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ORIGINAL PAPER

Late Holocene diatom assemblages in a lake-sediment core from Central Kamchatka, Russia

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Abstract Fossil diatom assemblages in a sediment core from a small lake in Central Kamchatka (Russia) were used to reconstruct palaeoenvironmental conditions of the late Holocene. The waterbody may be a kettle lake that formed on a moraine of the Two-Yurts Lake Valley, located on the eastern slope of the Central Kamchatka Mountain Chain. At present, it is a seepage lake with no surficial outflow. Fossil diatom assemblages show an almost constant ratio between planktonic and periphytic forms throughout the record. Downcore variations in the relative abundances of diatom species enabled division of the core into four diatom assemblage zones, mainly related to changes in abundances of *Aulacoseira subarctica*, *Stephanodiscus minutulus*, and *Discostella pseudostelligera* and several benthic species. Associated variations in the composition and content of organic matter are consistent with the diatom stratigraphy. The oldest recovered sediments date to about 3220 BC. They lie below a sedimentation hiatus and likely include reworked deposits from nearby Two-Yurts Lake. The initial lake stage between 870 and 400 BC was characterized by acidic shallow-water conditions. Between 400 BC and AD 1400, lacustrine conditions were established, with highest contributions from planktonic diatoms. The interval between AD 1400 and 1900 might reflect summer cooling during the Little Ice Age, indicated by diatoms that prefer strong turbulence, nutrient recycling and cooler summer conditions. The timing of palaeolimnological changes generally fits the pattern of neoglacial cooling during the late Holocene on Kamchatka and in the neighbouring Sea of Okhotsk, mainly driven by the prevailing modes of regional atmospheric circulation.

Keywords Diatoms · Climate change · Lake sediments · Holocene · Kamchatka

Introduction

Within the scope of the Russian-German project KALMAR (“Kurile-Kamchatka and Aleutean Marginal Sea-Island Arc Systems: Geodynamic and Climate

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Interaction in Space and Time"), lake sediments were recovered from Central Kamchatka to infer past environmental changes. One focus of the project was a palaeoecological evaluation of fossil diatom assemblages (Hoff 2010).

Until recently, palaeoecological and palaeoenvironmental studies in Kamchatka were limited to reconstruction of vegetation dynamics from pollen records in a few peat sections (Dirksen and Uspenskaia 2005; Dirksen and Dirksen 2008) and reconstruction of glacial dynamics in southern to Central Kamchatka (Zech et al. 1997; Savoskul 1999). Climate history of the last 400 years is well documented in tree-ring and ice-core records of Kamchatka (Solomina et al. 2007), whereas fossil diatom assemblages were only studied sporadically (Braitseva et al. 1968).

This study deals with the lacustrine sediment record from a small lake on the eastern slope of the Central Kamchatka Mountain Chain. The core spans the last three millennia at intermediate temporal resolution (20–50 years per sample). The main focus was palaeoecological interpretation of fossil diatom assemblages with respect to ancient lake development. Interpretation of diatom changes also took into account sedimentological data that indicate changes in the depositional environment. The aim of this study was to provide background information for interpreting palaeoenvironmental changes throughout the late Holocene in Central Kamchatka.

Regional setting

The study lake lies on the eastern flank of the Central Kamchatka Mountain Chain, the Sredinnyi Ridge [56°49.6′N, 160°06.9′E, 275 m above sea level (a.s.l.)] (Fig. 1). The Central Kamchatka Mountain Chain is mostly built of Neogene to mid-Pleistocene volcanic rocks and extinct volcanoes (Solomina et al. 2007). Mountain peaks and ridges closest to the lake are about 1,100 m a.s.l. The area is characterized by stone birch forest, giving way to subalpine shrubs with dwarf birch and shrub pine. Above the treeline, at about 500 m a.s.l., the higher mountain peaks are covered by subalpine meadows and tundra vegetation (Krestov 2003). In the generally maritime setting of Kamchatka, the study area represents Kamchatka's most continental climate. Maritime influences may come from the Pacific coast, about 150 km to the southeast, or from the Okhotsk Sea, 180 km to the west. The closest weather station lies 70 km to the

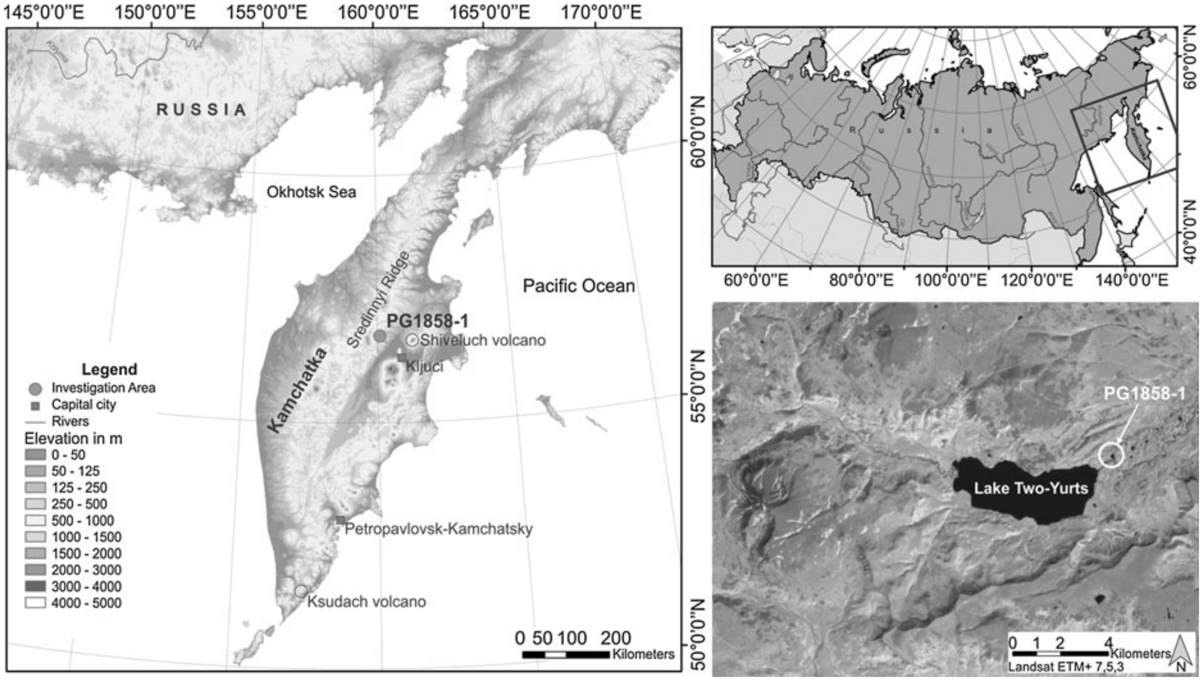

Fig. 1 Location of the study lake in the Two-Yurts Lake area on Kamchatka Peninsula, Russia

southeast, at Kljuci (56°19.0′N, 160°50.0′E, 29 m a.s.l.) (Fig. 1), and demonstrates the marked seasonality of climate (http://www.climate-charts.com/Locations/r/RA32389.php). In Kljuci, the average mean, maximum, and minimum temperatures are −0.7°C, 14.7°C, and −16.5°C, respectively, while precipitation on average ranges between 20 mm in April and 74 mm in August, with a yearly sum of 640 mm.

The study lake is located near Two-Yurts Lake. Two-Yurts Lake has a maximum depth of 28 m, a surface area of ~10 km^2, and occupies a former proglacial basin. Its palaeolimnology will be discussed elsewhere. Here we focus on the small lake located on the moraine arc that borders Two-Yurts Lake at its eastern outflow side (56°49.6′N, 160°06.3′E, 275 m a.s.l.) (Fig. 1). The lake lies within the birch forest zone, approximately 200 m below the modern tree-line. The almost triangular-shaped lake is 250–150 m across, with a maximum depth of about 5 m. It may be a kettle lake, which formed after the melting of relict glacial ice on the moraine. During field work in September 2007, the lake was ice-free and surface water temperature was 11.3°C. Although data on the duration of winter ice cover for the lake are lacking, we assume that permanent winter ice prevails from at least November to April, as suggested by usually negative air temperatures during that time at the Kljuci weather station. Because the study lake lies at an elevation ~250 m higher than the weather station, an even longer ice period might be expected. Lakewater pH is 8.6 and conductivity is 48 μS/cm, indicating low ion concentration. The waterbody is a seepage lake with no surficial outflow. It is fed by precipitation (rain as well as snow) and through groundwater inflow, and loses water to groundwater outflow and evaporation. Negative ^{2}H excess (*D*-excess) values of water samples fall below the global meteoric water line, providing evidence of the relatively closed nature of the lake system (Hoff 2010).

Materials and methods

Sample collection and sediment description

Fieldwork was undertaken in September 2007 as a part of a larger limnogeological campaign at Two-Yurts Lake. Sediment core PG1858-1 was collected from the study lake with a Russian peat sampler (100 × 1,000 mm) (Tolonen 1987), from a water depth of 2.5 m. It provided an undisturbed, ~1-m-long half-core section, which was sliced into 1-cm samples in the field. Repeated coring at overlapping depth intervals showed that we almost recovered the modern surface layer in the sediment section with core PG1858-1. The most important requirement for obtaining undisturbed cores with the Russian corer is that it has to be stuck completely in the mud for core recovery, otherwise overlying water washes out the unconsolidated, uppermost sediments. After several unsuccessful attempts that resulted in "wash-out" cores, and after making more accurate measurements of water depth, we were able to achieve a near-complete, surface-core recovery (Fig. 2). The obtained 1-m-long sediment core consists of gyttja with several ash layers (tephra) and includes a basal layer of diatomaceous silty clay in the lower 3 cm of the core. The ash layers range in thickness from a few mm to 5 cm. The same ash layers were identified in an onshore section dug close to the south shore of the lake.

Radiocarbon dating, geochemistry and diatom analyses

Sediment samples were freeze-dried and split into subsamples for micropalaeontological, sedimentological, and stratigraphic studies at AWI Potsdam. Core chronology was established using both AMS ^{14}C dating of the total organic carbon fraction at the Poznan Radiocarbon Laboratory in Poland (Table 1) and tephra analysis. Total carbon (TC) and total nitrogen (TN) were measured in the powdered samples with a "Vario EL III"-CNS-Elementar Analyzer (analytical precision ±5%). For determination of total organic carbon (TOC), powdered samples were first treated with 10% HCl at 80°C to remove carbonates and then measured again using the "Vario EL III"-CNS-Elementar Analyzer (Sieper et al. 2006). Sediments are barren of carbonate, as the TC and TOC values were virtually identical. Molar TOC/TN ratios, hereafter referred to as C/N ratios, were calculated to infer the source of organic matter. In addition, carbon stable isotope ratios (δ^{13}C) of organic matter were determined. The HCl-treated samples were placed into silver cups and combusted to carbon dioxide (CO_2) in a Heraeus Elemental Analyzer and then analyzed with a Finnigan Delta S mass spectrometer with an analytical precision of ±0.2‰. Results are presented

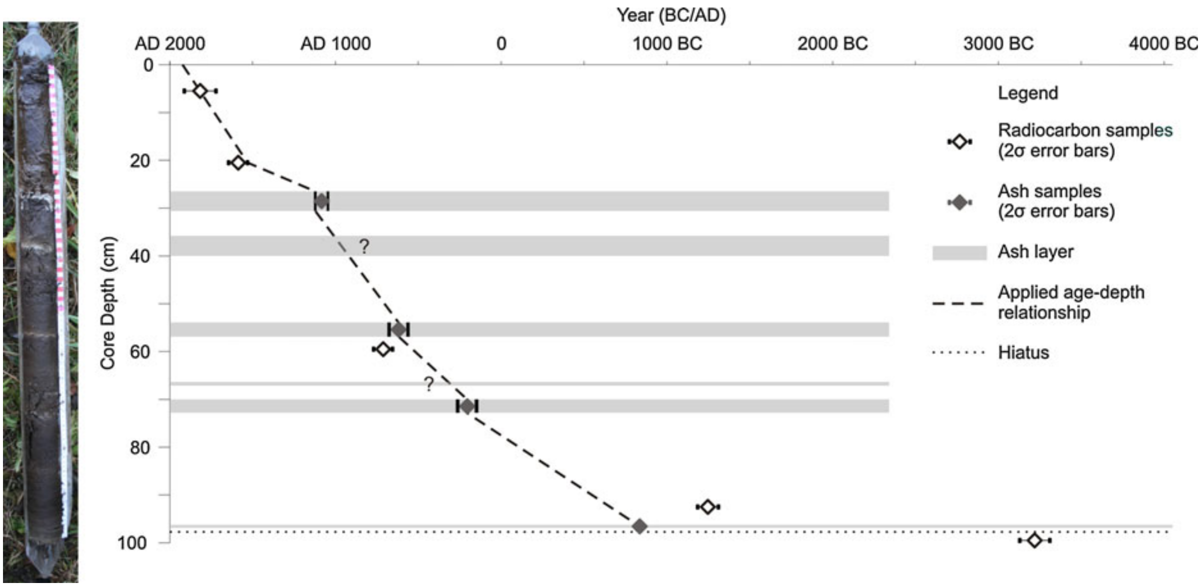

Fig. 2 Age-depth model and photograph of sediment core PG1858-1

Table 1 Radiocarbon ages, tephra ages and calibrated ^{14}C ages in core PG1858-1

Sample code/ash source	Core depth (cm)	Material	Age (^{14}C years BP)	Age (cal years BP)	Age (cal AD/BC)
Poz-31555	5–6	Bulk TOC	124 ± 1	133 ± 95	AD 1817 ± 95
Poz-31552	20–21	Bulk TOC	275 ± 30	362 ± 57	AD 1588 ± 57
Shiveluch 2 (SH_2)	27–31	Ash	965 ± 16	880 ± 42	AD 1070 ± 42
Shiveluch*	36–40	Ash	–	–	–
Shiveluch 3 (SH_3)	54–57	Ash	1,404 ± 27	1,319 ± 17	AD 631 ± 17
Poz-29023	59–60	Bulk TOC	1,300 ± 35	1,238 ± 39	AD 712 ± 39
Shiveluch*	67–68	Ash	–	–	–
Ksudach 1 (KS_1)	70–73	Ash	1,806 ± 16	1,756 ± 35	AD 194 ± 35
Poz-31554	92–93	Bulk TOC	3,000 ± 35	3,197 ± 62	1247 ± 62 BC
Shiveluch 2800	97	Ash	2,800	2,872	922 BC
Poz-27026	99–100	Bulk TOC	4,495 ± 35	5,169 ± 91	3219 ± 91 BC

Radiocarbon age calibration was done using the CalPal Online Program (0 cal years BP = AD 1950) (Danzeglocke et al. 2010). Tephra stratigraphy is based on Ponomareva et al. (2007). Tephra layers marked (*) could not be identified with confidence and were not used in the age model (Fig. 2)

as δ^{13}C, i.e. values per mille referred to the Vienna PeeDee Belemnite standard (VPDB) (Berger and Vincent 1986).

Preparation of diatom samples for light microscopy (LM) was done in accordance with standard methods (Schrader 1973; Fenner 1985). For more effective removal of organic matter, however, samples were heated for 20 h on a hotplate at 95°C with 37% H_2O_2. The processing time used was much longer than that proposed by the cited authors, because there was little loss of organic matter after heating for a short time. All preparation steps were done quantitatively according to the protocol of Battarbee (1973). Naphrax®, with a refraction index of 1.73, was used as a mounting medium for microscope slides. Identification and counting of diatom valves were done with a Zeiss Axioskop 40, ocular W-PI 10×/23, objective Achroplan 100× 1.25 oil Ph 3 ∞0.17, using both bright-field and phase contrast oil immersion optics (magnification 1,000×). A minimum of 500 diatom valves per sample were counted along vertical transects, excluding taxa that could not be identified to species level (e.g. *Pinnularia* spp.), if present. In addition to light microscopy, a scanning-electron microscope (SEM) (Ultra 55 Plus, Carl Zeiss SMT) was used to verify and document diatom identifications.

Taxonomic identification mainly followed Krammer and Lange-Bertalot (1986–1991), under consideration of Hustedt (1930–1966) and Kobayasi et al. (2006). Diatom results are expressed as relative abundances, i.e. as percentages of total diatom counts. The diatom diagram was drawn using the software package Tilia/Tilia-Graph/TGView (Grimm 1991). The CONISS program, as part of the software package Tilia/Tilia-Graph/TGView, was used to split the diatom diagram into diatom assemblage zones (DAZ). This method uses algorithms of a multivariate cluster analysis.

Results

Age-depth model

Five radiocarbon dates were obtained and converted to calibrated (calendar) ages BC/AD (0 cal years BP = AD 1950), using the CalPal Online program (Danzeglocke et al. 2010) (Table 1). Radiocarbon dates constrain the independent age determinations from tephra stratigraphy (Table 1). The age-depth relationships using tephra analysis and ^{14}C dates are similar (Fig. 2). Mineralogical properties show that five ash layers originated from eruptions of the Shiveluch Volcano, located 75 km WNW of the lake, while one ash layer is from the Ksudach Volcano in south Kamchatka (Dirksen et al. 2011). Of the six volcanic ash layers, the ages of four can be identified with high confidence, using reference tephra stratigraphy (Ponomareva et al. 2007). For calculating sample ages, tephra layers were treated as single events and intervening sediments were considered time-continuous. Assuming a constant sedimentation rate, linear interpolation between the tephra layers was used to generate the age-depth model. The final age-depth model used four ash ages and two radiocarbon ages (Fig. 2).

The oldest age of the gyttja sediments is based on the Shiveluch ash layer at 97 cm, dated to about 920 BC. The basal silty clay at 97–100 cm depth has an age of ~3220 BC, suggesting a sedimentation hiatus at the lithologic boundary between the basal deposits and the overlying gyttja. According to the applied age-depth model, the cored sequence above the hiatus spans approximately the last 2,800 years, with sedimentation rates apparently increasing upward from 0.2 mm/year near the base to 0.5 mm/year near the top. The applied age-depth model also shows that the topmost age is about AD 1912 and that sediments of the last century were not recovered in core PG1858-1. The downcore change in sedimentation rate might be related, in part, to sediment compaction with depth.

Diatom analysis

Fossil diatom assemblages contain benthic and planktonic taxa and possess a total of 95 diatom species in 26 genera that consistently appear at moderate abundances (Fig. 3). The most dominant species throughout the core is *Aulacoseira subarctica* (O. Müller) Haworth, with relative abundances up to 60% (Fig. 3). Other abundant taxa include *Stephanodiscus minutulus* (Kützing) Cleve et Möller (0.0–21.0%), *Discostella pseudostelligera* (Hustedt) Houk et Klee (0.0–15.9%), *Staurosira venter* (Ehrenberg) Cleve et Möller (0.8–24.5%), *Staurosira mutabilis* (W. Smith) Grunow (1.4–24.1%), *Psammothidium helveticum* (Hustedt) Bukhtiyarova et Round (0.0–15.9%) and *Karayevia suchlandtii* (Hustedt) Bukhtiyarova (0.0–11.7%). Four diatom assemblage zones (DAZ) were identified (Fig. 3).

DAZ I (100–97 cm; *ca.* 3220 BC) contains the basal diatomaceous silty clay below the hiatus. It is characterized by the highest diatom concentrations throughout the core, with up to 1.1×10^9 valves g^{-1}. It shows high percentages of *S. minutulus*, *S. venter*, *S. mutabilis*, and moderate percentages of *A. subarctica*. The species *S. alpinus* Hustedt and *Staurosira construens* Ehrenberg, though present in minor amounts, occur only in this zone.

DAZ II (96–86 cm; *ca.* 870–400 BC) shows higher amounts of *A. subarctica* than in DAZ I, and compared to the other zones, significant amounts of *Cocconeis placentula* var. *lineata* (Ehrenberg) VanHeurck, *Eunotia praerupta* Ehrenberg, *Gomphonema acuminatum* Ehrenberg, *Gomphonema olivaceum* (Hornemann) Brébisson and *Cavinula pseudoscutiformis* (Hustedt) Mann et Stickle. In addition, several taxa occur for the first time or at higher relative abundances above the

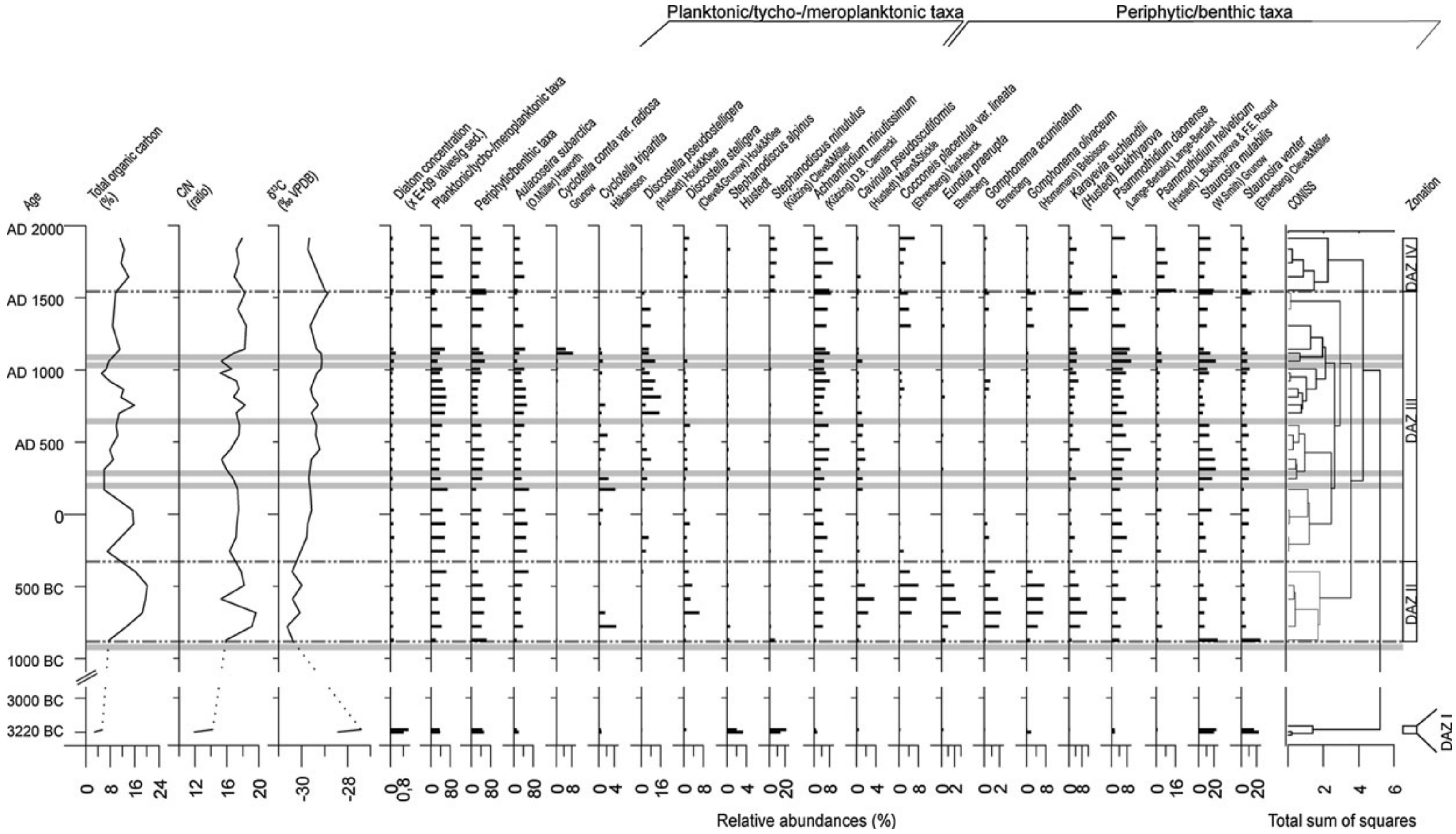

Fig. 3 Diatom stratigraphy of sediment core PG1858-1. Total diatom concentration and diatom assemblage zones (DAZ I–IV) are shown along with downcore variations in TOC, C/N and δ^{13}C. *Grey bars* indicate tephra layers

hiatus, including *Psammothidium daonense* (Lange-Bertalot) Lange-Bertalot, *P. helveticum*, *Achnanthidium minutissimum* (Kützing) Czarnecki, *K. suchlandtii* and *Discostella stelligera* (Cleve et Grunow) Houk et Klee. By contrast, *S. minutulus*, *S. alpinus*, *S. construens*, *S. venter*, and *S. mutabilis* strongly decrease or even disappear.

DAZ III (85–23 cm; 400 BC–AD 1400) is characterized by high amounts of *A. subarctica* and *D. pseudostelligera*, and near absence of *S. minutulus*. Among the subordinate species of the record, *P. daonense* reaches its highest amounts in DAZ III. Intermediate contributions come from *S. venter*, *S. mutabilis*, *P. helveticum*, *A. minutissimum*, and *K. suchlandtii*, while *C. placentula* var. *lineata*, *D. stelligera*, *E. praerupta*, *G. acuminatum*, *G. olivaceum* and *C. pseudoscutiformis* only occur at low abundance.

DAZ IV (22–1 cm; *ca.* AD 1400–1900) shows a sharp increase in the relative abundance of *S. minutulus*. Although *A. subarctica* still occurs at relatively high abundance, amounts of *D. pseudostelligera* decrease abruptly and totally disappear. In contrast to the other zones, and apart from the uppermost sample, *P. helveticum* (Hustedt) Lange-Bertalot reaches high percentages, between 7 and 19%.

Organic sediment fraction

TOC concentrations vary between 5.0 and 20%, mostly correlating with C/N ratios (Fig. 3). Maximum values of both variables occur above the basal silty clay layer, between 97 and 85 cm, and decrease slightly above 85 cm, with several minima and sub-maxima. Apart from the basal clay and one spike at 35 cm, the δ^{13}C ratios show low variability, with values between −29 and −30‰ VPDB (Fig. 3).

Discussion

Palaeoecology and lake development

Palaeoenvironmental interpretation of downcore changes in fossil diatom assemblages, with respect to preferences in temperature, pH, life form, and trophic status can only be achieved qualitatively, because there are no modern diatom training data sets for Kamchatka. The fossil diatoms of core PG1858-1 contain roughly equal amounts of taxa of planktonic/tycho-/meroplanktonic and periphytic/benthic origin (Fig. 3). Most are cosmopolitan taxa and many can be found in lake environments across the middle to high latitudes of the northern hemisphere (van Dam et al. 1994; Lotter and Biegler 2000; Bigler and Hall 2002; Kienel and Kumke 2002; Cremer and Wagner 2004; Smol et al. 2005; Solovieva et al. 2008; Medvedeva et al. 2009; Rudaya et al. 2009). The most abundant form is *A. subarctica* (20–60%), which also dominates in the nearby, 30-m-deep, silica-rich Two-Yurts Lake. It is also found in relatively high amounts in shallow lakes of south-central Kamchatka (Hoff 2010). It represents the dominant diatom in the 300-m-deep, volcanogenic Kurilskoye Lake of southern Kamchatka (Lepskaya et al. 2010). Moreover, it is found in Lake Baikal (Grachev et al. 1998), Lake Lama in central Siberia (Kumke et al. 2004), in northern and western European lakes (Sapozhnikova et al. 2000), in Canadian lakes (Moos et al. 2009), and even in large lake basins of central Mexico (Metcalfe 1988). *A. subarctica* is meroplanktonic. It is kept in suspension, as phytoplankton, in turbulent waters, but can settle and spend part of its life cycle on the lake floor (Gibson et al. 2003). Furthermore, the species lives under oligotrophic to mesotrophic conditions in silica-rich waters (Gibson et al. 2003; Rioual et al. 2007; Lepskaya et al. 2010). In the studied sediment core, other common planktonic taxa, present in variable abundance include *S. minutulus* (up to 21%) and *D. pseudostelligera* (up to 15.9%). Diatom taxa of the *Fragilariaceae* group generally contribute >20% to the whole diatom assemblage. These diatoms are widespread in alpine lakes (Lotter and Biegler 2000) and lakes in boreal forests and the Arctic tundra (Bigler and Hall 2002; Rühland et al. 2003), with long winter ice coverage. The third important group includes species of *Achnanthes* (20–30%), which are typical benthic diatoms in a wide range of ecological conditions (van Dam et al. 1994; Bigler and Hall 2002; Rühland et al. 2003). The downcore succession of fossil diatom assemblage zones (DAZ I–DAZ IV) and changes in sediment composition give insight into the lake development through time.

DAZ I (100–97 cm): ca. 3220 BC

This part of the record lies below a hiatus, which is also discernible in onshore peat sections

(Dirksen et al. 2011). The sediment composition is very different from that in the overlying section, as it is very fine-grained, grey in colour, has very low C/N ratios, and highest δ^{13}C ratios. Diatom concentration in this layer far exceeds the values in the overlying brownish-coloured gyttja sediments. The composition of organic matter (low C/N ratios) points to the dominance of planktonic organisms. DAZ I is characterized by high abundances of *S. venter*, *S. mutabilis*, *S. alpinus* and *S. minutulus*. The combination of these benthic and planktonic species is remarkable. Species of the *Fragilariaceae* group (e.g. *Staurosira* spp. and *Fragilaria* spp.) often occur in high abundances as dominant pioneer forms during early stages of postglacial lake development in many areas of the northern hemisphere (Laing et al. 1999; Solovieva and Jones 2002; Rudaya et al. 2009; Bezrukova et al. 2010). Other typical habitats for these species are alpine and Arctic to sub-Arctic lakes, with a short growing season and long-lasting annual ice cover (Lotter and Biegler 2000; Smol et al. 2005). On the other hand, the high amount of planktonic *Stephanodiscus* taxa implies a long, deep and vigorous spring circulation and early ice-out under low, but increasing light levels (Bradbury et al. 2002; Rioual et al. 2007), which also is true for associated *A. subarctica* in DAZ I (Gibson et al. 2003; Lepskaya et al. 2010). The planktonic diatom assemblage in DAZ I is quite similar to the assemblage of nearby Two-Yurts Lake (Hoff 2010). In an onshore peat section, the time interval of DAZ I is represented by reworked sand and gravel, possibly related to a landslide event, that also inserted big amounts of material very suddenly into Two-Yurts Lake (Dirksen et al. 2011). Geomorphological evidence for a landslide event and an associated tsunami during that time arises from breccia deposits around Two-Yurts Lake and the sand layer onshore of the studied lake (Dirksen et al. 2011). Because the studied lake lies 5 m higher than Two-Yurts Lake on top of a moraine arc, the flood scenario is reasonable to explain supply of allochthonous materials from Two-Yurts Lake. Sediments of DAZ I may consist of both reworked old local lacustrine sediments, with *Fragilariaceae* taxa and sediments enriched in *Stephanodiscus* taxa, deposited by the tsunami from Two-Yurts Lake into the study lake and settled out after the coarse material was deposited in the hydrologically closed lake basin.

DAZ II (97–86 cm): ca. 870–400 BC

The diatom-assemblage change to DAZ II is consistent with an abrupt change in lithology. The sediment above DAZ I consists of brownish-coloured, medium-grained gyttja. Diatom concentration decreases rapidly compared to the underlying sediments. The dating results and strong changes in lithology and diatom assemblage at 97 cm strongly support the interpretation of a hiatus and a break in lake development, perhaps caused by the flood scenario. DAZ II has low diatom concentrations, but high concentrations of organic carbon. It is characterized by the most negative δ^{13}C values ($-38.6‰$ VPDB) in the whole record, as is typical in lakes with low biological productivity (Meyers and Teranes 2001). High amounts of organic carbon are thus not related to planktonic matter, but to the presence of admixed remains from shallow-water macrophytes and/or terrestrial plant material, also indicated by maxima in C/N ratios (Meyers and Teranes 2001). Meroplankton, such as *A. subarctica*, accounts for $\sim$30% of the assemblage throughout DAZ II, while periphytic taxa ($\sim$70%) clearly dominate this early lake stage. In addition to *Psammothidium* spp. and taxa from the *Fragilariaceae* group, which show less variability throughout the sediment above the hiatus, DAZ II reveals maxima of *C. placentula* var. *lineata* (up to 8%), *E. praerupta* (up to 3%), *G. acuminatum* (up to 2%), and *G. olivaceum* (up to 7%). Though *Gomphonema* and *Cocconeis* species are cosmopolitan and show high tolerance for different ecological conditions, they commonly grow on aquatic macrophytes and other substrates (Ekdahl et al. 2008), supporting our interpretation for the macrophyte origin of organic matter. Even though it is species-dependent, many *Eunotia* species are indicative of acid conditions that can be caused by long-lasting seasonal ice cover (Finkelstein and Gajewski 2007). On the other hand, they might indicate the inflow of organic acids to the lake (Laing et al. 1999). This interpretation is reasonable and consistent with reforestation after the catastrophic event that caused the hiatus in lacustrine deposition. In summary, the depositional environment and palaeoecology of DAZ II likely reflects the pioneer stage in lake development, following the break in sedimentation.

DAZ III (85–23 cm): ca. 400 BC–AD 1400

Diatom concentrations remain stable at 0.13×10^9 valves g^{-1} through DAZ III, while the proportion of planktonic algae increases. This is consistent with a decrease in C/N ratios that remain below 15. A slight, but steady increase in δ^{13}C values towards less negative values (−30 to −29‰ VPDB) documents enhanced planktonic productivity towards the upper part of the interval. A spike in δ^{13}C (−28‰ VPDB) values appears above one of the Shiveluch ashes (36–40 cm), possibly reflecting a short period of a slightly increased biological productivity after an increase in nutrient influx from the volcanic eruption *ca*. AD 1000. The higher proportion of planktonic taxa is related to a twofold increase in *Discostella* taxa (formerly *Cyclotella* spp.) to values of up to 17%, with *D. pseudostelligera* as the most prominent *Discostella* species in our record. Those diatoms prefer weak spring circulation, and overall stable summer and early autumn temperature stratification of the lake. These requirements, in particular, hold true for *D. pseudostelligera* (Bradbury et al. 2002). This species is known to indicate reduced lake ice cover and/or stable summer stratification (Rühland et al. 2003, 2008; Rühland and Smol 2005). Other *Discostella/Cyclotella* species of DAZ III point to a marked seasonal succession of planktonic diatom blooms. It starts with *C. tripartita*, a spring-blooming species preferring oligotrophic conditions (Cremer et al. 2001) and ends with *C. comta* var. *radiosa*, adapted to reduced light availability and mesotrophic to eutrophic conditions, during the onset of autumn circulation (Rioual et al. 2007). *Cyclotella* generally represents a cosmopolitan diatom genus that even appears in Arctic lakes (Cremer et al. 2001; Kumke et al. 2004). In the course of global warming, a significant shift from *Aulacoseira*- towards *Discostella/Cyclotella*-dominated plankton communities has occurred in many lakes in the middle to high latitudes of the northern hemisphere (Rühland et al. 2008), including Arctic lakes (Smol et al. 2005). The role of *Cyclotella* taxa as indicators of lake warming in the past has been highlighted in several case studies from Siberia (Bezrukova et al. 2010), from a subarctic lake in Finnish Lapland (Korhola et al. 2002), from an alpine lake in Austria (Huber et al. 2010), and a subarctic lake in Alaska (Chipman et al. 2009). Whether the *Discostella/Cyclotella* signal in our sediment record is related to climate amelioration or simply reflects ontogenetic lake deepening is hard to determine. In summary, DAZ III indicates a period with the occurrence of typical spring bloomers, i.e. those that need turbulent water conditions, and a smaller proportion of planktonic diatoms with affinity to summer thermal stratification. Both the diatom assemblages and sedimentological variables point to lake deepening.

DAZ IV (22–0 cm): ca. AD 1400–1900

With an average value of 0.12 × 10^9 valves g^{-1}, diatom concentrations within DAZ IV are again stable, but slightly decreased compared to DAZ III, whilst C/N ratios remain stable, below 15. Towards the upper part of the record, slightly decreasing δ^{13}C values (−29 to −30‰ VPDB), as well as the planktonic/periphytic ratio, document a reversion to enhanced periphytic productivity. Furthermore, during the youngest documented lake stage, a marked change within the planktonic diatom assemblage took place: *A. subarctica*, as in DAZ II and III was dominant, while *Discostella/Cyclotella* taxa dropped to <5% in abundance and were replaced by up to 10% *S. minutulus*. As for *Aulacoseira* species, presence of planktonic *Stephanodiscus* taxa imply vigorous spring circulation under low, but increasing light levels after ice-out (Bradbury et al. 2002; Rioual et al. 2007). In contrast to *A. subarctica*, which represents a diatom of mesotrophic conditions (Gibson et al. 2003), the relatively high abundance of *S. minutulus* can be seen as an indicator of incipient eutrophication (Cremer et al. 2001; Millet et al. 2010). Conditions were more turbulent and the strong decrease of *D. pseudostelligera* suggests that summer stratification was less developed than during the former interval. The presence of *S. minutulus* may reflect nutrient recycling from the lake bottom through turbulence. With respect to benthic diatom species, *A. minutissimum* still dominates, but is associated with strongly increased proportions of *P. helveticum* (up to 15%). From modern observations in subarctic lakes, it is evident that the summer temperature optimum for the latter species is about 1–2°C degrees lower than that for *A. minutissimum* (Korhola 2007). In summary, the DAZ I diatom assemblage indicates a turbulent lake with high nutrient concentrations, under possibly relatively cool summer conditions.

Palaeoenvironmental implications

The downcore variability in diatom assemblages and lithology in the studied lake-sediment record reflects a relatively stable lacustrine depositional environment and limnoecology since about 870 BC, the oldest datum above a hiatus. Small changes in the diatom assemblages, nonetheless, reflect slight modifications of the environmental boundary conditions. The initial stage of the lake, between 870 and 400 BC, was probably followed by a period of lake deepening. After that, limnogeological conditions may have been related to the intensity of summer water-column stratification, as reflected by the variable abundance of *D. pseudostelligera*. This interpretation, however, is based on the variability of only one diatom species, so paleoclimatic inferences must be regarded with caution. We therefore restrict our interpretation to the upper part of the PG1858-1 record, where the absence of *D. pseudostelligera* during the last 500 years is consistent with climate cooling in Kamchatka during the Little Ice Age. Further evidence comes from changes in the benthic diatom assemblage, which shows high abundances of cold-summer-preferring *P. helveticum* at the expense of *A. minutissimum*. Pollen spectra in peat sections along the Pacific coast of Kamchatka also indicate climate deterioration after 1550 BC (Dirksen and Uspenskaia 2005). Tree-ring and ice-core records only extend back ~400 years, but also provide evidence for cold climate conditions during the Little Ice Age, which culminated around AD 1800 (Solomina et al. 2007).

Conclusions

Fossil diatom assemblages in lacustrine sediments of a small forest lake on the eastern slope of the Central Kamchatka Mountain Chain document changes in palaeolimnology related to ontogenetic changes of the depositional environment, which might have been partly overprinted by climate-driven changes of limnoecological boundary conditions:

1. After a landslide event *ca*. 3200 BC, continuous lacustrine sedimentation started above a hiatus at 870 BC. The initial lake stage between 870 and 400 BC was characterized by acidic, shallow-water conditions.
2. Between 400 BC and AD 1400, full lacustrine conditions were established, with highest contributions from planktonic diatoms between 400 BC and 1 BC, and between AD 600 and 1400.
3. The interval between AD 1400 and 1900 was likely characterized by summer cooling during the Little Ice Age, as indicated by abundance of diatoms that prefer strong turbulence and nutrient recycling, as well as cool summer conditions without summer thermal stratification. Sediments that might document warming during the last few decades, were not recovered in our sediment record.

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