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# Holocene environments of central Iturup Island, southern Kuril archipelago, Russian Far East

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**Abstract**

Two lake records document Holocene changes in sea level, vegetation, and climate on the Okhotsk and Pacific sides of central Iturup Island, southern Kuril Islands. The sediment cores originated within tidal flats that subsequently developed into a marine strait which crosscut the island as sea levels rose during the early Holocene. Brackish lagoons and eventually freshwater lakes formed by ~7100 cal yr BP associated with warmer than present conditions. Past vegetation changes indicate a clear Holocene thermal maximum recorded on the Pacific coast but a less distinct optimum on the western shores (~7200–6100 cal yr BP). A gradual cooling toward modern levels occurred ~6100–3500 cal yr BP. Four prominent layers of coarse sediment found in mid- to late Holocene lake deposits may correspond to intervals of climate cooling/dune formation previously documented in coastal sections. Although chronological limitations question the synchronicity of these events across the south Russian Far East, it seems probable that they have a regional signature. However, the mechanisms responsible for Holocene climatic changes are likely the result of complex interactions of hemispheric-scale atmospheric patterns, marine characteristics, and regional feedbacks rather than simply fluctuations in sea levels as suggested in the current interpretative model.

**Keywords:** Southern Kuril Islands; Holocene; Paleovegetation; Paleogeography; Paleoclimate

## INTRODUCTION

A major geographic feature of northeast Asia is the Okhotsk Sea (~$1.5 \times 10^6$ km$^2$), a marginal basin of the North Pacific that is bounded on the north and west by the Russian mainland, on the south by Sakhalin and Hokkaido Islands, and on the east by Kamchatka Peninsula and the Kuril archipelago (Fig. 1a). The sea has strongly influenced both past and present landscapes, particularly in the southern Russian Far East (SRFE). For example, the warm Soya Current, which today flows along the western shores of the southern Kuril Islands, allows the northern extension of temperate Eastern Asiatic flora into what is otherwise boreal vegetation (Pietsch et al., 2003). The primary driver of Holocene environmental change along the coastal SRFE mainland and Kuril Islands has been purported to be a series of transgressions and regressions within the Okhotsk Sea linked to variations in global ice volume as climate shifted between comparatively warmer (transgression) and cooler (regression) conditions (Korotky et al., 1996, 1997, 2000; Korotky, 2002; Razjigaeva et al., 2002, 2004, 2008). However, evaluating the accuracy of this stepped sea-level history for the southern Okhotsk Sea has been particularly challenging as the paleodata on which the scheme is based are from discontinuous records of exposed marine and terrestrial sections, some of which have limited dating control.

As part of the Kuril Islands Biocomplexity Project, a joint American-Russian-Japanese investigation into the impact of environmental changes (e.g., volcanic eruptions, tsunamis, and climatic shifts) on human subsistence-settlements patterns within island locales, we researched the Holocene landscape and climate histories of the islands through multiproxy studies of lacustrine sediment cores. One goal within the broader project was to evaluate the Holocene climate/sea-level model both in terms of chronology and number of environmental changes as defined by the discontinuous section data through the analysis of continuous lake records. To that end, we present results from Maloye Lake (45°05.067′N, 147°41.722′E; ~0.3 meters above sea level [m asl]) and Kasatka Lake

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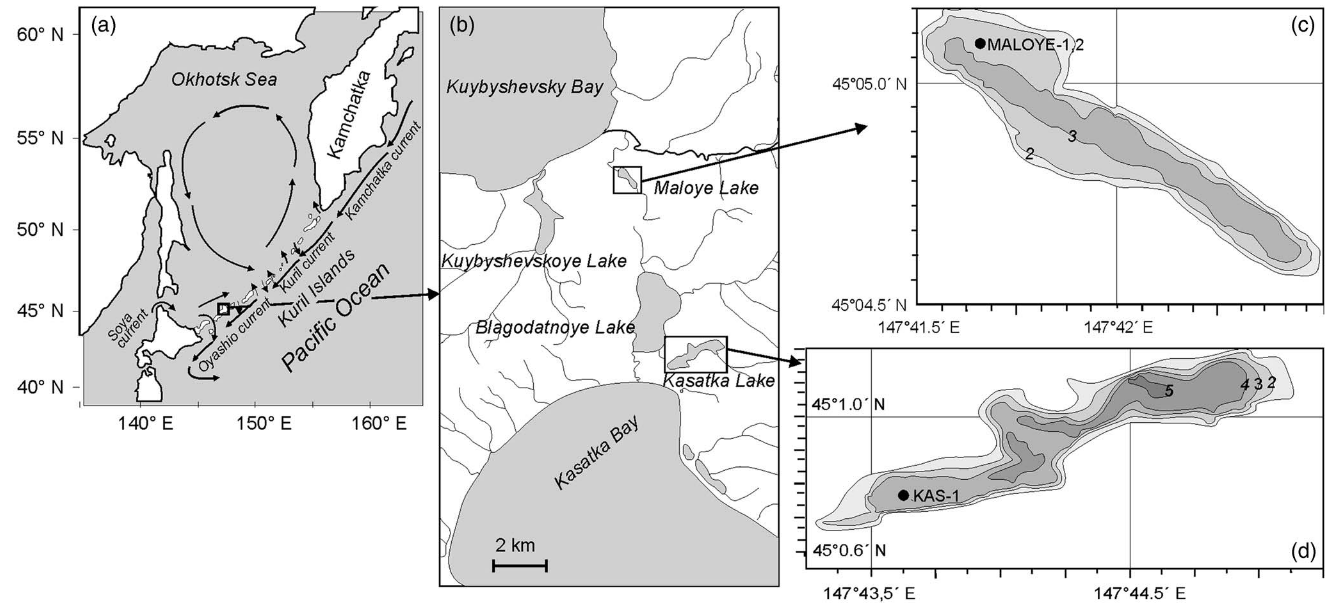


**Figure 1.** Maps showing details of the study area: location of Kuril Islands (Iturup Island indicated by the square) and marine currents (a); drainage patterns and locations of Kasatka and Maloye Lakes in Kubyshevskiy Isthmus, central Iturup Island (b); bathymetric map of Maloye Lake with depths shown in 1 m intervals (c); bathymetric map of Kasatka Lake with depths shown in 1 m intervals (d). Coring locations are indicated on the bathymetric maps by dark circles.

(45°00.748′N, 147°43.688′E; ~2.8 m asl), located on central Iturup Island in the southern Kuril archipelago (Fig. 1b).

## Study area

Kasatka and Maloye Lakes lie ~650 m and ~900 m from the Pacific and Okhotsk sides of Iturup Island, respectively, within the ~9-km-wide Kuybyshevskiy Isthmus. The low (~125–40 m asl), rolling topography of the Isthmus is flanked by volcanic complexes (~500–1600 m asl). The latter are formed by the Quaternary Bogatyrskii and Late Neogene Fregatskii complexes, which are dominated by andesites, basalts, tuffs, and conglomerates (Kotlyakov, 2009). Unconsolidated Quaternary sediments of marine, alluvial, lacustrine, and eolian origin characterize the Isthmus proper.

The climate of the SRFE is monsoonal, controlled by the development of (1) the Asiatic Low and the North Pacific High in summer and (2) the Siberian High and Aleutian Low in winter (Martyn, 1992). Summer is dominated by moist, mild air masses flowing in a north–northeasterly direction. In contrast, airflow in winter is to the south–southeast bringing in relatively cold, dry air. On Iturup Island, August/January are the warmest/coolest months with mean temperatures of 15°C and −5°C, respectively (data from the Kurilsk meteorological station located ~25 km to the north of the study sites; Kotlyakov, 2009). Precipitation is greatest from July to November with September being the wettest month (mean ~280 mm) and June the driest (~130 mm).

Three ocean currents originating in the North Pacific and Japan Sea influence the climates of the Kuril Islands (Gorbarenko et al., 2004). The warm, high-salinity Soya Current penetrates into the southwestern Okhotsk Sea and subsequently separates to flow to the northeast and southeast within the southern islands (Fig. 1a). To the north, the cooler Kamchatka Current splits in the central Kurils with a portion of the waters entering the Okhotsk Sea where they become part of a larger gyre, which dominates circulation in northern and central regions. These waters return to the Pacific Ocean through Bussol' Strait, generating the Oyashio Current. This circulation pattern helps to moderate conditions in the southern Kuril Islands while retaining cool climates in the north. Additionally, the archipelago's central mountain system acts as a barrier to the chilly fog and bitter winds associated with the cool Oyashio Current, thereby increasing the relative warmth of western versus eastern island landscapes (Razjigaeva et al., 2002).

*Betula ermanii* forests (sometimes with *B. platyphylla*) occupy ~38% of Iturup Island and are found primarily on lower slopes along the Pacific coast and in the interior or as open forest-meadow in the north (Urusov and Chipizubova, 2000; Razjigaeva et al., 2002). To the south of Vetrovoy Isthmus (~45°15.000′N) coniferous species are more common. On the central island, open *Larix kamtschatica* (syn. *L. kurilensis*) woodlands, sometimes in association with tree *Betula*, occupy coastal and interior areas. *Pinus pumila* occurs above ~400 m asl. Forests of southern Iturup include *Abies sachalinensis* and *Picea ajanensis* (syn. *P. microsperma*), which require slightly warmer and/or moister conditions. Coastal meadows can be extensive throughout the island and often cover large dune fields, which have been stabilized primarily by *Leymus mollis* and other xerophytes.

## Study sites

Maloye and Kasatka Lakes are located <1 km from the Okhotsk and Pacific coasts, respectively. Both lakes are

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bordered on their coastal sides by stabilized dune fields. Maloye Lake has one main inlet and a single active outflow channel to the Okhotsk Sea, and it consists of a single basin (Fig. 1c). Three elevated beach terraces (highest ~2 m) were noted on the western side of the lake. Kasatka Lake is formed by two deep basins within a largely flat lake floor (Fig. 1d); it has one sizable surface inlet and no observable surface outlet. The lake is nearly surrounded by hills (maximum elevation 90 m asl), providing a more sheltered setting than the open, windswept terrain near Maloye Lake.

Open *Larix* parkland characterizes some lowlands on central Iturup Island, such as the isthmus where Maloye and Kasatka Lakes are located. Vegetation near Maloye Lake is a mix of *Poa-Sasa* meadows and woodlands. *Betula ermanii* and *Larix kamtschatica* occur as scattered stands along the western shore and at higher elevations in the nearby hills, whereas an almost pure conifer woodland grows near the south end of the lake. *Pinus pumila*, although not seen along the lakeshore, forms thickets at mid- to higher elevations. The forest near Kasatka Lake, which includes more temperate species than near Maloye Lake, is dominated by broadleaf trees (*Betula ermanii*, *Alnus hirsuta*, and *Quercus crispula* with occasional *Acer mayrii*). *Larix* occurs mostly as individuals within the forest rather than in stands as seen at Maloye Lake. *Sorbus sambucifolia* and *Pinus pumila* are also found throughout the forest and in thickets along the shores of the lake and streams. Meadows, which are more extensive at Maloye, include a variety of microhabitats.

## MATERIAL AND METHODS

Sediment cores were raised from Kasatka and Maloye lakes (Fig. 1c and d) in water depths of 290 and 200 cm, respectively, during summer 2007, using a modified 5-cm-diameter Livingstone piston corer (Wright et al., 1984) for deep sediments and a 3-cm-diameter Plexiglas tube for the sediment-water interface. Core sections were split in the laboratory, described through visual inspection, and photographed. Magnetic susceptibility (MS) samples were collected continuously along the core using polystyrene containers of in 6.3 $cm^3$ volume. Palynological and diatom subsamples were taken from these cubes after MS analyses were completed.

MS ($k$) was measured and subsequently studied at high temperatures with an MFK1-FA multifunction kappabridge with CS-3 high-temperature control units (AGICO Ltd.). Selected samples and magnetic extracts were continuously measured for susceptibility as the temperature was raised from room temperature to 700°C and cycled back to 50°C. The composition and structure of particular detrital grains were examined using a QEMSCAN (quantitative evaluation of minerals by scanning electron microscopy) complex.

Organic matter $\delta^{13}C$, sedimentary $\delta^{15}N$, and organic carbon and nitrogen samples were analyzed on an elemental analyzer to determine total organic carbon (TOC) and total nitrogen (TN) concentrations, coupled to a Thermo Delta Advantage isotope ratio mass spectrometer for $\delta^{13}C$ and $\delta^{15}N$ measurements. All isotope values are reported in per mil units (‰) according to the relationship $\delta X = [(R_{sample}/R_{standard}) - 1] \times 1000‰$, where $X$ is the element of interest and $R$ is the measured isotopic ratio. All carbon isotope measurements are relative to the Vienna Peedee belemnite standard, and all nitrogen measurements are relative to atmospheric nitrogen. No pretreatments were used as carbonates are an insignificant component of the sediment samples selected for analysis. Replicate measurements of internal standards run during these analyses yielded coefficients of variation of 1.61% and 1.04% for TOC and TN, and precision of 0.2‰ for the stable isotope measurements.

Palynological samples were prepared following standard procedures (Paleoclimates of Arctic Lakes and Estuaries, 1994), and palynomorphs were identified with a Motic-EF-PL microscope at 600× and 1000× magnification. Percentages of individual pollen and spore taxa are based on the sum of identified arboreal, nonarboreal, and unknown pollen grains. Subsum percentages were calculated using the sum of all pollen and spores. Pollen sums exceed 300 and 600 known pollen grains for Maloye and Kasatka Lakes, respectively. Pollen zonation was done by visual inspection. Plant taxonomy follows Czerepanov (1995); shrub *Alnus* pollen represents *Duschekia.*

Diatom samples were processed following Proshkina-Lavrenko et al. (1974). Taxa were identified under oil immersion with Amplival Zeiss and Axioplan 40 light microscopes at 1000× magnification. A minimum of 400 diatom valves were identified per sample. Diatom taxonomy and ecology are based on Kramer and Lange-Bertalot (1986, 1988, 1991a, 1991b) and van Dam et al. (1994). Criteria used to assess water salinity represented by a diatom assemblage are as follows: fresh salinity, <0.2‰; fresh-brackish, <0.9‰; brackish-fresh, 0.9–1.8‰; and brackish, 1.8–9.0‰ (van Dam et al., 1994).

### Age models

A set of four and six radiocarbon dates were obtained for the Maloye and Kasatka records, respectively (Table 1). No discrete tephra layers were noted in the cores. The paucity of plant macrofossils, particularly in Kasatka Lake, resulted in a chronology based primarily on bulk sediment samples. The 2960 $^{14}C$ yr BP date, which was deemed too old, and the 8480 and 7220 $^{14}C$ yr BP ages, which statistically overlap at 2σ, were not used in the Kasatka age model. The 7025 $^{14}C$ yr BP bulk-sediment date at the bottom of unit 3 (freshwater lake) was eliminated from the Maloye chronology because it is likely too old given that regional high stands in sea level occurred between 6500 and 6000 $^{14}C$ yr BP (Korotky et al., 2000).

We experimented with a variety of age models for both records including linear interpolation, linear regression, and Bayesian statistics (Blaauw and Christen, 2011). Results of the three methods for ages within freshwater deposits were similar, probably reflecting the small number of dates used in modeling (see Supplementary Materials, e.g., using the Bacon age-depth model). Because the lakes are only separated

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**Table 1.** Radiocarbon and calibrated ages, Kasatka and Maloye Lakes.

| Lake | Lab no. | $^{14}$C age | Calibrated mean age (cal yr BP) | Calibrated age range (2-sigma) | Depth (cm) | Material dated |
|---|---|---|---|---|---|---|
| Kasatka | CAMS-143085 | 2960 ± 30[a] | 3135 | 3005–3242 | 90–91 | Bulk sediment |
| | CAMS-136958 | 2590 ± 45 | 2686 | 2495–2785 | 258.5–259.5 | Unidentified plant macrofossil |
| | CAMS-143086 | 4075 ± 30 | 4589 | 4442–4805 | 390–391 | Bulk sediment |
| | CAMS-152308 | 5390 ± 70 | 6164 | 5995–6300 | 449–451 | Bulk sediment |
| | CAMS-142309 | 7220 ± 140[a] | 8054 | 7764–8349 | 650–653 | Bulk sediment |
| | CAMS-152310 | 8480 ± 500[a] | 9569 | 8362–11,067 | 731–734 | Bulk sediment |
| Maloye | CAMS-136959 | 385 ± 35 | 427 | 317–510 | 75 | Unidentified plant macrofossil |
| | CAMS-136960 | 2840 ± 30 | 2948 | 2865–3063 | 212 | Unidentified plant macrofossil |
| | CAMS-136962 | 3995 ± 35 | 4472 | 4408–4569 | 498 | Unidentified plant macrofossil |
| | CAMS-143089 | 7025 ± 40[a] | 7865 | 7760–7950 | 1035–1040 | Bulk sediment |

[a]Indicates date not used in the age model. Dates were calibrated using CALIB 6.0 (http://calib.qub.ac.uk/calib/calib.html; Stuiver and Reimer, 1993).

by ~8 km, we presumed that changes from marine strait to lagoon to freshwater lake would be nearly synchronous, even though they are on opposite sides of Iturup Island. Although use of <7000 $^{14}$C yr BP dates in the age models yielded similar dates for establishment of a freshwater lake (~6300 $^{14}$C yr BP, Maloye; 6200 $^{14}$C yr BP, Kasatka), timing of the marine–lagoon transition differed by ~2600 $^{14}$C yr. Furthermore, extrapolated basal ages for marine deposits were unrealistically old given comparisons to the palynological data. We therefore are limited to assigning the saltwater deposits and pollen zones 1 and 2 to the early Holocene. As for the Mid- to Late Holocene portions of the cores, the ages of the sandy units, which appear to have a regional significance, differ between lakes by up to 1000 $^{14}$C yr with age assignments in the Maloye record being more consistent with regional trends. Consequently, paleoenvironmental changes presented in this article represent the Maloye age scheme only and are meant as a working model rather than a definitive chronology.

## RESULTS

Results are described according to sediment (lithology, magnetics, and stable isotope geochemistry) and paleobotanical (diatoms, pollen, and spores) characteristics.

### Sediment characteristics

The cores from Maloye and Kasatka Lakes are dominated by sands and silts with occasional occurrences of gravel and marine shells. We have divided the cores into three sedimentary units (Table 2) with silty sand/sandy silt (unit 1) replaced by laminated silt (unit 2) and, in the uppermost part of the cores, a massive silt with layers of sand or silty sand (unit 3). Magnetic characteristics generally vary with the lithological changes in both lakes. Unit 1 has the highest MS (450–32,000 × $10^{-6}$ SI [Maloye] and 227.2–22,530 × $10^{-6}$ [Kasatka]; Fig. 2a and b). MS in unit 2 (143.7–1772 × $10^{-6}$ SI [Maloye] and 55.6–4835 × $10^{-6}$ SI [Kasatka]) is lower than unit 1. The highest MS in unit 3 corresponds to the four sandy layers.

Transmission microscopy revealed abundant dark spherules in units 1 and 2. The back-scattered electron images of the spherules are bright (Fig. 2c), and QEMSCAN measurements indicate that they are predominantly composed of iron and sulfur with small concentrations of aluminum and silicon (Fig. 2d). These inclusions are nonmagnetic and mainly consist of pyrite. Some of them occur in the diatoms, frequently in the form of chains (Fig. 2c). When heated, the pyrite transforms into monoclinic pyrrhotite, which is expressed by a sharp increase in MS at 320°C in the $k(T)$ cooling curves.

**Table 2.** Sediment description, Kasatka and Maloye Lakes.

| Sediment unit | Sediment description | Depth (cm), Kasatka Lake | Depth (cm), Maloye Lake | Depositional environment |
|---|---|---|---|---|
| Unit 1 | Massive silty sand to sandy silt with intermittent layers of sand, gravel, and shells | 892–610 | 1541–1085 | Tidal flat, marine strait |
| Unit 2 | Laminated silt | 610–505 | 1085–1053 | Brackish lagoon |
| Unit 3 | Massive silt with layers of sand or sandy silt; plant fragments in upper 100 cm | 505–0 | 1053–0 | Freshwater lake |
| Sediment subunits | | | | |
| 3a | Sandy silt or silty sand layer | 505–410 | 980–800 | Freshwater lake |
| 3b | Sandy silt or silty sand layer | 346–340 | 565–558 | Freshwater lake |
| 3c | Sandy silt or silty sand layer | 284–275 | 436–395 | Freshwater lake |
| 3d | Sandy silt or silty sand layer | 145–141 | 131–110 | Freshwater lake |

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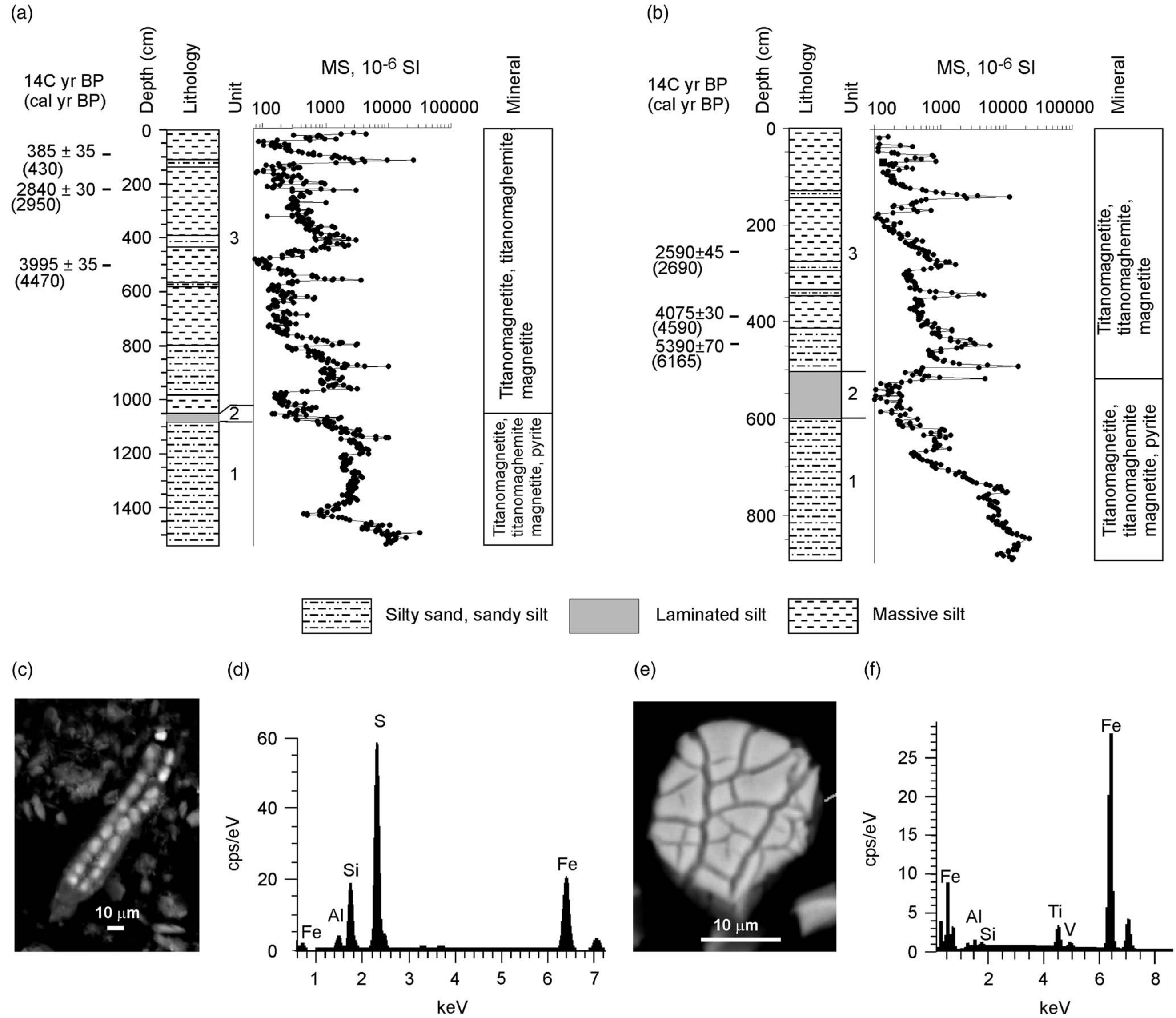


**Figure 2.** Lithology, magnetic susceptibility (MS), and mineral characteristics for Maloye and Kasatka Lakes. (a) Summary for Maloye Lake. (b) Summary for Kasatka Lake. (c) Back-scattered electron (BSE) images of spherules (which often form chains) within a diatom. (d) Elemental content of spherules. (e) BSE image of detrital grains. (f) Elemental content of detrital grains. Rounded mean calibrated ages are given in parentheses.

Titanomagnetite, titanomaghemite, and magnetite constitute the detrital magnetic minerals (Fig. 2f). The energy-dispersive spectroscopy data indicate that typical grains contain Fe (≤69%), Ti (≤7.9%), O (≤24.54%), trace amounts of aluminum and silicon, and rare occurrences of magnesium and vanadium. The characteristic fracturing of the grains (the dark fields in Fig. 2e) are likely caused by low-temperature oxidation. The *k*(*T*) curves show the Curie temperature of magnetite and low titanium magnetite to be between ~570°C and 580°C. Titanomaghemites cause a sharp decrease in MS at ~370°C–390°C (maghemite–hematite transition) in the heating curves.

## Geochemistry

Unit 1 sediments in Maloye and Kasatka Lakes are dominated by low carbon and nitrogen content and relatively high $\delta^{13}C$ and $\delta^{15}N$ values (Fig. 3). A fairly abrupt change occurs at the transition into unit 2 in all these parameters. Carbon and nitrogen content gradually increases above this transition, until approximately midway into unit 3, where values generally become more constant (~550 cm in Maloye and ~200 cm in Kasatka). Decreases, typically sudden, occur in organic content corresponding to the coarser layers in unit 3 (Table 2). The most abrupt decline in $\delta^{13}C$ happens within unit 2 and the lower part of unit 3, with more gradual shifts up-core. In Maloye Lake, $\delta^{15}N$ values decrease quickly into unit 2; above this transition, $\delta^{15}N$ is fairly low (3‰) and constant (range 2‰ – 4‰). In Kasatka Lake, $\delta^{15}N$ is lowest within unit 2 (~3‰) and then increases to relatively constant values (~3.5‰) for the remainder of the core. The carbon-to-nitrogen ratios for Kasatka Lake are relatively low (~8) and constant, suggesting a dominance of aquatic sources

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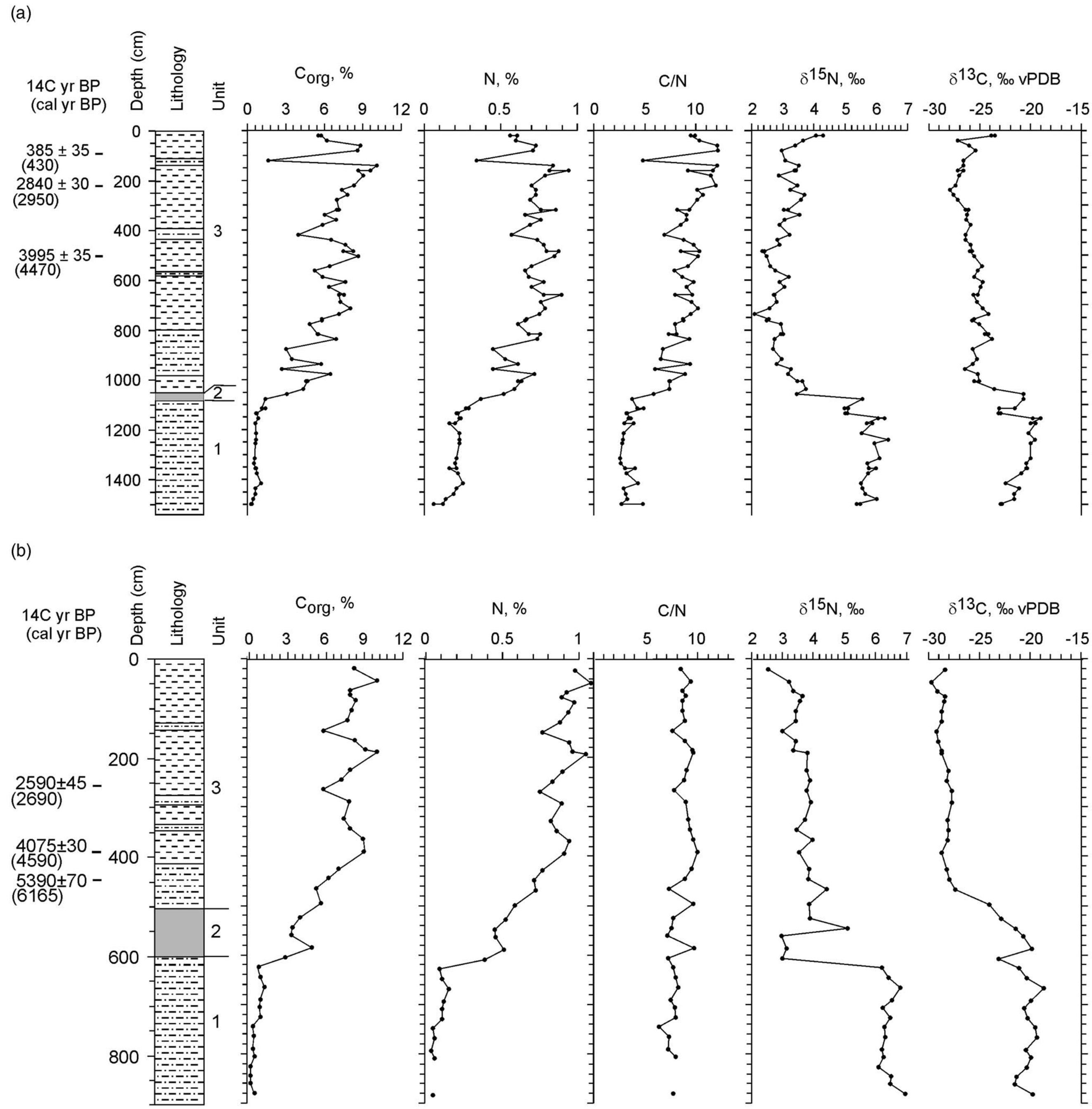


**Figure 3.** Down-core profiles of carbon, nitrogen, C/N ratio, $\delta^{15}N$, and $\delta^{13}C$ for Maloye Lake (a) and Kasatka Lake (b). See Table 2 for description of sediment units. Rounded mean calibrated ages are given in parentheses. Carbon isotope measurements are relative to the Vienna Peedee belemnite (vPDB) standard.

throughout the record (Meyers and Ishiwatari, 1993; Meyers, 1997). In Maloye Lake, values in unit 3 range from 8 to 10, again consistent with aquatic sources.

## Paleobotanical results: diatoms

Changes in diatom assemblages generally parallel the sedimentologic shifts in the Maloye and Kasatka cores with unit 1 dominated by marine taxa, unit 2 by brackish-water diatoms, and unit 3 by freshwater species (Fig. 4). Neogene taxa, whose source is likely the unconsolidated sediments of the Kuybyshevskiy Isthmus, occur throughout both cores but are most abundant in unit 1 (e.g., ≤7% *Neodenticula kamtschatica* and lesser values of *Stephanopyxis turris*, *Pyxidicula zabelinae*, and *Coscinodiscus marginatus* f. *fossilis*, not shown in Fig. 4). Unit 1 is also characterized by low concentrations of diatoms, whereas valve concentrations markedly increase in units 2 and 3.

The basal-most samples in unit 1 at Maloye Lake (>1500 cm) are dominated by the marine sublittoral (near-shore) species *Paralia sulcata* and *Diploneis smithii*. In mid- to

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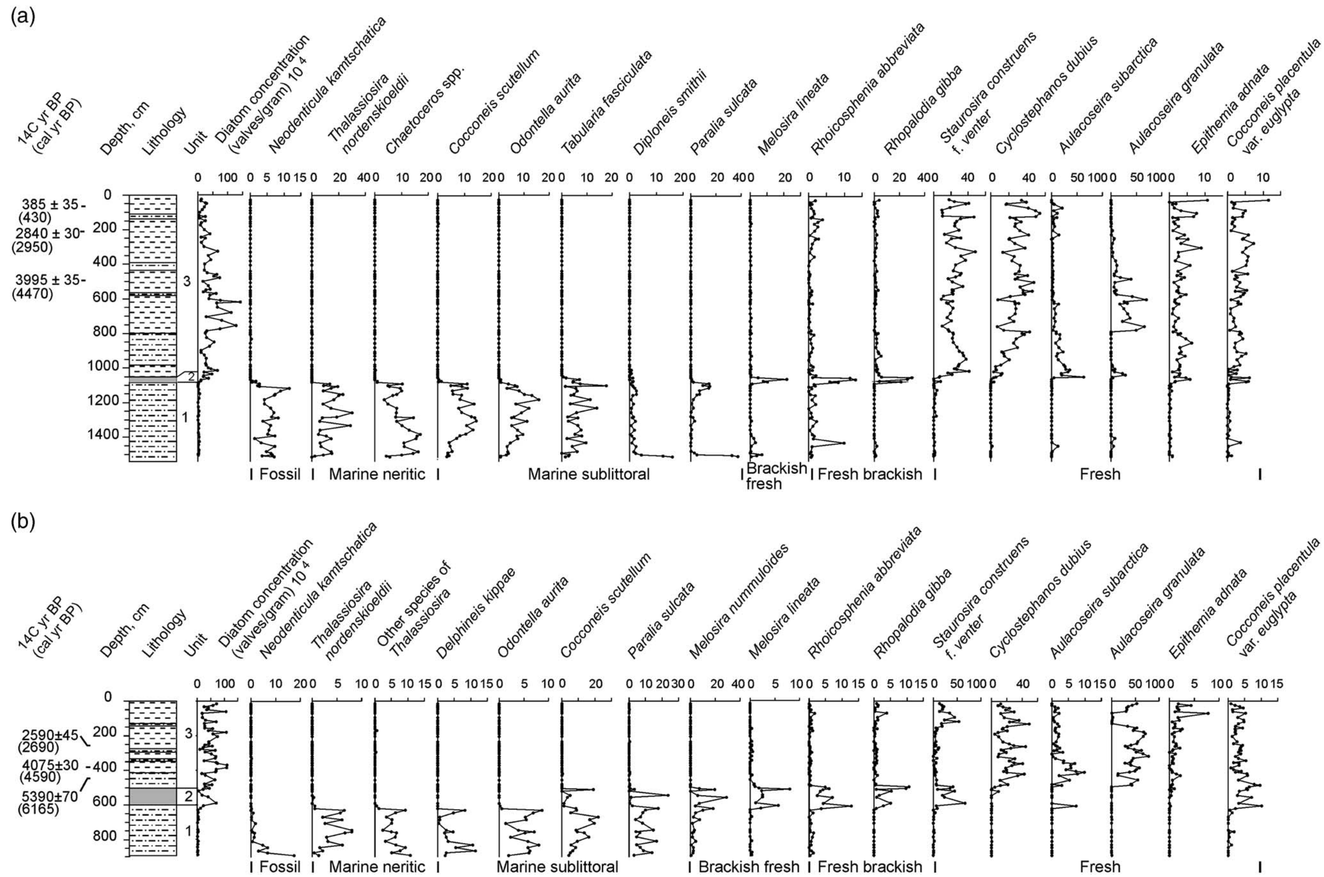


**Figure 4.** Diagram showing select major diatom taxa from Maloye Lake (a) and Kasatka Lake (b). See Table 2 for key to sediment descriptions. Rounded mean calibrated ages are given in parentheses.

upper unit 1 (1495–1085 cm), the neritic (shallow-shelf) *Thalassiosira nordenskioeldii* and *Chaetoceros* spores are the principal types. However, sublittoral taxa (e.g., *Cocconeis scutellum* and *Diploneis smithii*) continue to be important.

Diatom assemblages at Kasatka Lake also show variability within unit 1, but retain a marine character throughout. In lower unit 1 (890–820 cm), the assemblage is distinguished by neritic, pelagic (free-floating), and sublittoral taxa (e.g., coldwater *Thalassiosira trifulta*, *Thalassiothrix longissima*, *Delphineis kippae*, and *Odontella aurita*). In mid- to upper unit 1 (820–610 cm), species diversity is high with taxa from sublittoral (e.g., *Paralia sulcata* and *Delphineis surirella*), neritic (e.g., *Thalassiosira nordenskioeldii*), and pelagic (e.g., *Thalassiosira pacifica*) groups. An overriding characteristic in this part of the core is the consistently high percentages of the sublittoral taxon *Cocconeis scutellum.*

Unit 2 in both cores is marked by increases in the concentration of diatom valves and the change from marine to brackish or euryhaline (organisms tolerant of a range of salinity) assemblages. Samples are characterized by high percentages of sublittoral marine *Paralia sulcata*, brackish *Melosira nummuloides*, and fresh-brackish *Rhoicosphenia abbreviata*. The percentages of freshwater diatoms also increase, as illustrated by *Staurosira construens* f. *venter*.

The highest concentrations of diatom valves occur in unit 3 where freshwater taxa replace brackish forms. At Maloye Lake, *Cyclostephanos dubius* and *Staurosira construens* f. *venter* are the most consistently abundant species. However, some assemblage variation occurs within the unit. For example, *Aulacoseira granulata* is abundant from ~770 to 560 cm, whereas *Aulacoseira subarctica* is common in the lower part of the unit. In general, the Kasatka record shows greater variability as compared with Maloye. For example, the euryhaline taxon (van Dam et al., 1994) *C. dubius* is important from 450 to 325 cm, 275 to 240 cm, and 175 to 100 cm in Kasatka Lake. Other short-term changes include high values of freshwater *S. construens* f. *venter* and fresh-brackish *Rhopalodia gibba* (500–490 cm), freshwater *A. granulata* (485–140 cm), freshwater *S. construens* f. *venter* and *C. dubius* (140–65 cm), and freshwater *A. granulata*, *S. construens* f. *venter*, and *C. dubius* (65–15 cm).

## Paleobotanical results: pollen and spores

Pollen zones do not correspond to the sediment/diatom units indicating that the palynological data are reflecting changes in the vegetation and not depositional environments. The Maloye (Fig. 5a) and Kasatka (Fig. 6a) records are dominated by arboreal taxa, particularly *Betula* and *Quercus* with a variety of temperate broadleaf species (e.g., *Juglans*, *Ulmus*, *Tilia*, *Acer*, and *Fraxinus*) and conifers (*Pinus* subg. Haploxyon, *Picea* sect. Eupicea, *Larix*). Graminoids are the most abundant nonarboreal taxa with a rich minor flora

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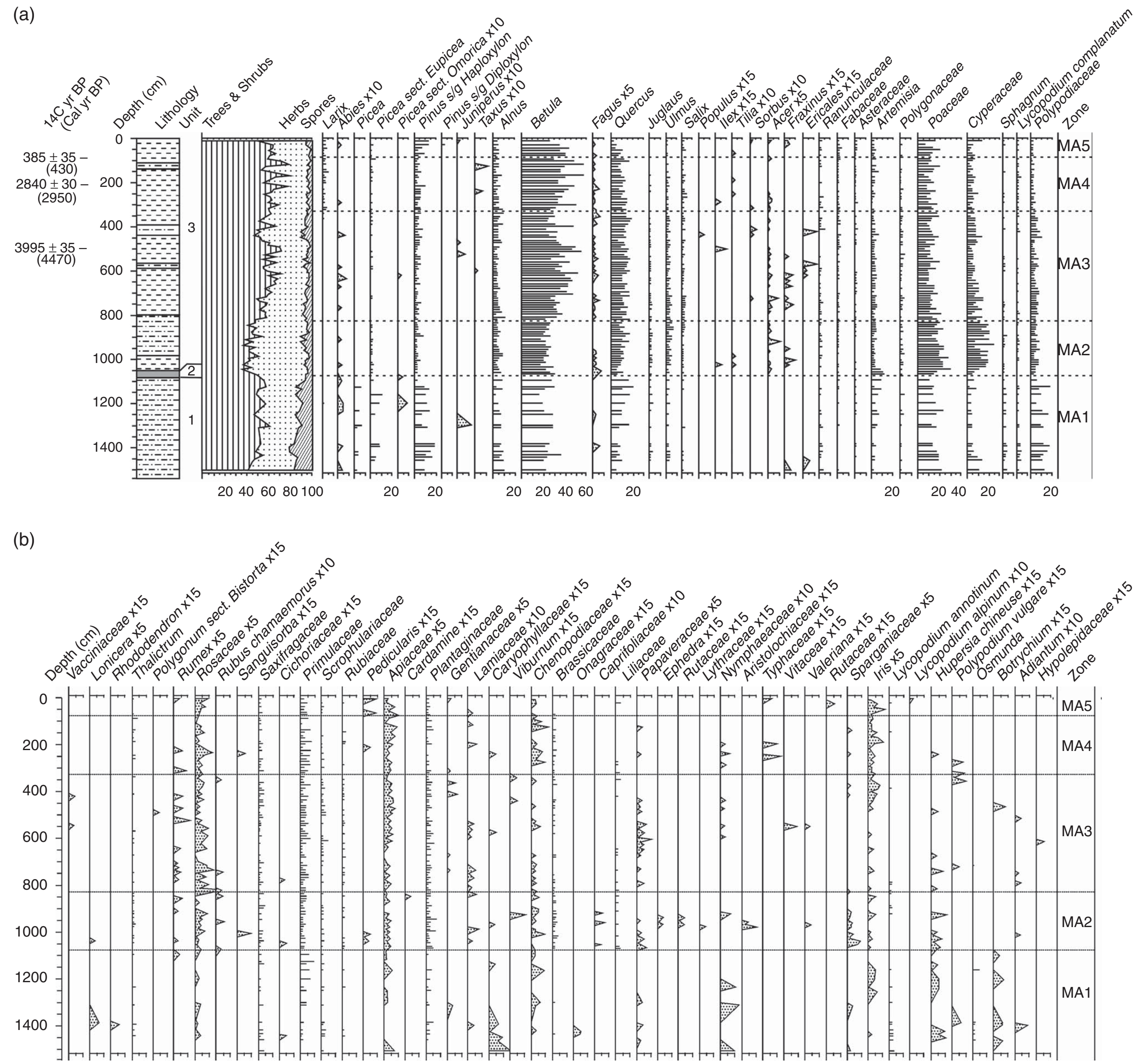


**Figure 5.** Diagrams showing percentages of major (a) and minor (b) taxa from Maloye Lake. See Table 2 for key to sediment descriptions. Individual taxa are expressed as percent of the pollen sum; trees and shrubs, herbs, and spore subsums are based on the sum of arboreal, nonarboreal, and spore taxa. Rounded mean calibrated ages are given in parentheses.

indicative of a variety of microhabitats (Figs. 5b and 6b). Polypodiaceae is the dominant spore type in both cores with lesser percentages of *Lycopodium* spp. and *Sphagnum*. Aquatics occur in minor amounts and include Nymphaeaceae, Typhaceae, and Sparganiaceae.

## HOLOCENE ENVIRONMENTS OF ITURUP ISLAND AND IMPLICATIONS FOR UNDERSTANDING PALEOCLIMATES OF THE KURIL ISLANDS

The following discussion describes the development of the Kasatka and Maloye basins (Table 2, Figs. 2–4) and the vegetation and climate history of central Iturup Island (Figs. 5 and 6) using a provisional age scheme developed for Maloye Lake. We consider these patterns in light of previous Holocene reconstructions for the southern Kuril Islands (Fig. 7) and their inferences for understanding mechanisms of climate change in the Okhotsk region.

### History of the Maloye and Kasatka basins

Sediment, geochemical, and diatom characteristics indicate a marine origin for unit 1. The presence of Neogene diatom taxa, coarse sediments, and low concentrations of valves suggest significant erosional input from the island. Low organic content is consistent with poor preservation in higher-energy marine and erosional environments. Anoxic

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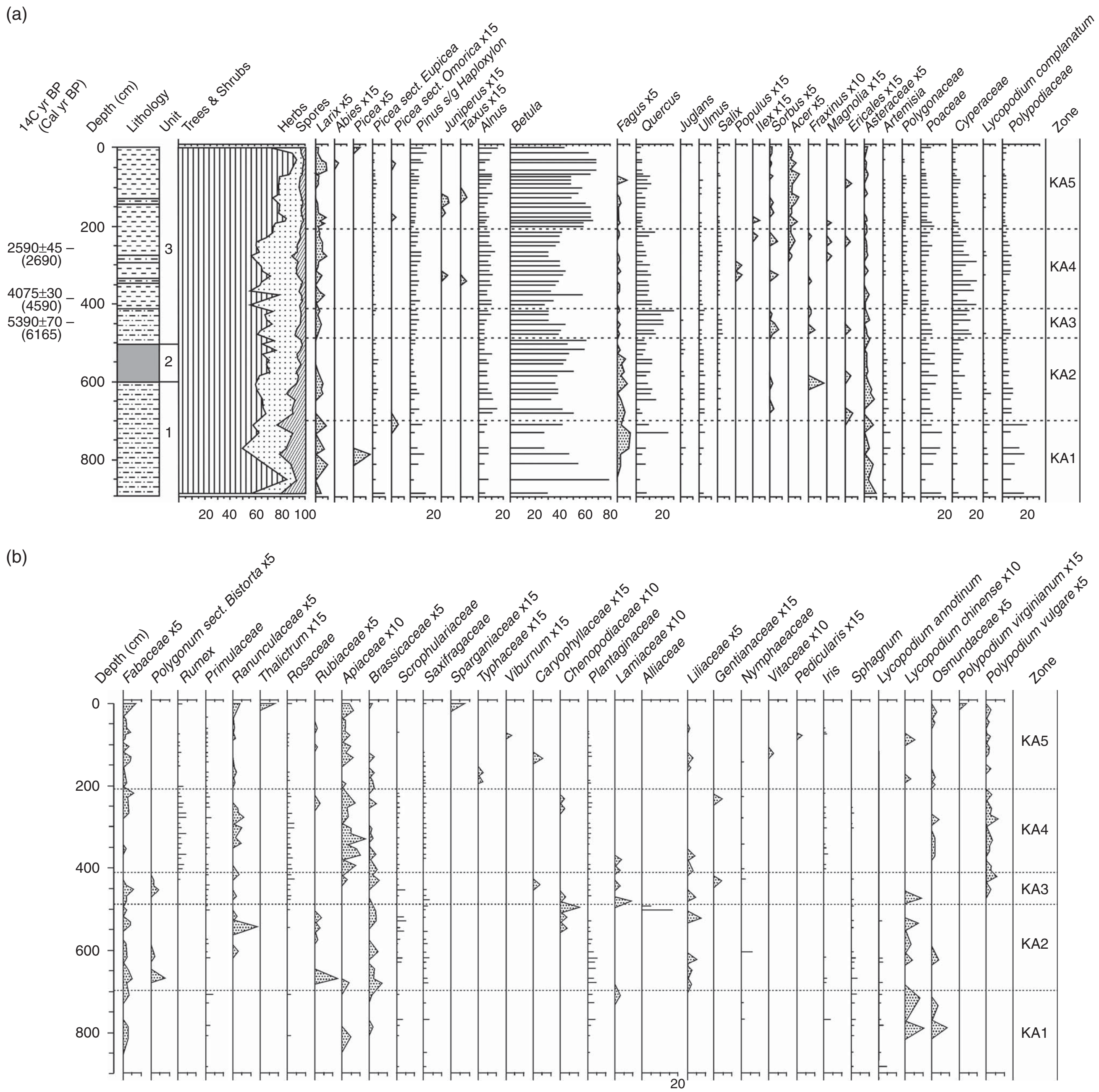


**Figure 6.** Diagrams showing percentages of major (a) and minor (b) taxa from Kasatka Lake. See Table 2 for key to sediment descriptions and percentage calculations. Rounded mean calibrated ages are given in parentheses. See Table 2 for key to sediment descriptions and Fig. 5 for information about percentage calculations.

conditions are indicated by the formation of Fe sulfides. Relatively high $\delta^{13}C$ and $\delta^{15}N$ are comparable with values for organic material of marine origin (Walinsky et al., 2009; Anderson et al., 2015). The problematic radiocarbon dates in the lower parts of the cores limit definitive age assignment for unit 1. However, regional sea-level curves and dated marine horizons in sections along the southern Kuril coasts indicate rapid sea-level rise to above modern limits by ~7000–6500 $^{14}C$ yr BP (7800–7400 cal yr BP; Korotky et al., 2000).

Diatom complexes indicate the presence of two types of marine environments. High percentages of marine sublittoral species (e.g., *Paralia sulcata* and *Diploneis smithii*) in lower unit 1 (Maloye, 1505–1500 cm; Kasatka, 890–820 cm) suggest the basins originated in near-coastal conditions, such as tidal flats. Further evidence is provided by shells of *Protothaca staminea* found in the Kasatka core. These mollusks represent a species that today inhabits sandy substrates in the lower half of the intertidal zone (water depths up to 10 m). High MS (lower unit 1), which reflects the concentration of detrital magnetic minerals, likely accumulated under unstable hydrodynamic conditions, such as found in tidal settings.

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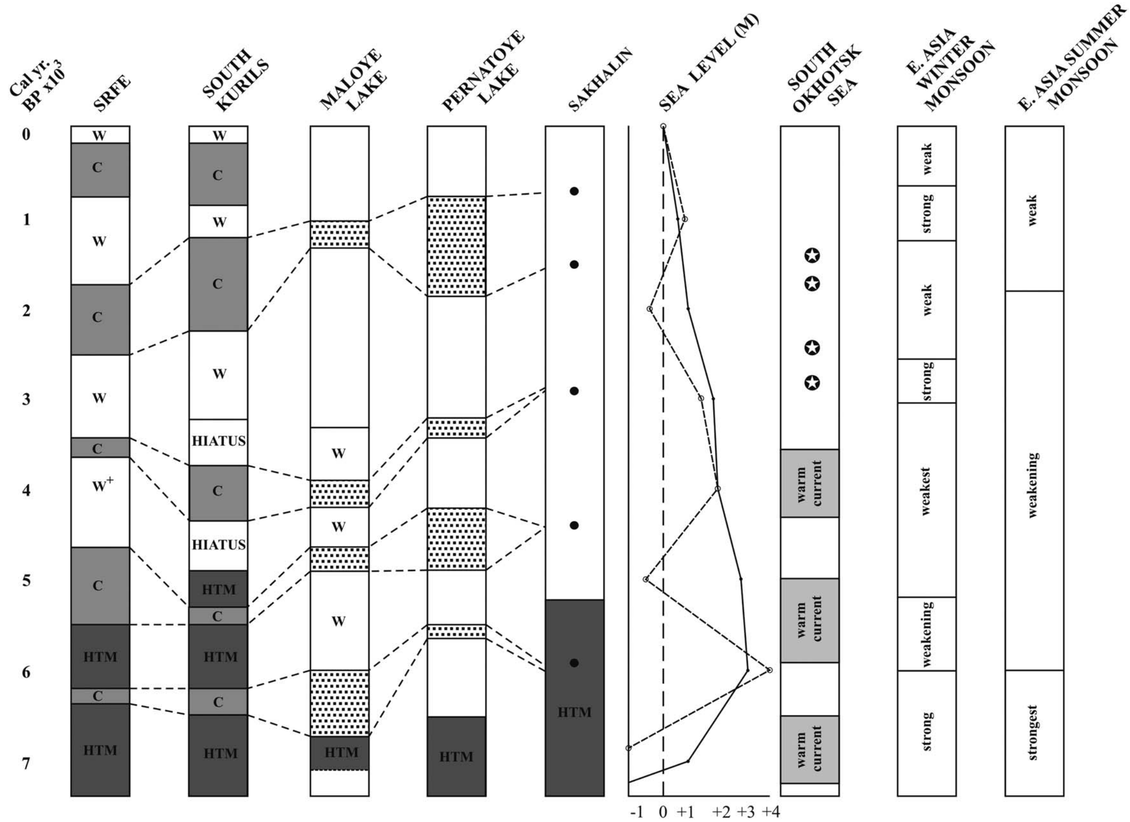


**Figure 7.** Summary of mid- to late Holocene environmental changes in the southern Russian Far East (SRFE). (1) Relative climate changes for the SRFE (Korotky, 2002). HTM, Holocene thermal maximum; W/W$^+$, relatively warm; C, relatively cool. (2) Relative climate changes for the southern Kuril Islands (Korotky et al., 2000; Razjigaeva et al., 2002, 2004). (3) Relative climate changes for Maloye Lake; dots indicate sandy layers (this study). Note that the HTM extends to 6100 cal yr. (4) Relative climate changes for Pernatoye Lake; dots indicate sandy layers (Minyuk et al., 2013; Anderson et al., 2015). (5) Climate events for Sakhalin Island; solid dots indicate brief cooling events (Leipe et al., 2015). (6) Changes in relative sea level for Singapore region (solid line) and northern Japan (dashed line; Sakaguchi et al., 1985; Bird et al., 2010). (7) Times of intensified warm currents in the southern Okhotsk Sea; stars indicate brief intervals of intensification of the Tsushima Warm Current (Kawahata et al., 2003). (8) Changes in the East Asian winter monsoon (Wang et al., 2008). (9) Changes in the East Asian summer monsoon (Chen et al., 2015). For the purpose of comparison to trends in the sea-level/climate model for the Russian Far East, the sand layers in the Maloye and Pernatoye cores have been linked to cool intervals in columns 1 and 2, but the pollen data from the lakes do not indicate any related cooling.

The tidal flats eventually gave way to a shallow strait (upper unit 1; Maloye, 1495–1085 cm; Kasatka, 820–640 cm) that perhaps bisected what is now central Iturup Island. Given the modern topography this water body was likely narrow. Evidence for the continued rise in sea levels includes high diatom diversity and a mix of neritic (e.g., *Thalassiosira nordenskioeldii* and *Chaetoceros*), sublittoral (e.g., *Cocconeis scutellum*, *Odontella aurita*, and *Tabularia fasciculata*), and pelagic (e.g., *Thalassiosira pacifica* and *Coscinodiscus radiatus*) ecological groups. Again, the age for the shift from tidal flat to marine strait in what is now the Kuybyshevskiy Isthmus is uncertain. However, Razijaeva et al. (2002) reported the flooding of the Vetrovoy Isthmus (~55 km to the north of our study area) during the Holocene thermal maximum (HTM) or prior to ~6000 $^{14}$C yr BP (~6800 cal yr BP), and Korotky et al. (2000) described inundated isthmuses on Kunashir Island associated with maximum sea levels at ~6500–6300 $^{14}$C yr BP (~7400–7200 cal yr BP).

The lagoonal sediments (unit 2) record the shift from brackish-fresh to fresh-brackish conditions as the Maloye and Kasatka basins transitioned from marine-coastal environments to freshwater lakes. With the establishment of a lagoon, the hydrodynamic mode became quieter as indicated by the appearance of finer-grained and laminated sediments. The decrease in $\delta^{13}$C and $\delta^{15}$N in organic material deposited during this transition is consistent with the increasing influence of freshwater/terrestrial contributions to the carbon and nitrogen signatures. Likewise, a greater organic content signifies a less dynamic sedimentary environment, consistent with the presence of finer-grained materials. MS is at or near the lowest values in the core indicating lower concentrations of detrital magnetic minerals and a quieter hydrodynamic regime. Anoxic conditions were suitable for the formation of pyrite, and sulfur was supplied from salts in the marine water. High values in *Rhopalodia gibba* mark the final phase of the lagoon-to-lake (unit 2 to unit 3) transition at both sites. Extrapolated ages for the Maloye core suggest that

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the lagoon was short lived between ~6400 and 6200 $^{14}C$ yr BP (~7400–7100 cal yr BP).

The establishment of a freshwater lake (unit 3) is marked clearly by the shift in diatom assemblages (e.g., increases in *Staurosira construens* f. *venter*, *Cyclostephanos dubius*, *Aulacoseira granulata*, and *A. subarctica*) and presence of lacustrine silts. The $\delta^{13}C$ and $\delta^{15}N$ values in both lakes are typical for organic matter of mainly freshwater origin. Organic matter content is at its highest in unit 3, with a general rise that may suggest increasing productivity as the lakes aged. Finally, the shift to freshwater conditions is marked by a change in magnetic minerals and loss of pyrite.

Variability in diatom complexes suggests three major changes in lake conditions during the mid- to late Holocene:

- Between ~6200 and 5200 $^{14}C$ yr BP (~7100–6000 cal yr BP; Maloye, 1045–785 cm; Kasatka, 475–360 cm), maximum percentages of *Aulacoseira subarctica* occurred. *A. subarctica* is a filamentous, acidophilous, pelagic species indicating oligo-mesotrophic conditions and the presence of cool water temperatures possibly linked to relatively cool climate (Krammer and Lange-Bertalot, 1991a; Krammer and Lange-Bertalot, 1991b; van Dam et al., 1994; Gibson et al., 2003; Tuji and Houki, 2004).
- Between ~5100 and 4300 $^{14}C$ yr BP (~5800–4900 cal yr BP; 775–570 cm), *A. granulata* became a codominant taxon in the Maloye assemblage accompanied by a decline in *A. subarctica*. At Kasatka Lake, high values of *A. granulata* persisted through most of the freshwater record except for a decline during the late Holocene (~140–65 cm). The increase in *A. granulata* suggests a high phosphorus concentration, conductivity, and eutrophic state of the lake waters (Miettinen, 2003). The taxon requires turbulent mixing to remain suspended in the water column (Bormans and Webster, 1999; Wang et al., 2008). *A. granulata* is the most thermophilic species of the genus *Aulacoseira*, having maximum populations in water temperatures >20°C. Hence, the high relative abundances of *A. granulata* likely represent times of elevated winds, warmer temperatures, and/or possibly a shallowing lake level.
- By ~4200 $^{14}C$ yr BP (~4700 cal yr BP; 560 cm), the modern diatom assemblage is in place at Maloye Lake. It is dominated by *Cyclostephanos dubius* and *Staurosira construens* f. *venter*. *C. dubius* is a typical eutrophic diatom found in shallow, nutrient-rich lakes (van Dam et al., 1994; Bradshaw and Anderson, 2003). This species also prefers water with high phosphorus (Pla et al., 2005). Changes in the size of *Cyclostephanos* valves suggest a gradual lowering of Maloye Lake. In contrast to the western site, the modern diatom complex established relatively recently (~65 cm) at Kasatka Lake.

Shifts in diatom complexes can reflect local, within-basin, and/or broader paleoclimatic patterns. In the cases of Maloye and Kasatka Lakes, it seems that the changes represented in the previously mentioned events are caused primarily by local influences. In the case of event 1, the abundance of *Aulacoseira subarctica* in Kasatka Lake is much lower than in Maloye (≤9.8% and ≤63.1%, respectively), suggesting that relatively warmer temperatures occurred on the Pacific side of the island ~6200–5200 $^{14}C$ yr BP (~7100–6000 cal yr BP). A similar east–west discrepancy exists today, which likely relates more to geomorphology (an open, windswept landscape near Maloye in contrast to the more protected setting near Kasatka) than regional climate. Today, warmer conditions generally prevail on the Okhotsk versus Pacific sides of the south Kuril Islands related to marine currents, a pattern that was established by the mid-Holocene (Gorbarenko et al., 2004). Additionally, the interval when the diatoms suggest cool waters/air temperatures occurs during the HTM as indicated by the pollen records (see the next section).

The decline in *A. subarctica* and rise of *A. granulata* (event 2) could reflect a shift from relatively cool to warm water/air temperatures. However, maximum values for *A. granulata* at Maloye, although appearing during warmer than present conditions, occur after the HTM, which suggests that temperature is not the main influence on this part of the diatom record. A similar conclusion can be drawn from the Kasatka data, where variations in *A. granulata* do not correspond to pollen-based paleoclimate interpretations. *A. granulata* and *Cyclostephanos dubius* (event 3) can both be indicative of changing lake levels, which would be consistent with observed, albeit undated, paleoshorelines noted at Maloye Lake. No evidence of lake-level changes was found at Kasatka Lake, although *C. dubius* has a distinct dominance in the intervals 450–325 cm, 275–240 cm, and 175–100 cm. This stratigraphic pattern probably was caused by a change in trophic levels within the lake, as other proxies do not suggest climate-driven fluctuations in lake levels.

A feature that perhaps does represent a more regional paleoclimatic signature is the presence of the four sandy layers (unit 3), which are characterized by the following: (1) coarser sediments, (2) increased MS caused by high concentrations of detrital magnetic minerals, (3) abrupt decreases in $\delta^{13}C$ and $\delta^{15}N$ signifying higher input of coarser minerals, (4) a low concentration of diatom valves, and (5) an abundance of attached diatoms (e.g., *Cocconeis placentula* var. *euglypta* and *Epithemia adnata*). These layers possibly are correlated to similar sandy horizons in Pernatoye Lake (50°02.43′N, 155°23.71′E; 20 m asl), northern Kurils (Anderson et al., 2015). Three to four major intervals of active eolian processes including dune formation have been described throughout the SRFE (Korotky et al., 1988, 1996, 2000; Razjigaeva et al., 1996; Korotky, 2002). The newly exposed shelves associated with marine regressions of up to –4 m below modern mean sea level are postulated as source material for the dunes. Erosion of the dunes during subsequent marine transgressions resulted in the buildup of coastal landforms, such as spits and storm ridges. The repetition of accumulation and erosional cycles led to a dynamic mid- to late Holocene coastal history both on the islands and mainland. Today, large stabilized sand dunes are located

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near Maloye, Kasatka, and Pernatoye Lakes and, given this regional scenario, may reasonably be remnants of these geomorphic processes.

## Vegetation history of central Iturup Island

Prior to ~7000–6500 $^{14}$C yr BP (~7800–7400 cal yr BP; Razijgaeva et al., 2002), the vegetation on both the Okhotsk and Pacific sides of Iturup Island was *Betula*-conifer forest (zones MA1 and KA1), perhaps with conifers being more abundant near Maloye Lake. *Picea* was the most common evergreen near both sites (probably represented by *P. glehnii*/*P*. sect. Eupicea and *P. ajanensis*/*P*. sect. Obovata), with a lesser presence of *Larix* (Kasatka only) and *Abies* (Maloye only). Broadleaf trees included *Quercus*, *Ulmus*, and *Juglans*. The understory supported *Pinus pumila* and *Duschekia* shrubs. The former may have grown in dense thickets as suggested by the present-day ecology (Grishin et al., 2005) and occurrence of high percentages of Polypodiaceae spores in modern spectra associated with such settings (Anderson and Lozhkin, 2017).

Summer temperatures on central Iturup were warmer than present as indicated by the greater presence of broadleaf trees and evergreen conifers. Conditions on the Pacific side may have been slightly cooler and/or drier as suggested by somewhat (1) higher pollen percentages of *Quercus* at Maloye (≥10%) as compared with Kasatka (generally <10%) and (2) higher *Picea* and *Pinus* percentages (generally ≥10% at Maloye and ≤10% at Kasatka) and trace amounts of *Abies* at Maloye. However, in contrast to the Maloye record, the Kasatka pollen spectra indicate that warming began while sea levels were still high (zone KA2; upper unit 1 and unit 2). *Betula* probably remained the dominant tree taxon. During this period, *Quercus* likely became more abundant and *Larix* less common on the landscape.

As sea level lowered and freshwater lakes were established at ~6200 $^{14}$C yr BP (~7100 cal yr BP; zone MA2 and upper zone KA2), a temperate broadleaf forest with a dominance of tree *Betula* and *Quercus* replaced the conifer-broadleaf forest. *Ulmus*, *Juglans*, and *Duschekia* remained important landscape elements. Other warm deciduous taxa (*Tilia*, *Acer*, and *Ilex*) became established but were only minor components in the forest. *Pinus pumila* decreased and was restricted to nearby hillslopes or possibly no longer grew in the area. The change in pollen assemblages suggests conditions that were warmer and drier than previously.

The HTM is not clearly marked in the Maloye record, but modest shifts in arboreal pollen toward temperate broadleaf taxa perhaps indicate that the Holocene optimum occurred during zone MA2 (~6300–5300 $^{14}$C yr BP; 7200–6100 cal yr BP). The decline in *Abies*, *Picea*, *Pinus pumila*, and Polypodiaceae implies that climates were drier than previously. The increase in graminoid pollen, particularly of Cyperaceae, marks a more open landscape, a change that at first might seem to contradict an increased presence of temperate forest taxa. However, this shift most likely represents the establishment of coastal meadows as dune fields and sea levels stabilized. The persistence of relatively high graminoid pollen percentages in zones MA3–MA5 combined with the types and diversity of minor pollen taxa indicate that meadows, which today characterize coastal areas of Iturup Island, have been present since the early to mid-Holocene.

The highest percentages of *Quercus* pollen (zone KA3) unmistakably designate the HTM at Kasatka Lake. As on the Okhotsk side, *Betula* was likely reduced in the Pacific forests, and temperate trees (e.g., *Juglans* and *Ulmus*) continued as minor members of this community. In contrast to Maloye, *Larix* grew near Kasatka Lake, perhaps suggesting slightly cooler conditions on eastern Iturup Island.

Previous research on Iturup and Kunashir Islands documents the HTM as occurring between 6500 and 5000 $^{14}$C yr BP (7400–5700 cal yr BP; Korotky et al., 2000; Razigaeva et al., 2002, 2004). Sea levels of +3.5–2.5 m (6500–5000 $^{14}$C yr BP; –5700 cal yr BP) and +2.5–3.0 m (6500–6300 $^{14}$C yr BP; 7400–7200 cal yr BP) represent the highest Holocene sea stands for Iturup and Kunashir Islands, respectively. The formation of a freshwater basin at Maloye Lake at ~6200 $^{14}$C yr BP (~7100 cal yr BP) would suggest that regression began prior to 5000 $^{14}$C yr BP (5700 cal yr BP) as inferred from the Iturup sections. This relatively early age for lake establishment is more consistent with the Kunashir record where lowering sea levels began at ~6300 $^{14}$C yr BP (~7200 cal yr BP).

Cooler environments are indicated by the decline in *Quercus* pollen in zone KA4. This shift is not as clearly marked in the Maloye record, but the increase in *Betula* pollen (zone MA3; ~5300–3300 $^{14}$C yr BP; ~6100–3500 cal yr BP) likely corresponds to decreasing temperatures. However, climate remained warmer than present on both sides of the island as indicated by the continued importance of *Betula*, *Quercus*, and other temperate broadleaf species. Gradual but continuous cooling is indicated in zones MA4, KA4, and KA5. For example, by ~3300 $^{14}$C yr BP (~3500 cal yr BP), *Larix* established near Maloye Lake, although *Betula* and *Quercus* with *Ulmus* and *Juglans* remained important forest elements. The decline of *Betula* and *Quercus* pollen and increase of *Pinus* pollen (385 $^{14}$C yr BP; 430 cal yr BP; zone MA5 and upper zone KA5) suggest a final cooling and the development of *Betula-Larix* forests with *Pinus pumila*, a vegetation community that today characterizes the hillsides in central Iturup Island. This gradual cooling from the HTM is not consistent with the numerous paleoclimate fluctuations inferred from the section data (Fig. 7).

## Understanding Holocene climates of the Kuril Islands

The traditional paradigm for explaining variation in Holocene environments in the SRFE has long been based on the link of relatively cool/warm climates to marine regressions/transgressions, with formation of dune fields and other accumulating coastal landforms during times of low seas (Fig. 7; Korotky et al., 1988, 1996, 1997, 2000). This interpretative framework not only brought together the results from an impressive number of multiproxy studies of coastal and near-coastal sections from the Okhotsk islands and mainland, but it also offered a regional perspective for understanding the challenging dynamics of this terrestrial-marine system. In adding the lake records to the south Okhotsk database, we wanted to address two of the basic tenets behind the current interpretive framework: (1) that changes in Holocene climates are similar and synchronous across the SRFE and (2) that the sea-level/climate model is the most robust one for explaining mechanisms of regional change. The presumption is that similarity in character and timing of environmental changes would support a broadscale forcing, whereas temporal variability in the records would suggest more local causes behind the observed changes.

The highly tectonic nature of the Okhotsk area, especially of the Kuril archipelago, immediately raises questions about the reliability of region-wide sea-level reconstructions. Local tsunami or earthquake activity certainly has left an imprint on individual Kuril Island histories, resulting in disparities in the timing and magnitude of change across the study area (Fitzhugh et al., 2016). Although undoubtedly tsunamis and earthquakes influenced local sea-level and coastal landforms, the detailed study of modern to late Holocene episodes suggests occurrences on a temporal scale that differs from that documented in the longer-term paleorecords. For example, examination of ancient tsunamis in the central Kuril archipelago over the last 2300 cal yr BP indicates inundations every ~65 cal yr, although the largest tsunamis (recorded at least 100 m inland) recur every ~750 cal yr (MacInnes et al., 2016). Thus, the timing of the tsunami-related changes in these late Holocene studies appears to be more frequent than coastal changes proposed in the SRFE/south Kurils sea-level/climate model (Fig. 7). Coastal displacement associated with vertical movement is also variable in the Okhotsk region with both rapid offset associated with local earthquakes (e.g., the 1994 Shikotan earthquake caused local subsidence of up to −55 cm; Sedaeva et al., 2012) and longer-term coastal shifts associated with tectonic movements (e.g., irregular and reversed movement of −1.1 to +10.9 mm/yr for areas of the southern Kamchatkan coast over the last 2000 cal yr; Pinegina et al., 2010). Such complexity in the timing, magnitude, and/or direction of change (i.e., uplift or subsidence) might reasonably be expected to result in greater differences in coastal histories (especially between the more tectonically stable and sheltered mainland and the Kuril archipelago) as compared with the SRFE scheme. If there is a general accuracy in the timing and number of mid- to late Holocene events (Fig. 7) as related to sea-level fluctuations, whether or not they are caused by climate change, then the idiosyncrasies of tectonic-related events has been "smoothed" out in the section data suggesting a broader regional mechanism responsible for the observed changes. Perhaps a more likely source of temporal "noise" is in the local or regional chronologies themselves as opposed to local tectonic activity. For example, differences of <1000 cal yr (Fig. 7) may not be surprising given the discontinuous nature of the sections and the limited availability of radiocarbon dates for some intervals. From this perspective, the temporal discrepancies among records arguably may be more apparent than real and perhaps are a function of the age models or quality of dating control available for the various locales.

Despite differences in timing, the numbers of relatively warm and cool intervals reconstructed for the SRFE and south Kurils over the last ~5500 cal yr BP are similar (Fig. 7). A recent study of a well-dated peat core from northwest Sakhalin Island (Leipe et al., 2015) also shows four post-HTM cooling events, although the climatic reversals were briefer and generally less severe than those inferred in the regional schemes. In contrast, palynological data from the Kuril Islands lakes do not support multiple climatic fluctuations but rather trace warming up to the HTM followed by gradual cooling (note that for purposes of evaluating the sea-level/climate model, the sand layers in the Maloye and Pernatoye cores have been linked in Fig. 7, although the pollen data do not indicate an associated cooling). Differences in the lacustrine and nonlacustrine pollen records might be expected given the variety of depositional environments represented. Lake sediments integrate a broader paleovegetation signal and trace a continuous vegetation history from one locale. In contrast, the sections represent temporal "snapshots" with the SRFE/south Kuril schemes formed by integrating time slices from multiple sites. Changes in coastal dynamics and landforms could reasonably result in modification of the local vegetation, and palynological data from sections would be more sensitive to such shifts as compared with the more integrative lake records. The apparent nonresponse of vegetation in the lake records suggests that mid- to late Holocene climatic variability was muted and more in line with minor cooling events documented for Sakhalin Island. Korotky and colleagues also have suggested that some of the post-HTM fluctuations were relatively minor despite the inference of significant changes in sea level and coastal landforms (Korotky, 2002; Razjigaeva et al., 2004).

The SRFE/south Kuril paleoenvironmental scheme relies on sedimentologic and diatom evidence (e.g., marine vs. terrestrial deposits) as much as or more than pollen for determining the times and nature of changes, and the former two proxies show a greater commonality between the lacustrine and nonlacustrine data sets. Previous work in the greater Okhotsk region (e.g., Kumano et al., 1990; Korotky et al., 1997, 2005) has shown a similar coastal evolution as traced in the lake cores (i.e., an early Holocene high stand, followed by the occurrence of shallow shelves, lagoons, and exposed land). In contrast to the lake records, where a freshwater basin persisted throughout the mid- to late Holocene, data from exposures suggest four episodes of marine transgressions/regressions (Korotky et al., 1996). The southern (Okhotsk and Pacific side) and northern Kuril lake cores include four sandy layers, which roughly correspond to mid- to late Holocene SRFE/south Kuril cool intervals (including an interval within the HTM; Fig. 7) and perhaps reflect times when coastal dynamics and/or dune formation were more active.

Although the timing is not synchronous, the presence and approximate association of the sand layers to proposed cool

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intervals is tantalizing. Previous investigations have claimed a regional similarity of paleoenvironmental histories, including climate, vegetation, and landforms, from Japan northward through the Kurils to the Komandar Islands (northwest Pacific), thereby suggesting a region-wide forcing behind the trends in the paleodata (Korotky et al., 2000, 2005; Razjigaeva et al., 2004). The sea-level/climate relationship is the one most prominently discussed. The occurrence or nonoccurrence of punctuated Holocene sea-level history has been debated for some time (see Bird et al., 2010), but a recent study of the tectonically stable shelf near Singapore suggests a rapid rise until ~8100 cal yr BP, followed by a stable interval at ~7800–7400 cal yr BP, a second rise culminating in the mid-Holocene, and a gradual regression to modern levels (Fig. 7). This curve contrasts with one from northern Japan where two intervals of lower and three intervals of higher than present sea levels occurred over the past ~6000 cal yr BP. In neither case do sea-level patterns correspond to the paleoclimatic fluctuations in the SRFE/south Kurils, and thus the sea-level/climate model does not seem to account for either variability in reconstructed vegetation or coastal dynamics.

Other regional factors that could influence the paleoenvironmental history include changes in Okhotsk currents and/or shifts in atmospheric circulation. Times of intensification of warm waters in the southern Okhotsk Sea do not correspond to either numbers or timing of warm terrestrial conditions (Fig. 7). However, warm currents did dominate prior to ~3500 cal yr BP, an interval that includes the HTM and a subsequent time when conditions were cooling but still were warmer than present. The Okhotsk region is on the northern edge of the East Asian monsoon, and although of variable strength during the mid- to late Holocene, fluctuations in neither summer nor winter monsoon intensity correlate with inferred times of climatic change (Fig. 7). Other regional and extraregional factors (e.g., Bond events, shifts in sea ice or sea-surface temperatures in the North Pacific) could also potentially affect conditions in the Okhotsk region. Yet the timing or characteristics of Holocene fluctuations do not seem comparable to the observed paleoenvironmental changes (Bond et al., 1997; Gorbarenko et al., 2004; Harada et al., 2014). Not surprisingly, these rather simple chronostratigraphic comparisons (Fig. 7) suggest that nonlinear relationships among atmospheric, marine, and biological systems ultimately determine the Holocene history of the Okhotsk region. Although additional proxies and better dated records are still needed, a full understanding of this interesting and vital area of northeast Asia will likely only come with application of conceptual or numerical models that systematically examine the multiple mechanisms and feedbacks that determined the changes observed in both lacustrine and nonlacustrine records.

## CONCLUSIONS

The addition of continuous lacustrine records to the Okhotsk paleoenvironmental database has done more to question than confirm the environmental history of the SRFE. Palynological data from lake sites in the northern and southern Kuril Islands suggest climate change was minimal and/or gradual during the mid- to late Holocene in contrast to more fluctuating conditions interpreted from section data.

Unlike the palynological results, diatoms, lithology, and geochemistry from the lake cores reflect a similarity in coastal histories (maximum high stand during the HTM with formation of marine straits crosscutting some islands, followed by lagoons and terrestrial landforms) as described from coastal sections. Active dune formation during the mid- to late Holocene is suggested in the lake deposits by sandy layers that have a relatively high MS because of higher concentration of detrital magnetic minerals and low concentration of diatom valves, an abundance of attached diatoms, and low $\delta^{13}C$ and $\delta^{15}N$ signifying a higher input of coarser minerals.

Although earthquake and tsunami activity affected local areas, especially in the Kuril Islands, the asynchronicity in inferred paleoclimatic/sea-level fluctuations proposed in the SRFE/south Kurils schemes is of a scale that is unlikely to be related to tectonic events. The current data set does not allow for dismissing the reality of temporal discrepancies among records, but some of the variability may relate to poor dating control and age models rather than variability of paleoenvironmental events.

Changes in geomorphology and diatom complexes described from sections have been linked to sea-level oscillations caused by warming and cooling climates. Although the lake cores provide some additional evidence of times of enhanced coastal activity, timing is again a question. However, the mechanisms responsible for Holocene climatic changes are likely the result of complex interactions of atmospheric patterns, marine characteristics, and regional feedbacks rather than simply fluctuations in sea levels.

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## Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/qua.2017.21

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