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ORIGINAL PAPER

A multiproxy record of Holocene environmental changes from the northern Kuril Islands (Russian Far East)

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Abstract Diatom, rock magnetic, geochemical, and lithological studies of a sediment core from Paramushir Island (northern Kuril Archipelago) trace environmental shifts from bog to salt-water lagoon to freshwater lake over the past 10,000 ^{14}C BP. Organic-rich mesic landscapes dominated the southern island until ~8200 ^{14}C BP. Transgression of the Sea of Okhotsk onto the island began sometime after 8200 ^{14}C BP, resulting in the formation first of a salty (~8200–5700 ^{14}C BP) then a brackish (~5700–5200 ^{14}C BP) lagoon. With lowering of sea level after 5200 ^{14}C BP, a freshwater lake formed, which has remained to the present day. This history parallels regional trends in the Russian Far East, where maximum sea levels occurred between ~8000 and 4600 ^{14}C BP, peaking at ~6400 ^{14}C BP. Sandy levels within the lake core suggest four intervals of aeolian activity (~4900–4800 ^{14}C BP; 4300–3800 ^{14}C BP; 3200–3000 ^{14}C BP; 1900–900 ^{14}C BP), perhaps related to drier than present climates. Palynological data indicate a dominance of *Pinus pumila–Duschekia kamtschatica* shrub tundra in the lowlands ~8200–5800 ^{14}C BP, marking the Holocene thermal maximum. This vegetation contrasts to modern, which established ~5800 ^{14}C BP and is a mix of coastal meadow, *Betula–Salix* low shrub tundra, and scattered *Pinus* and *Duschekia* thickets. The palynological record shows little response to mid-to-late Holocene climatic fluctuations except for a decrease in *Pinus* shrubs perhaps caused by changes in snow cover and/or summer temperature during the Little Ice Age.

Keywords Diatoms · Geochemistry · Magnetism · Palynology · Northeast Asia

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Introduction

Quaternary research in the Russian Far East, beginning over 40 years ago, has been built upon the principles of interdisciplinary investigations (Korotky et al. 1980; Korotky 2002; Razjigaeva et al. 2002). Paleoenvironmental studies have traced the history of dynamic landscape changes and striking climatic fluctuations during the late Pleistocene and Holocene. However, this work focused primarily on the study of alluvial and buried organic deposits (e.g., peats, paleosols) and only recently has turned to the examination of lake records (Lozhkin et al. 2010). One such multiproxy investigation involves a Holocene-age core from Pernatoye Lake in the northern Kuril Islands (Fig. 1). Although paleobotanical and paleomagnetic results have been published previously (Cherepanova et al. 2009; Anderson et al. 2009; Lozhkin et al. 2010; Minyuk et al. 2013), we present for the first time a compilation of all site data, including new information on isotope and elemental geochemistry and site chronology. When combined, these paleoenvironmental proxies present a detailed picture of lake-basin development and changes to the surrounding landscape.

Pernatoye Lake (50° 02.43′N, 155° 23.71′E; 6 m above sea level) is located ~0.5 km from the Sea of Okhotsk on Vasil'ev Peninsula, which forms the southern tip of Paramushir Island (Fig. 1). Paramushir is one of three northernmost islands in the Kuril Archipelago, lying ~80 km to the south of Kamchatka Peninsula. While much of the island is mountainous, formed by currently inactive volcanoes, the peninsula has low-lying relief with occasional rolling hills. Pernatoye Lake is ~1.35 km long, ~0.6 km wide, has an area of ~0.47 km^2, and maximum water depth of 1.8 m. It is an open basin with an inlet draining from the Karpinskii Range (maximum elevation ~1700 m asl) to the north and an outlet flowing to the Sea of Okhotsk. The lake is separated from the sea by a dune field that: (1) extends in a north–south direction for ~3 km; (2) has a width of ~0.8 km; and (3) possesses dune heights of ~15–30 m (Pakahomov 2011).

The vegetation on Parmushir Island is a mix of shrub and herbaceous communities (Grishin et al. 2005; Urusov and Chipizubova 2000). Shrubs dominate mountain slopes, where *Pinus pumila* (Pall.) Regel (~1.7 m height) forms impenetrable thickets up to ~1400–1500 m asl. *Duschekia kamtschatica* (Regel) Czer. and *Sorbus sambucifolia* (Cham, and Schlecht.) M. Roem. comprise lesser but still important components of these upland communities. At lower elevations, *Pinus pumila* and *Duschekia kamtschatica* are found as individuals or scattered in small groups on the landscape. In well-developed thickets, ferns (e.g., *Lycopodium clavatum* L., *Dryopteris expansa* (C. Presl.) Fraser-Jenkins and Jermy) are often associated with both shrubs (Grishin et al. 2005). Gallery forests of *Chosenia macrolepis* (Pall.) A. Skvorts grow in the Tukhara River valley ~22 km to the northeast of Pernatoye Lake (Urusov and Chipizubova 2000). Although protected sites can support limited stands, *Larix cajanderi* Mayr and *Betula ermanii* Cham. are not common on the island (Grishin 2000).

Moist to mesic coastal meadows, found near the lake, are dominated by Poaceae spp. (particularly *Calamagrostis langsdorffii* (Link) Trin. Cyperaceae) Juss. and a variety of forbs (e.g., *Rubus chamaemorus* L., *Polygonum bistorta* L., *Artemisia* L., Apiaceae Lindl., *Delphinium* L., *Viola* L.). Both upright and prostrate forms of *Salix* L. occur on southern Paramushir Island but are not common near the study site. In contrast, ericaceous species (e.g., *Empetrum sibiricum* V. Vassil., *Vaccinium uliginosum* L., *V. vitis-idaea* L.) are abundant locally. *Pinus pumila* (≤1 m

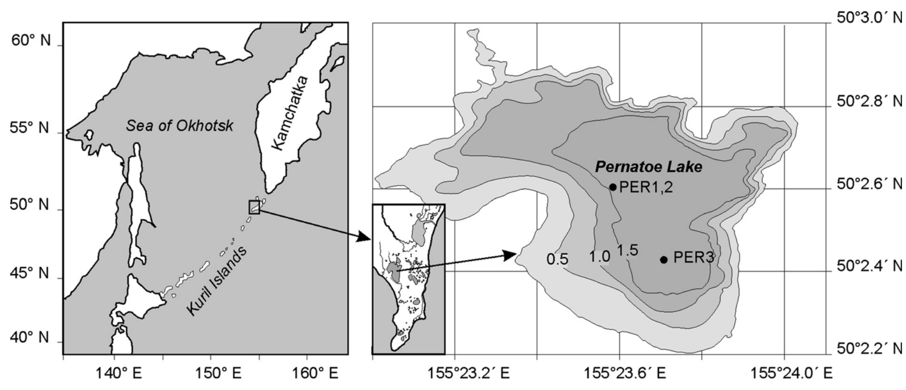

Fig. 1 Maps showing: location of Paramushir Island within the Kuril Islands; location of Pernatoye Lake on Vasil'ev Peninsula; lake bathymetry; and coring locations (PER1, PER2, PER3). Results from PER3 are presented in this paper

height) grows in scattered thickets around the lake, and only one shrub of *Duschekia kamtschatica* was observed at lakeside.

The research at Pernatoye Lake is part of the Kuril Island Biocomplexity Project, a joint American–Russian–Japanese investigation into the impact of environmental changes, such as volcanic eruptions, tsunamis, and climatic shifts, on human subsistence-settlements patterns in an island setting.

Materials and methods

A 696-cm-long core (PER3; Fig. 1) was raised from the southeastern sector of the central basin in Pernatoye Lake during summer, 2007, using a modified 5-cm-diameter Livingstone piston corer (Wright et al. 1984) for deep sediments and a 3-cm-diameter plexiglass tube for the uppermost flocculent layer. Core sections were split in the laboratory, photographed, and subsampled for palynological, diatom, paleomagnetic, and geochemical analyses. Changes in core sediments initially were described through visual inspection and subsequently supplemented by elemental and isotopic geochemistry and magnetic characteristics.

Samples for analysis of magnetic susceptibility (MS, k) and elemental geochemistry were collected continuously along the core length in 6.3 cm^3 polystyrol containers; palynological and diatom subsamples were taken from these cubes after MS analyses were completed. Hysteresis parameters, including saturation remanence (J_{rs}), saturation magnetization (J_s), induced magnetization (J_i), coercive force (H_c), and remanence coercivity (H_{cr}), were measured with a J-meter automatic coercive spectrometer (Burov et al. 1986). MS and k were measured and then studied at high temperatures with a MFK1-FA multifunction kappabridge with CS-3 high-temperature control units (AGICO Ltd.). Major and rare element concentrations were determined using a multichannel WDXRF spectrometer SRM-25 and VRA-30 XRF spectrometer. Loss-on-ignition (LOI) was measured as described by Heiri et al. (2001). The chemical composition of the selected mineral grains was determined with a Camebax microprobe. Iron-bearing minerals were examined using a QEMSCAN complex, which combines scanning electron microscopy (EVO-50) with Quantax Espirit energy dispersive X-ray spectroscopy (Bruker AXS).

Organic matter $\delta^{13}C$, sedimentary $\delta^{15}N$, total organic carbon (OC) and total nitrogen (TN) samples were analyzed at 5 cm intervals. Samples were acid washed (1 N HCl), rinsed in DI water 5 times, freeze dried, and then analyzed in an elemental analyzer to determine OC and TN concentrations, coupled with a Finnigan Deltaplus isotope ratio mass spectrometer for $\delta^{13}C$ and $\delta^{15}N$ measurements. All isotope values are reported in permil units (‰) according to the relationship $\delta X = [(Rsample/Rstandard) - 1] \times 1000$ ‰, 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 (VPDB) standard, and all nitrogen measurements are relative to atmospheric nitrogen. Replicate measurements of internal standards run along with TOC, TN, sedimentary $\delta^{13}C$ and sedimentary $\delta^{15}N$ samples yielded coefficients of variation of 4.4, 6.9, 1.2 and 2.8 %, respectively. Analytical precision, calculated from analysis of standards distributed throughout each run, deviated less than ±0.2 % for both carbon and nitrogen stable isotopes, and less than ±0.5 % of the sample value for %N and %C.

Samples for diatom analysis were processed using procedures described by Proshkina-Lavrenko et al. (1974). Sediment dispersal and removal of organic matter was done by treatment with dilute sodium tripolyphosphate and hydrogen peroxide, respectively. Taxa were identified with Amplival Zeiss and Axioplan 40 light microscope at 1000× using oil immersion. With the exception of a few samples, a minimum of 350 individual specimens were identified. Species diversity was calculated based on the number of taxa counted in 10 transects under an 18 × 18 mm cover slip. Estimates of diatom concentrations were calculated using valve counts per slide transect using a consistent: (1) 1-g-sediment weight; (2) 50 ml of pretreatment solution; and (3) 0.06 ml of diatom suspension under the cover slip. Diatoms were grouped qualitatively based on their ecologies.

Palynological samples were prepared following standard laboratory procedures (PALE 1994), and palynomorphs were identified using a Motic-EF-PL microscope at 600× and 1000×. Following traditional pollen nomenclature, *Alnus* Hill pollen in the Pernatoye record represents the shrub *Duschekia kamtschatica*. Plant taxonomy follows Czerepanov (1995). Percentages of individual pollen taxa were based on a sum of identified and unidentified pollen. Spore

Table 1 Radiocarbon and calibrated ages for Pernatoye Lake

Lab no	Material dated	Depth (cm)	^{14}C Age (year BP)	Calibrated weighted mean (cal year BP)	2σ range
CAMS-133391	Fibrous terrestrial plant material	37	2180 ± 40	2195	2060–2330
CAMS-137160	Wood fragment	80	2760 ± 35	2850	2780–2950
CAMS-137385	Mixed plant material; likely terrestrial	584–586	6335 ± 40	7290	7170–7410
CAMS-137384	Bulk sediment	584–586	7325 ± 30	8110	8030–8190
CAMS-133390	Twigs	646–646.5	8160 ± 40	9110	9010–9260
CAMS-133392	Twigs	667–668	8790 ± 50	9830	9600–10,150
CAMS-133389	Mixed terrestrial plant material	696	10,000 ± 40	11,480	11,350–11,600

percentages were calculated using the pollen sum. Subsums were determined using total pollen and spores. Zonation was done qualitatively based on changes of major taxa.

A set of 7 AMS radiocarbon dates were obtained from the Pernatoye core (Table 1). These dates are supplemented by a whitish tephra at 642–643 cm that is likely from the Kurile Lake-Il'inskaya caldera-forming eruption (known as the KO tephra) and is well-dated to ~7600 ^{14}C BP (Ponomareva et al. 2004). This tephra also was noted in buried peats in nearby test pits. Because of the variation in depositional environments and related sedimentation rates, we have employed a simple linear interpolation for the Pernatoye chronology. Paleoenvironmental histories in the Russian Far East are standardly reported in ^{14}C year BP, and we thus report trends in the Pernatoye record in radiocarbon years. However, calibrated ages are also provided in Table 1, Discussion, and Conclusions. Unless otherwise noted ages are in radiocarbon years. Calibration was done using CALIB 6.0 (http://calib.qub.ac.uk/calib/calib html; Stuiver and Reimer 1993), the northern atmospheric calibration dataset and no reservoir correction.

Results

Age model

Seven radiocarbon and 1 tephra date were available for use in age modeling. However, 2 samples (1 bulk and 1 mixed terrestrial plants) from 584 to 586 cm yielded ages that differed by ~1000 year. In northern-latitude lakes, bulk sediments have generally provided "too old" ages as compared to terrestrial plant macrofossils (Bigelow and Edwards 2001). In the context of the Pernatoye lagoon, the 6335 ± 40 BP date (plant macrofossils) seems more reasonable than that of 7325 ± 30 BP (bulk sediment), because a mid-Holocene high-sea-level stand for Karaginsky Island to the north (Melekestsev and Kurbatov 1997) and Kunashir Island to the south (Korotky et al. 2000) has been dated to 6300–6500 BP. We presume that the interval dominated by salt-water diatoms in the Pernatoye basin (500–646 cm) represents this high stand.

The construction of an age model for the Pernatoye record is challenging because: (1) sediments between 80 and 585 cm lacked plant macrofossils, leaving this portion of the core undated; and (2) dramatic changes in depositional environments likely resulted in large differences in sedimentation rate. Even in the lacustrine portion of the core, lithological variations caution against extrapolating the sedimentation rate between the radiocarbon-dated levels at 37 and 80 cm to determine the age of the lagoon-lake transition at 429 cm. However, given the paucity of paleoenvironmental data from the northern Kurils, we feel obliged to offer at least a preliminary age-model associated with the paleoenvironmental interpretations. This model excludes the 7325 ± 30 BP date and includes the 7600 BP date for the KO tephra.

Lithology

Lithology is variable in the Pernatoye core, but 3 general depositional units were defined, marking the change from terrestrial to lagoonal to lacustrine environments (Table 2). Unit 1 (646–696 cm) consists of peaty sediments that show greater sand input in the upper levels. Unit 2 (429–646 cm) is predominantly silt, with decreasing organic content from subunits 2a to 2b. Silts become sandier towards the top of unit 2

Table 2 Sediment description, Pernatoye Lake

Unit/ subunit	Depth (cm)	Sediment	Color	Depositional environment; approximate ^{14}C age
3	0–429	Sandy silt with layers of fine to medium grained sand (13–30; 122–153.5; 177.5–180.5; 250.5–251.5; 380–391 cm)	2.5Y4/2; 2.5Y5/1	Lacustrine 0–5200 BP
2	429–646	Silt or organic-rich silt (630–646) with sandy silt (429–505 cm)		Lagoon 5200–8200 BP
2b	429–500	Massive silt with increasing sand above 505 cm; tephra 642–643 cm	2.5Y3/1	5200–5700 BP
2a	500–646	Silt intermixed with organic material	10YR 3/2	5700–8200 BP
1	646–696	Peat with increasing sand above 669 cm	10YR2/1; 10YR2/2	Terrestrial 8200–10,000 BP

(429–500 cm). The upper silty unit (unit 3, 0–429 cm) includes layers of black fine- to medium-grained sand. No gradation was evident in any of the thicker sand layers within the core.

Rock magnetism

Magnetic characteristics generally vary with lithology (Minyuk et al. 2013). Sands are characterized by the highest MS, J_s, and J_{rs}, whereas massive silts and peat have the lowest magnetic parameters (Fig. 2). The bottom portion of the core is dominated by low J_s and J_{rs} but high H_{cr}, H_c, and J_{rs}/J_s. The H_{cr}/H_c ratios show a steady up-core increase. The hysteresis characteristics, J_{rs}/J_s and H_{cr}/H_c, indicate that pseudo-single domain particles in the Day diagram (Day et al. 1977) occur predominantly from 505 to 696 cm. In contrast, magnetic particles between 0 and 505 cm tend towards a multidomain state. Sediment magnetization in the lower part of the core displays a significant paramagnetic component. Unit 3 includes titanomagnetite, titanomaghemite, and magnetite, whereas iron sulfides and iron hydroxide (predominantly pyrite and lepidocrocite) occur in units 1 and 2. Pyrite is framboidal and often is found in diatom valves.

Inorganic geochemistry

Two groups of elements reflect changes in core lithology and associated depositional environments (Fig. 3). The first group, represented by unit 2, displays positive correlations between Al_2O_3 and Na_2O (r = 0.90); Al_2O_3 and K_2O (r = 0.82); Al_2O_3 and Ba (r = 0.81); Al_2O_3 and Sr (r = 0.71); Al_2O_3 and Zr (r = 0.75); and Al_2O_3 and Rb (r = 0.63). The second group includes TiO_2, Fe_2O_3, MnO, MgO, CaO, and SiO_2. These elements are closely related to grain size and have correlation coefficients of: 0.96 for TiO_2 and Fe_2O_3; 0.9 for TiO_2 and MgO; 0.92 for TiO_2 and MnO; −0.81 for TiO_2 and SiO_2; and 0.96 for Fe_2O_3 and MnO. Note that the SiO_2 curve reflects both detrital and biogenic silica. As the surrounding bedrock is basalt and andesite with low quartz content, we presume the SiO_2 values are dominated by biogenic silica.

Organic carbon, nitrogen and organic $\delta^{13}C$ and $\delta^{15}N$

Organic carbon content is highest (~40 %) in the peats of unit 1 and abruptly decreases to ~5 % in unit 2 (Fig. 4). Within Unit 2a, C/N ratios and $\delta^{15}N$ generally decrease up-core, whereas $\delta^{13}C$ increases. Organic carbon content is highly variable but somewhat greater in the lacustrine sediments of Unit 3. The C/N ratio is typically below 10, indicating dominance by aquatic materials. A general increase in $\delta^{13}C$ occurs in unit 3, reaching highest values just below the core top. The $\delta^{15}N$ is low (generally below 0) and highly variable in this unit, with no apparent trend.

Diatoms

Changes in diatoms, like the geochemical and paleomagnetic data, parallel lithological variations and are referred to as units (Fig. 5; Cherepanova et al. 2009). The peat of unit 1 is characterized by: (1) peaks in *Pinnularia divergentissima* (Grun.) Cl., *Eunotia*

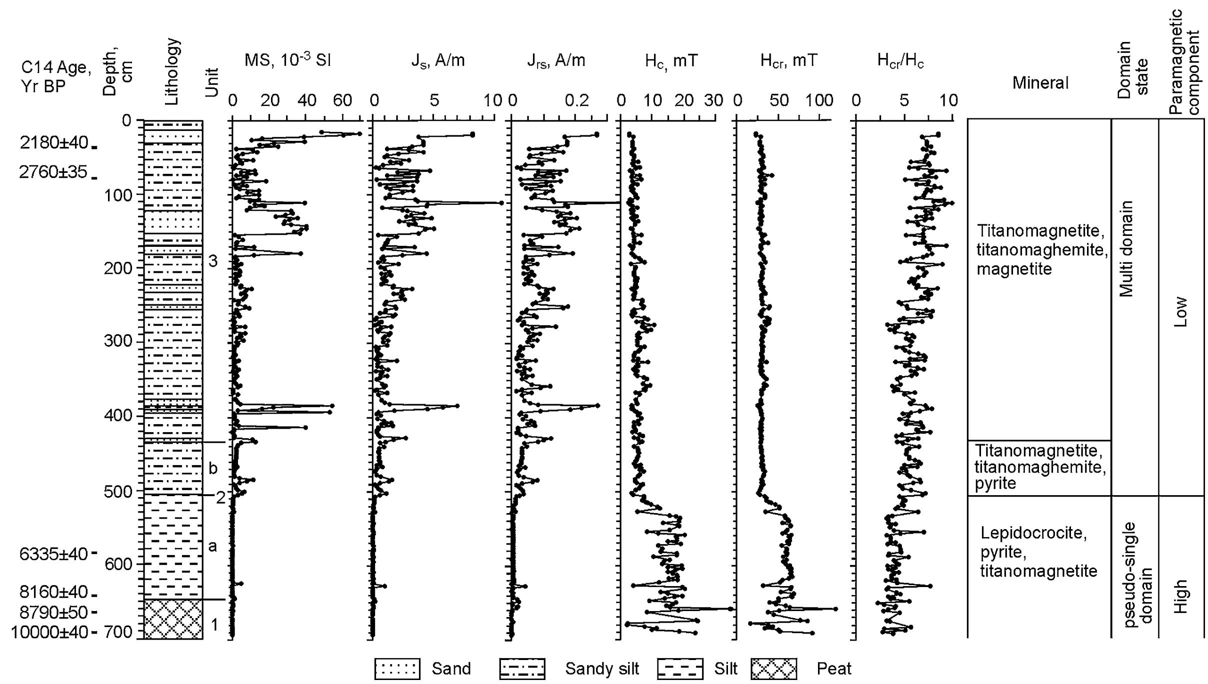

Fig. 2 Rock magnetic data from the Pernatoye basin (modified from Minyuk et al. 2013). See text for additional details on lithology

exigua (Bréb.) Rabenh., *E. glacialis* Meister, and *E. bilunaris* (Ehr.) Schaarschmidt; (2) low concentration of diatom valves; and (3) low species diversity (80 taxa). These latter two criteria increase somewhat in unit 2. This unit is dominated by the brackish water species *Melosira nummuloides* Ag. However, there are peaks in marine coldwater [*Thalassiosira kryophila* (Grun.) Jørg., *T. hyalina* (Grun.) Gran, *T. nordenskioeldii* Cl., *T. gravida* Cl., and *Bacterosira bathyomphala* (Cl.) Syvertsen and Hasle] and epiphytic taxa [*Cocconeis scutellum* Ehr. and sublittoral *Paralia sulcata* (Ehr.) Cl.] from 500 to 646 cm (subunit 2a). Benthic mesohalobus species occurring in unit 2 have low abundances but high species diversity. The highest core values for valve concentration and species diversity occur in unit 3. Samples are dominated by the freshwater diatom *Staurosira construens* var. *venter* (Ehr.). The subdominant diatoms are represented by freshwater epiphytes *Epithemia adnata* (Kütz.) Bréb. and *Cocconeis placentula* var. *euglypta* (Ehr.) Grun. Taxa with small valves [*Staurosira construens* Ehr., *Staurosirella pinnata* (Ehr.) Williams & Round, *Pseudostaurosira brevistriata* (Grun.) Williams & Round, *Fragilaria neoproducta* (Lange-Bert.) Williams & Round] have high species diversity.

Palynology

Five pollen zones were determined qualitatively (Lozhkin et al. 2010; Anderson et al. 2009), and with the exception of unit 1 (peat), zone boundaries do not correspond to sediment changes (Fig. 6). Zone P1 is dominated by Cyperaceae pollen with one sample showing high percentages of *Sphagnum* spores. Zone P2, also associated with organic-rich sediments, is marked by an increase in *Sphagnum* spores and pollen of *Alnus* and *Pinus* subg. Haploxylon.

Shrub and subshrub taxa (*Pinus* subg. Haploxylon, *Alnus*, *Betula* L., Ericales) dominate zones P3–P5, with high spore percentages of Polypodiaceae Bercht. and J. Presl. Temperate deciduous tree taxa (e.g., *Quercus* L., *Fagus* L. *Fraxinus* L., *Juglans* L., *Ulmus* L.) occur in minor amounts (<2 %) in zones P3 to P5, with combined percentages being the greatest in zone P5. Zone P3 contains the highest values of *Pinus* pollen and some of the largest percentages of Polypodiaceae spores. Increases in *Alnus* pollen percentages with high *Pinus* and Polypodiaceae percentages characterize zone P4. Zone P5 is demarcated by a decrease in *Pinus* pollen and Polypodiaceae spores and slight increases in *Alnus* and to a lesser extent

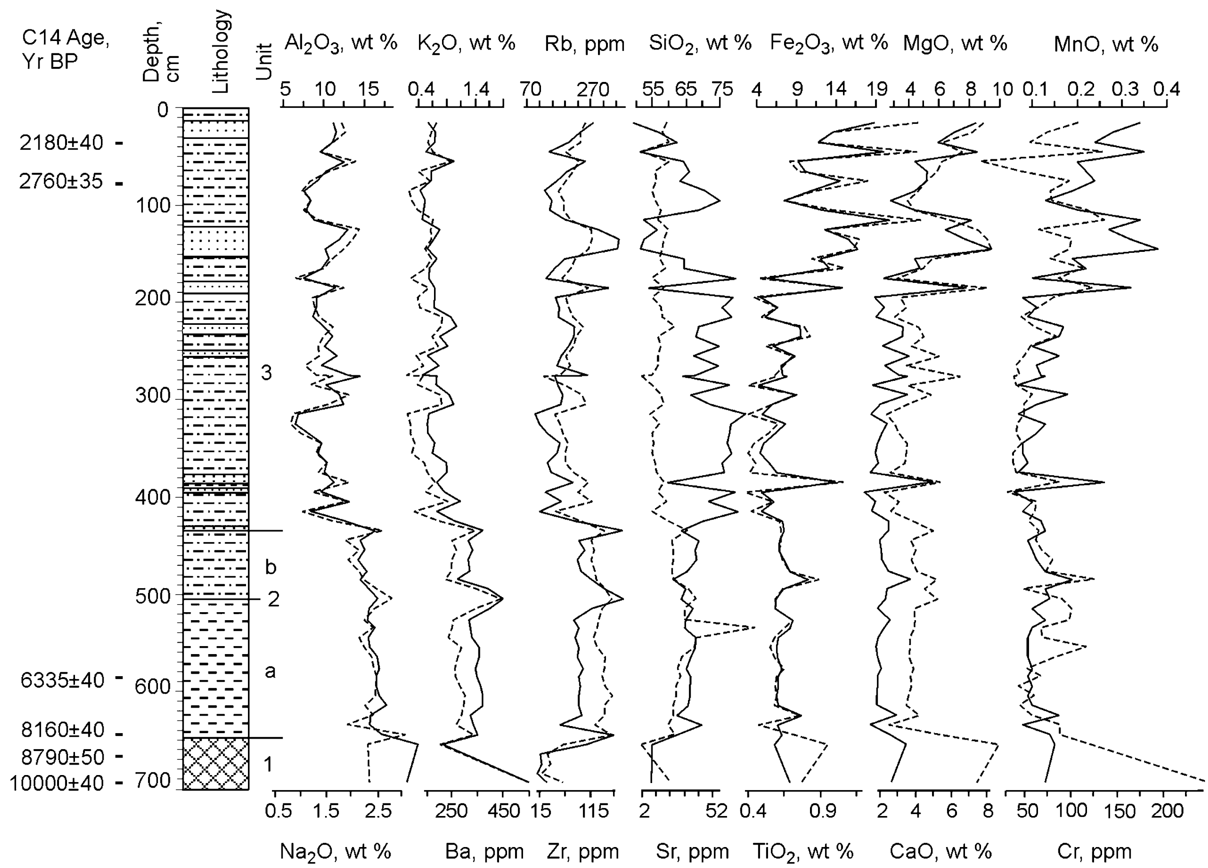

Fig. 3 Inorganic geochemical data from the Pernatoye basin. *Solid curves* represent elements listed at the *top of the figure* and *dashed curves* for elements at the *bottom*. See Fig. 2 for key to lithology

Betula pollen percentages. A short interval (~10–20 cm) of decreased/increased *Pinus*/*Alnus* percentages occurs near the top of the record.

Discussion

The environmental history of the Pernatoye basin has been summarized in Fig. 7. Changes in lithology are represented in the far right panel, including an age-depth curve and an age scale. Diatom data, grouped according to ecology, combined with the sediment facies reflect sea-level fluctuations. Representative geochemical and magnetic curves indicate changes in depositional environments. Palynological data trace the paleovegetation. We have divided the following discussion into 3 parts of basin history, vegetation history, and paleoclimatic implications.

History of the Pernatoye basin

The Pernatoye record indicates that boggy landscapes (unit 1) developed on southern Paramushir Island by at least ~10,000 BP (~11,400 cal BP; Fig. 7). The dominance of an organic-rich terrestrial environment during the early Holocene is suggested by: (1) the highest organic content within the core (Fig. 4); (2) elevated values of Cr, Ni, and Ba, byproducts of organic processes (Fig. 3; Sharma et al. 2004; Lauquet et al. 2001); (3) high P_2O_5, CaO, and Al_2O_3 indicative of accumulating humic material (Fig. 3; Wilson et al. 2010); (4) low MS reflecting the small mineral content (Fig. 2); and (5) plant microfossils consistent with the presence of an organic-rich, moist depositional environment (Fig. 5). The palynological data (Fig. 6) suggest that the initial matrix of the bog was formed by Cyperaceae (zone P1) but that *Sphagnum*

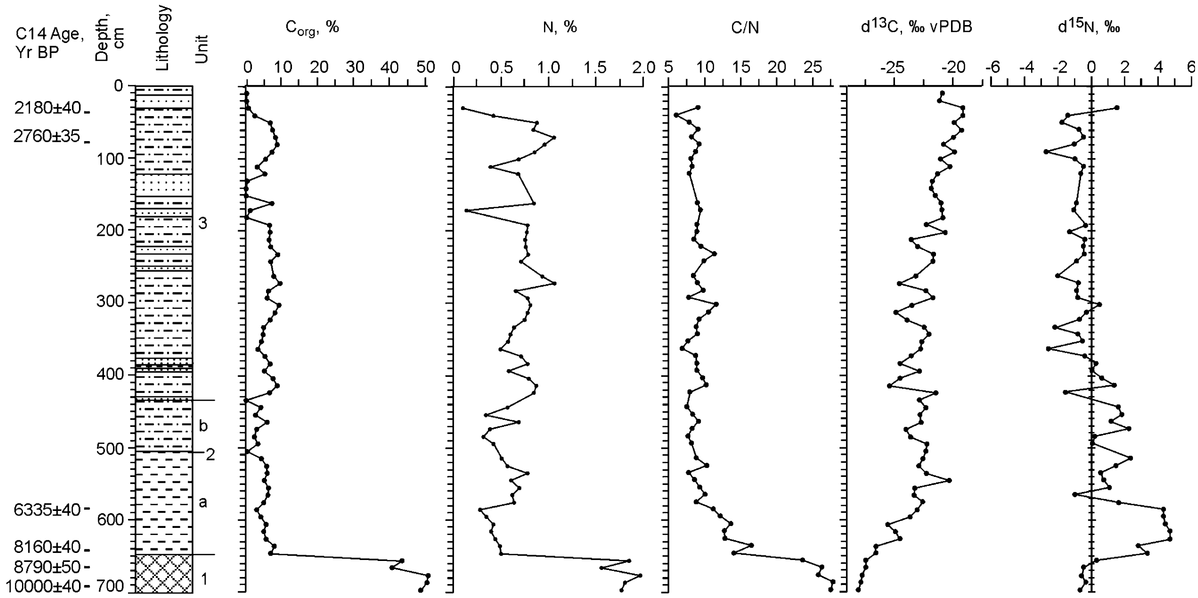

Fig. 4 Organic carbon, nitrogen and organic $\delta^{13}C$ and $\delta^{15}N$ from the Pernatoye basin. See Fig. 2 for key to lithology

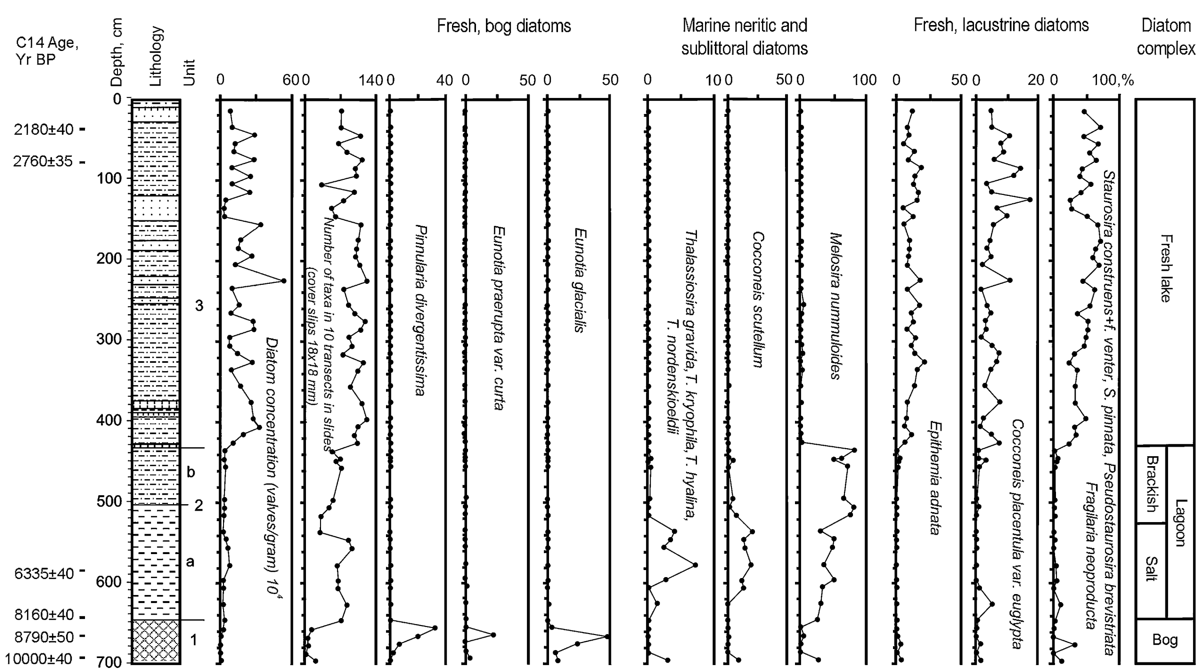

Fig. 5 Diatom data from the Pernatoye basin. Taxa are organized by depositional environment: peat (fresh bog assemblage); lagoon (marine neritic and sublittoral assemblage, subdivided into salt and brackish waters); and lake (fresh lacustrine assemblage). See Fig. 2 for key to lithology

dominated by ~9300 BP (~10,500 cal BP). Diatom concentrations (Fig. 5) and associated silica levels (Fig. 3) are low as would be expected in peaty material. The abundance of *Pinnularia divergentissima* and *Eunotia exigua* and moderate occurrences of *Chamaepinnularia soehrensis* (Krasske) Lange-Bert.

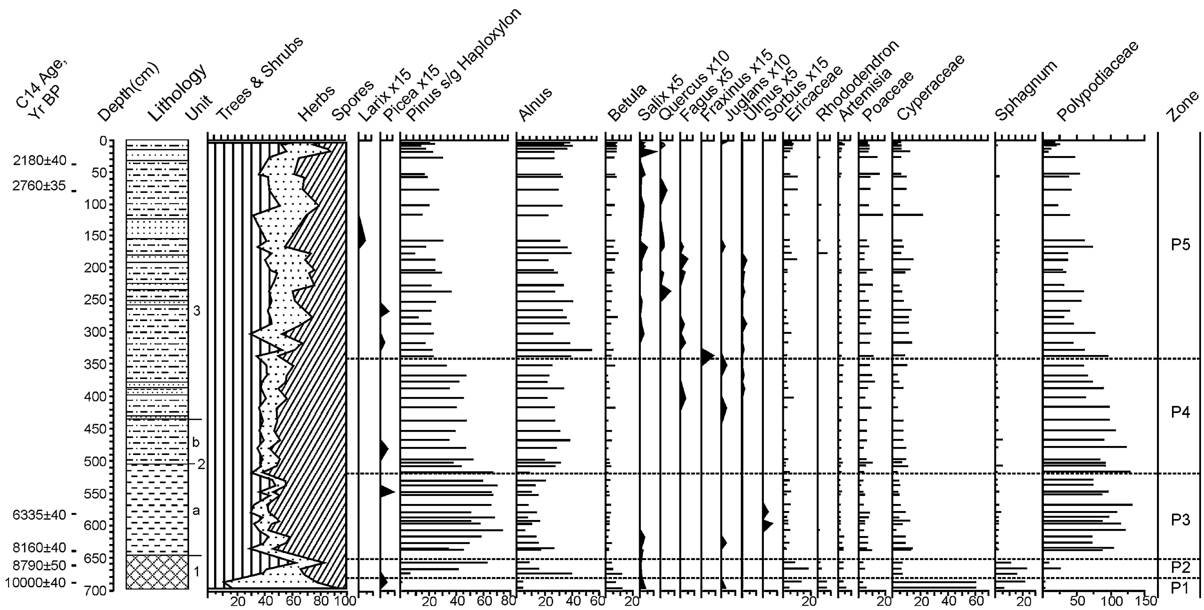

Fig. 6 Percentage diagram showing the main pollen and spore taxa. See Fig. 2 for key to lithology

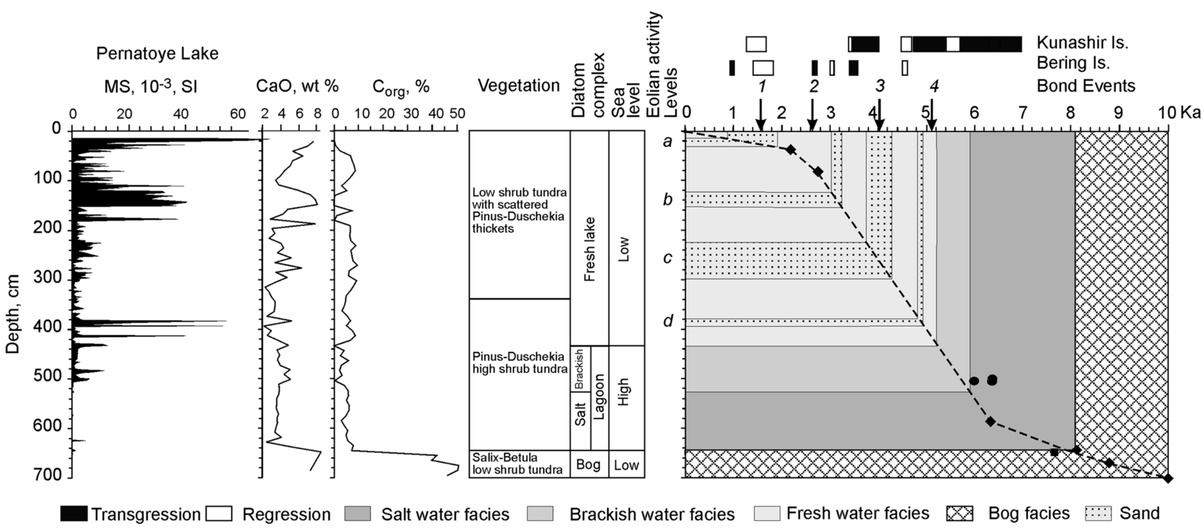

Fig. 7 Summary illustrating paleoenvironmental changes in the Pernatoye (modified from Minyuk et al. 2013). A ^{14}C age-depth curve is included in the fifth panel (*diamonds* indicate radiocarbon dates; *square* is the date of the KO tephra; *circles* represent dates for regional highs in sea-level). Sandy intervals in the fresh water lake are indicated by *a*–*d* to the *left* of the fifth panel. *Numbers in italics* at the *top* of this panel denote Bond events. The *black* and *white bars* above panel 5 indicate periods of transgression and regression, respectively, documented for Kunashir and Bering islands. The Holocene thermal maximum is represented by the high shrub tundra zone

& Krammer and *Eunotia fallax* A.Cl. var. *fallax* are consistent with the presence of mossy environments (Krammer and Lange-Bertalott 1986, 1988, 1991). These diatom taxa, in addition to *Eunotia glacialis*, indicate substrates with variable moisture and suggest the development of a raised bog.

The shift from organic-rich (unit 1) to predominantly inorganic sediments (unit 2) beginning ~8200

BP (~9100 cal BP) reflects a major change in depositional environment within the Pernatoye basin (Fig. 7; Table 2). Shifts in the diatom communities (Fig. 5) indicate that the basin was inundated with salty (unit 2a; 8200–5700 BP: 9100–6500 cal BP) to brackish (unit 2b; 5700–5200 BP; 6500–6000 cal BP) waters. Cold water-temperatures are indicated by *T. kryophila*, *T. hyalina* (Grun.) Gran, *T. nordenskioeldii* Cl., *T. gravida* Cl., and *Bacterosira bathyomphala*. The sublittoral, epiphytic, and benthic diatoms, taken together, imply shallow water depths within a littoral zone. Evidence of riverine influences is absent in the diatom data, even though the vegetation changes (particularly the increase in *Pinus pumila*) suggest increased snow cover and at least seasonal input to the basin with spring melt. The lack of rheophilic diatoms more probably reflects a deeper and/or larger basin where the rheophils did not reach the coring site. The development of such lagoons or lagoon-lakes is common today in both the southern Kuril Islands and along the Primor'ye mainland. A radiocarbon date of ~6300 BP (~7200 cal BP;) and a probable tephra age of ~7600 BP (~8400 cal BP) suggest that higher-than-present sea levels were well established by the mid-Holocene on Paramushir Island.

The marine nature of unit 2 is further indicated by the enrichment of Ba, a characteristic of sediments from the Sea of Okhotsk (Fig. 3; Sato et al. 2002; Gorbarenko et al. 2007), and Sr, an element more typical of marine than freshwater environments (Yudovich and Ketris 2011). Unit 2 also is high in K_2O, Na_2O, Rb, and Zr, which indicates no changes in the basin catchment and is consistent with diatom data indicating an absence of inflowing streams.

Temperature-dependent susceptibility indicates the presence of pyrite in unit 2, a mineral that has been associated with saltwater conditions in paleostudies in Japan and Korea (Fig. 2; Kato et al. 2003; Yang et al. 2008). The occurrence of pyrite is likely due to the high sulfate content of ocean water and often is found in saltwater diatoms (Minyuk et al. 2013). The high values of $\delta^{15}N$ in unit 2a is consistent with nutrient supply from marine nitrate, which is often higher in $\delta^{15}N$ as compared to terrestrial watershed sources. The presence of pyrite and lepidocrocite in the salt-water sediment (unit 2a) results in high H_c and H_{cr} and in the paramagnetic component of magnetization. During transgressions, the anoxia of marine waters containing sufficient amounts of sulfate leads to precipitation of pyrite. Later during lowered sea-levels oxic conditions dominated, and pyrite was partly oxidized to lepidocrocite (note the high H_c H_{cr} in the peat reflects the presence of oxic conditions and high lepidocrocite content). SiO_2 is low throughout unit 2 likely reflecting the low diatom concentrations.

Sediment homogeneity and consistency of magnetic characteristics (Fig. 7) in unit 2a suggest a stability in depositional environment between ~8200 BP (~9100 cal BP) and ~5700 BP (~6500 cal BP). A shallowing of the lagoon beginning ~5700 BP (~6500 cal BP; unit 2b) is indicated by the greater input of terrestrial sand, as suggested by increases in MS, J_s, and J_{rs} and a low paramagnetic component (Fig. 2). A dramatic rise in *Melosira nummuloides* indicates a decrease in salinity, which could be consistent with a decline in marine nitrate as implied by the decrease in $\delta^{15}N$ (Figs. 4, 5).

A freshwater lake (unit 3) formed in the Pernatoye basin ~5200 BP (~6000 cal BP) as shown by the: (1) dominance of freshwater diatom species (Fig. 5); (2) increases in rock magnetic parameters having the greatest multidomain particles (Fig. 2); (3) shifts in rare earth/isotopic elements (Fig. 3); and (4) decrease in $\delta^{15}N$ (Fig. 4). The brackish-freshwater transition is also marked by a sharp increase in SiO_2 content likely related to an increase in biogenic opal and diatom concentration. Peaks in MS, J_{rs} and J_s depend on grain-size, and the largest values of these parameters mark the high magnetic mineral-content in the sand layers of unit 3 (Fig. 2).

During the past ~5200 year, Pernatoye Lake supported a diverse, species-rich assemblage of fresh water diatoms, dominated by *Staurosira construens* (Fig. 5). Relatively high productivity within the lake is suggested by the dominance of aquatic organic matter as indicated by low C/N, and high $\delta^{13}C$ ratios (Fig. 4). Epiphytic diatom taxa *Epithemia adnate*, *Rhopalodia gibba* (Ehr.) O. Müll., and *Cocconeis placentula* var. *euglypta* were abundant, suggesting the persistence of a shallow lake with plentiful aquatic plants. Small inflowing streams are indicated by *Achnanthidium lanceolatum* Bréb. ex Kütz., *A. exiguum* (Grun.) Czarnecki, *Karayevia clevei* (Grun.) Round & Bukhtiyarova, *Martyana martyi* (Héribaud) Round and *Planothidium frequentissimum* (Lange-Bert.) Lange-Bert.

Vegetation history of the Pernatoye area

The earliest portion of the Pernatoye core (Figs. 6, 7) indicates the presence of moist, organic-rich environments, initially dominated by Cyperaceae (~10,000–9300 BP; ~11,400–10,500 cal year BP; zone P1) and then *Sphagnum* (~9300–8200 BP; ~10,500–9100 cal BP; zone P2). The relatively high percentage of ericaceous pollen, which typically is under-represented in palynological records, provides further evidence of extensive boggy landscapes.

Although variations in Cyperaceae and *Sphagnum* percentages primarily reflect changes in the local substrate, other pollen taxa (e.g., *Salix*, *Betula*) behave independently of the depositional environment and reflect a more regional vegetation record. Prior to ~9300 BP (~10,500 cal BP), *Salix*, *Betula*, and ericads were the most common woody species. Given the boggy nature of the landscape, *Betula* shrubs probably formed scattered thickets in slightly better-drained areas, whereas the broader ecological ranges of *Salix* and ericaceous species indicate a more widespread occurrence. *Duschekia kamtschatica* and *Pinus pumila* became important landscape components after ~9300 BP (~10,500 cal BP). Although the development of a *Sphagnum* bog at this time could reflect hydrological changes, the expansion of *Pinus* and *Duschekia* suggest both increasing summer temperatures and greater seasonal precipitation.

A major change in the basin environment, as indicated by the switch from bog (unit 1) to lagoon (unit 2) would strongly influence local pollen input (e.g., the sharp decrease in Cyperaceae pollen percentages as the record shifts from bog to lagoon). Thus, shifts in pollen assemblages might occur even though the regional vegetation remained unchanged. However, the Pernatoye data suggest that vegetation change did appear in the Vasiliev lowlands at the time of rising sea-levels (zone P3, ~8200–5800 BP; ~9100–6500 cal BP). At this time, *Pinus pumila* and *Duschekia kamtschatica* dominated the woody taxa, forming dense thickets both on mountain slopes and in the lowlands, although meadow and heath communities were also present near the lake. The dramatic increase in Polypodiaceae spores in zone P3 suggests a drying of the substrate near the site. Today ferns are commonly found in association with thickets of high shrub *Pinus pumila* and *Duschekia kamtschatica* in the northern Kuril Islands (Grishin et al. 2005), suggesting that the extent of woody vegetation was greater than present beginning after ~8200 BP (~9100 cal BP). Problems with chronological control and changes in sediment types make pollen accumulation rates problematic. However, *Pinus* pollen and total pollen concentrations are highest in zones P2 and P3 with total concentrations primarily between ~12,000 and 13,000 g cm^3 (Electronic Supplementary Material ESM1). Total concentrations decline to between ~5000 and 7500 g cm^3 in zone P4, a decrease that does not correspond to changes in sediment type (Table 2) indicating that the change in pollen concentration is not necessarily a reflection of variations in depositional environment. Although not conclusive, the concentration data are consistent with the interpretation of a relative abundance of *Pinus* on the landscape, possibly being at a maximum from ~8200 to ~5800 BP (~9100–6500 BP).

Shrub communities remain important components of the southern Paramushir vegetation during the mid-and-late Holocene. However, *Pinus pumila* apparently became less common after ~4600 BP (~5300 cal BP; zone P5), probably with *Pinus* communities primarily situated in the mountains. The decrease in Polypodiaceae and *Lycopodium* spores between zones P4 and P5 would favor this interpretation, suggesting a reduction in lowland thickets. The present-day vegetation near the lake does not support significant numbers of *Pinus pumila* or *Duschekia* even though the modern pollen spectrum (0 cm) contains significant percentages of both taxa. This comparison would suggest that the main population of *Duschekia*, even though pollen percentages remain relatively high, also retreated to the mountain slopes ~4600 BP (~5300 cal BP). Trace percentages of more temperate deciduous species (*Quercus*, *Fagus*, *Juglans*, *Ulmus*) increase after ~4600 BP (~5300 cal BP). These taxa represent long-distance pollen transport as broadleaf deciduous taxa expanded on the mainland and in the southern Kurils (Korotky 2002; Razjigaeva et al. 2004). Vegetation generally remained stable over the last ~4600 ^{14}C year. The southern Paramushir lowlands were occupied by a mosaic of coastal meadows, heaths, and shrub thickets, similar to that seen on the modern landscape. However, decreases in *Pinus* and increases in *Alnus* and total herb pollen percentages at ~30 cm suggest a decline in the conifer shrub and perhaps moderate increase in herbaceous communities at ~600 BP (~560 cal

BP). The appearance of sand layers during the mid-to-late Holocene may reflect drier conditions. Palynological data indicate no vegetation response with the exception of event c where pollen samples are sterile. In this latter case, the absence of pollen is related to preservational issues in the thick sand layer rather than an absence or decline in vegetation.

The Pernatoye record, comparisons and paleoclimatic implications

Although only a single site and thus should be used cautiously, we examine possible correlations between the Pernatoye record and regional trends, focusing on the paleoclimatic implications of sea-level and vegetation variations.

Investigations in the Russian Far East and northern Japan indicate rapid increases in sea level beginning ~8000 BP (~9000 cal BP), transgressions that have been linked with post-glacial climatic amelioration (Maeda et al. 1994; Sakaguchi 1983; Korotky et al. 2005; Razjigaeva et al. 2004, 2008). Although the direct correlation of a sea-level rise and climatic warming is complicated in the seismically active Kuril archipelago, the regional timing is consistent with the initial formation of a lagoon in the Pernatoye basin at ~8200 BP (~9100 cal BP). The palynological data further suggest that this transgression was indeed associated with climatic warming. The greater than modern presence of *Pinus pumila* in the southern Paramushir lowland by ~8200 BP (~9100 cal BP) indicates mean July temperatures of at least 12 °C (present day mean July temperature ~8.9 °C) and sufficiently warm and/or wet conditions to protect the evergreen shrub from desiccation during cool seasons (Andreev 1980). By ~8000 BP (~9000 cal BP), warm, moist conditions are registered to the north in the central interior of Kamchatka Peninsula, where a mixed *Betula–Larix–Picea* forest reached its maximum extent (Dirksen et al. 2013).

Korotky (2002) placed the Holocene thermal maximum (HTM) between ~7800 and 4800 BP (~8600–5600 cal BP) for the southeastern Russian mainland and adjacent islands. During the maximum Holocene transgression, sea level was ~2.5–3 m higher than modern (Korotky et al. 1997, 2005; Sakaguchi 1983), which resulted in active erosion and high sediment input to coastal zones (Razjigaeva et al. 2004; Korotky et al. 2000). The age of this highest sea-stand centered on ~6400 BP (~7300 cal BP; Melekestsev and Kurbatov 1997; Korotky et al. 2004). The Pernatoye data, given the limitations in dating control, generally are consistent with this regional pattern (lagoon formation ~8200–5200 BP (~9100–5900 cal BP) with a possible high-stand at ~6400 BP (~7300 cal BP). The abundance of *Pinus pumila–Duschekia* tundra on southern Paramushir Island suggest maximum temperatures between ~8200 and 5800 BP (~9100–6600 cal BP). Coastal forests in Kamchatka became more widespread in response to a warmer, more "continental" climate associated with the HTM ~6200–5000 BP (~7200–5700 cal BP; Dirksen et al. 2013).

Between ~4700 and 4500 BP (~5400–5300 cal BP) deposits from the southern Kuril Islands and Japan indicate that sea levels dropped to 4–5 m below present, and the regression has been correlated with the end of the HTM (Razjigaeva et al. 2002; Korotky et al. 2000, 1997; Sakaguchi 1983). These studies further suggested that the lowered seas and abundance of sediment deposited during times of transgression led to the formation of sizable dune fields on the larger islands. The formation of freshwater Pernatoye Lake at ~5200 BP (~5900 cal BP) seems to have occurred prior to the regional regression. This discrepancy perhaps reflects problems with the age model or possibly local variations in sea-level history. The decline in *Pinus pumila* between ~5800 BP (6600 cal BP) and ~4600 BP (~5300 cal BP) suggests a gradual decline in seasonal snow-cover and mean summer temperature to modern conditions. Shifts in forest distribution and increases in shrub populations on Kamchatka also indicate cooling beginning ~5000 BP (~5700 cal BP; Dirksen et al. 2013).

Variations in paleobotanical data and/or site sedimentology suggest that the Kuril-Kamchatka area experienced smaller scale shifts in paleoclimate and sea levels during the mid-to-late Holocene (Korotky et al. 2000; Korotky 2002; Dirksen et al. 2013). Minyuk et al. (2013) suggested that the sand events in the Pernatoye record, which are also recorded in peaks in paleomagnetic parameters, have parallels to paleoenvironmental shifts on Kunashir Island (southern Kurils) and/or Bering islands and possibly to Bond events (Bond et al. 1997; Fig. 7 panel 5). Given the quality of dating control at Pernatoye Lake these links must remain tentative. However, the intervals of sand deposition do not seem consistent with sea-level changes. That is, events a (~900–1900 BP; ~800–1865 BP) and b (~3000–3200 BP; ~3100–3400 cal BP) are associated with marine regressions. In contrast, events c (~3800–4300 BP; ~4200–4900 cal BP) and d (~4800–4900 BP; ~5600 cal BP) happened during a time of sea-level rise. Although late-Holocene climatic fluctuations are noted throughout the region, they are relatively minor (Razjigaeva et al. 2004; Dirksen et al. 2013; Korotky 2002), with the main climatic shift beginning ~4800–4600 BP (~5600–5300 cal BP) as conditions cooled following the HTM. Perhaps these sand events correspond to cooler and/or drier intervals. Yet unlike the records from these other regions, the palynological data from Pernatoye Lake indicate a relatively stable vegetation over the past ~4600 BP (~5300 cal BP), with the exception of a decline in *Pinus pumila* ~600 BP (~560 cal BP) that may reflect Little Ice Age influences. These results suggest that if the sediment changes were climatically influenced, the southern Paramushir vegetation was buffered from most late Holocene fluctuations perhaps reflecting its island location within cool coastal waters.

Conclusions

The interdisciplinary study of the Pernatoye basin provides the following record of landscape changes on southern Paramushir Island:

(1) The Pernatoye core begins in a peaty deposit indicating the presence of organic-rich terrestrial environments ~10,000–8200 BP (~11,400–9100 cal BP). A marine transgression began after ~8200 BP (~9100 cal BP) as indicated by the development of first a salty (~8200–5700 BP; 9100–6500 cal BP) and then a brackish (~5700–5200 BP; ~6500–6000 cal BP) lagoon. After 5200 BP (~5900 cal BP), lowering seas resulted in the formation of a freshwater lake, which has persisted to present.

(2) Boggy landscapes were initially dominated by Cyperaceae (~10,000–9300 BP; ~11,400–10,500 cal BP) and then *Sphagnum* (~9300–8200 BP; ~10,500–9100 cal BP) peat with woody species of *Salix*, *Betula*, and ericads. Between ~8200 and 5800 BP (~9100–6600 cal BP), *Pinus pumila* and *Duschekia kamtschatica* formed dense thickets in both the lowland and mountain slopes. A decrease in *Pinus* shrubs began ~5800 BP (~6600 cal BP) with a second decline at ~4600 BP (~5300 cal BP). The modern low shrub tundra (with only isolated *Pinus* and *Duschekia*) and coastal meadows established ~4600 BP (~5300 cal BP). A brief decrease in *Pinus* ~600 BP (~560 cal BP) is the only notable change in pollen spectra during the late Holocene.

(3) Holocene climatic fluctuations in southern areas of the Russian Far East have often been associated with sea-level changes with transgressions associated with warming and regressions with cooling (Korotky 2002; Razjigaeva et al. 2002, 2004, 2008; Dirksen et al. 2013). Unfortunately, radiocarbon dates are lacking from the lagoon section of the core, but if our age model is correct, then seas were higher than present from ~8200 to 5200 BP (~9100–5900 cal BP). This interval approximates that defined from the palynological data for maximum warmth (8200–5800 BP; ~9100–6600 cal BP). Although the paleovegetation suggests cooling/drying began ~5800 BP (~6600 cal BP), conditions remained warmer and/or wetter than present. In other areas of the Russian Far East the HTM terminated ~4800–4600 BP (~5600–5300 cal BP; *Ibid.*), an age in accord with the establishment of modern vegetation near Pernatoye Lake but not with high sea-stands on Parmushir Island. The late Holocene pollen spectra, with the exception of a possible Little Ice Age fluctuation, do not reflect regional climatic patterns documented elsewhere (Korotky 2002 reported seven climatic oscillations since 4000 BP; ~4500 cal BP). Late Holocene sand events in the Pernatoye core may relate to drier conditions but their timing is inconsistent with regional climatic or sea-level trends.

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