskii Cape contain material, which formerly was deposited at the distant SE- and S-coast of the basin. During the last millennium three major events have triggered the formation of turbidity currents, which subsequently caused the deposition of three distal turbidites (1030 AD, 1310 AD, 1670 AD) as far as at the deep-water site near Cape Ivanovskii (Morgenstern *et al*. 2013).

The shallow-water sites of cores BAIK08-1, BAIK10-4 (Fig. 1) are free of turbidites (Fig. 2). We assume that shallow-water sites could not be reached by turbidity currents, which just followed the *thalweg* along the flat deep basin plain. Sand content (up to 30.5%) of shallow-water sites originate from coastal sources. The near-shore sources are proved by contents of up to 33.6% olivine and of up to 2.4% spinel in the deposits of shallow-water core BAIK08-1 (Tab. 2). The two rare minerals characterize the white marbles of the *Sharyzalgaiskaya Series* (Early Precambrian) at the prominent outcrop *Belaya Vyemka* near Cape Ivanovskii (Melnikov, 2011). In contrast, the mineral composition of deep-water pelagic muds and of the interstratified turbidites does not contain any spinel and only very small amounts of olivine (<1%). Therefore, we suggest that deep-water sediments near the steep north-shore of Southern Lake Baikal are barely influenced by terrestrial particle input from the nearby catchment, despite being deposited less than 3000 m from the coast.

This is confirmed by the sediments of the tributaries around *Belaya Vyemka* (Fig. 1), which contain very low contents of olivine (<1.6%) and spinel (<0.2%) (Tab. 3). It is assumed, therefore, that the transport of these specific minerals from the *point source* at shore to the depositional sites at the slope takes not place by the direct influx from streams and tributaries but by occasional near-shore, coast-parallel currents. Measured currents along the north-shore within the upper part of the water column can reach speeds of up to 0.15 m s^{-1} (Schmid *et al*., 2008). These currents seem not be able to transport the minerals olivin and spinel as far as to the deep-water sites of the cores BAIK00-1 and BAIK08-2. Traces of destabilization of sediments by seismic activities (Kuzmin *et al*., 2000, Vologina *et al*., 2012) or by degassing of gas hydrates (De Batist *et al*., 2002) have not been observed in either core of shallow- or deep-water sites. The undisturbed deposits near Cape Ivanovskii are, therefore, excellent sedimentary records to analyse recent and past environmental processes in Lake Baikal.

CONCLUSIONS

For the first time, sediments from two adjacent coring sites (less than 2500 m apart) in ocean-like Lake Baikal have been studied to define the influence of terrigenous material on near-coast deposits of deep basin sites and to determine the differences between slope and deep basin sedimentation within 3000 m from the shoreline. The study site near Cape Ivanovskii at the N-shore of southern Lake Baikal was particularly chosen because it is situated close to *Belaya Vyemka*, a geological outcrop, famous for its white Precambrian marbles containing two rare minerals: olivine [$(MgFe)_2SiO_4$] and spinel [$MgAl_2O_4$]. These two minerals have been used as markers to identify the influence of terrigenous input to the near-coast deposits at the site. Up to 33.6% olivine and 2.4% spinel have been determined in the shallow-water sediments, whereas the content in the deep-water sediments is only 3.4% olivine with no spinel. The homogenous, greenish-grey sediments at both shallow-water (48-58% clay, 16-26% silt) and at deep-water sites (57-68% clay, 25-30% silt) are representative of calm depositional conditions (Vologina and Sturm 2009). However, striking differences in Holocene sedimentation rates have been discovered at the shallow-water site (<0.003 cm a^{-1}) and at the deep-water site (0.036 cm a^{-1}). Contour currents of 0.02-0.15 m sec^{-1} along the slope (Schmid *et al*. 2008) are suggested to persistently winnow fine silt and clay particles, thus being responsible for the reduced sedimentation rates at shallow-water sites near Cape Ivanovskii. Low sedimentation rates at shallow-water sites (550 m water depth) cause deep oxidation of the upper part of the sediments down to 22 cm.

As in other parts of the lake, planktonic diatom assemblages and spiculae of sponges dominate the composition of the homogenous sediments (Bradbury *et al*., 1994). *Cyclotella minuta* (up to 96.3%), *Aulacoseira baicalensis* (up to 62.1%) and *Aulacoseira skvortzowii* (up to 57.2%) are the main species in shallow-water deposits. Deep-water sediments contain up to 99% *Cyclotella minuta*, up to 42% *Aulacoseira baicalensis* but higher amounts of chrysophyte cysts and spiculae. Both assemblages clearly represent Holocene diatom communities. The down-core disappearance of Holocene diatoms and the synchronous onset of *Stephanodiscus flabellatus* in shallow-water cores indicate the transition to deposits of Pleistocene age and very low Holocene sedimentation rates, induced by long-lasting winnowing of particles. Pelagic deep-water sediments at the study site are characterized by much higher sedimentation rates and the occurrence of intercalated turbidites, which reach a thickness of 3 cm to 29.5 cm, show an upward-grading and contain up to 62% sand and up to 2.8% terrestrial plants. Typically they are reduced in planktonic diatoms, chrysophytes and spiculae and contain higher amounts of benthic and ancient (Pliocene/Pleistocene) diatoms. Concentrations of Si_{bio} (<14.1%), C_{org} (<2.3%) and N_{tot} (<0.1%), are distinctly lower in turbidites. We suggest that the sources of the turbidites are situated at far-distant delta depot-centres at the SE- and S-coast of the southern basin of Lake Baikal.

In summary, this study shows striking differences of sedimentation rates at shallow-water and deep-water sites. It proves that pelagic deep-water sediments near steep, cliff-like slopes are barely influenced by terrestrial particle input from the nearby catchment, although they are less than 3000 m from the coastline.

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