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# A 2000 year record of climatic change at Ongoke Lake, southwest Alaska

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**Abstract** We analyzed sediments of the past 2000 years from Ongoke Lake, southwest Alaska, for organic carbon, organic nitrogen, biogenic silica (BSi), and diatom assemblages at decadal to centennial resolution to infer limnological changes that may be related to climatic variation in southwestern Alaska. The chronology is based on a $^{210}$Pb profile from bulk sediments and nine AMS $^{14}$C ages from terrestrial plant macrofossils. Four of the $^{14}$C ages span a core depth interval of 60.5 cm but are statistically indistinguishable from one another with a mean of ~1300 AD, which compromises the determination of temporal trends at Ongoke Lake and comparison with other paleoclimate records. The diatom record suggests changes in the duration of ice cover and strength of thermal stratification that are probably related to temperature variation. This variation includes a cold interval around the first millennium cooling (FMC) and a warm interval spanning the medieval climate anomaly (MCA). However, the lake-sediment record shows no clear signals of temperature variation for the period of the Little Ice Age (LIA) or the twentieth century. Climatic changes during these periods may have been manifested through effective-moisture (precipitation minus evapotranspiration) variation in the Ongoke Lake area. We estimate water depths and infer effective-moisture fluctuations by applying a regional transfer function to our diatom record. Together with inferences from diatom autecologies, this water-depth reconstruction suggests that effective moisture increased steadily from 50 BC to 350 AD, which was followed by relatively dry conditions between 550 and 750 AD and relatively wet conditions between 750 and 1450 AD. Effective moisture was low from ~1450 to 1850 AD, coinciding with the LIA; an alternative age model places this interval between ~1315 and 1850 AD. During the past

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150 years, effective moisture increased, with estimated water depths reaching peak values in the second half of the twentieth century. This study offers the first paleolimnological record for inferring centennial-scale climatic variation over the past two millennia from southwestern Alaska.

**Keywords** Late Holocene paleoclimate ·
Little Ice Age · Medieval climate anomaly ·
First millennium cooling · Diatoms ·
Biogenic silica · Water-depth reconstruction ·
Alaska

## Introduction

The climate system of northern high-latitude regions is highly sensitive to both natural and anthropogenic forcings (Overpeck et al. 1997; Serreze et al. 2000; Esper et al. 2002; Moberg et al. 2005). For example, the greatest warming of the instrumental period in North America occurred in Alaska and northwest Canada over the past ~50 years (IPCC 2007). This warming trend is anticipated to continue at an accelerated pace with profound ecological and socio-economic consequences. Paleoclimate records provide information on natural variability against which the patterns and causes of recent and future changes can be evaluated (e.g. Bradley et al. 2003; Jones and Mann 2004). Although numerous paleoclimate studies have been conducted in the Arctic and Subarctic (e.g. Kaufman et al. 2004), most of these studies documented climatic change at millennial time scales. Detailed records of late-Holocene climatic variation remain scarce from these regions.

In Alaska, several decades of paleoclimate research provide a large proxy database for reconstructing late-Quaternary climatic change (e.g. Anderson and Brubaker 1994; Brubaker et al. 2002). High-resolution climate records of the late-Holocene have also begun to accumulate from tree-ring and lake-sediment analyses (Wiles et al. 1998; Hu et al. 2001a; Davi et al. 2003; Loso et al. 2006; McKay et al. 2008; Tinner et al. 2008). Some of these records indicate climatic cooling at ~200–650 AD (first millennium cooling—FMC; Wiles et al. 2004, 2008) and at ~1600–1720 AD (little ice age—

LIA). These cold periods are separated by warm conditions between ~850 and 1200 AD, which may be related to the medieval climate anomaly (MCA). The manifestation of these climatic events, however, remains unclear in other areas of the North Pacific rim, including southwestern Alaska. Furthermore, previous high-resolution paleoclimate studies of the past two millennia focused on warm-season temperature reconstruction. Little is known about variation in the moisture regime that may have accompanied temperature changes.

In this study, we reconstruct climatic change over the past 2000 years at Ongoke Lake (59°15′ N, 159°25′ W, 75 m asl) in southwestern Alaska. Several recent studies have demonstrated that the region experienced abrupt climatic shifts during the last glacial-interglacial transition (e.g. Hu et al. 2006) and cyclic climatic variability over the Holocene (Hu et al. 2003), attesting to the sensitivity of the regional climate to large-scale forcings. These existing paleoclimate records do not encompass the past 2000 years. Here we infer limnological and climatic changes from diatom and geochemical analyses of the Ongoke Lake sediments.

## Study area

Ongoke Lake is situated southeast of the Ahklun Mountains approximately 50 km northwest of Dillingham, Alaska (Fig. 1). It lies within the Bristol Bay Lowlands, a polar ecoregion characterized by moist soil conditions, discontinuous permafrost, shrub tundra plant communities, and maritime climate moderated by the Bering Sea and North Pacific Ocean (Nowacki et al. 2001). Weather-station data of 1920–2004 (WRCC 2007) indicate that mean annual rainfall in Dillingham is 67 cm year⁻¹, with approximately 40% occurring between July and September. Annual snowfall amounts to 228 cm on average. Mean annual temperature in Dillingham is 1.2°C, with the January mean of −8.8°C and July mean of 13.1°C.

Ongoke Lake has a surface area of ~29 ha and a watershed area of ~260 ha (Fig. 1). In mid-June of 2004, the lake had a maximum depth of ~7 m in the northern portion, gently shallowing to the south. The lake has one small inlet and two small outlet streams that drain into the Ongoke River (Fig. 1). Ongoke
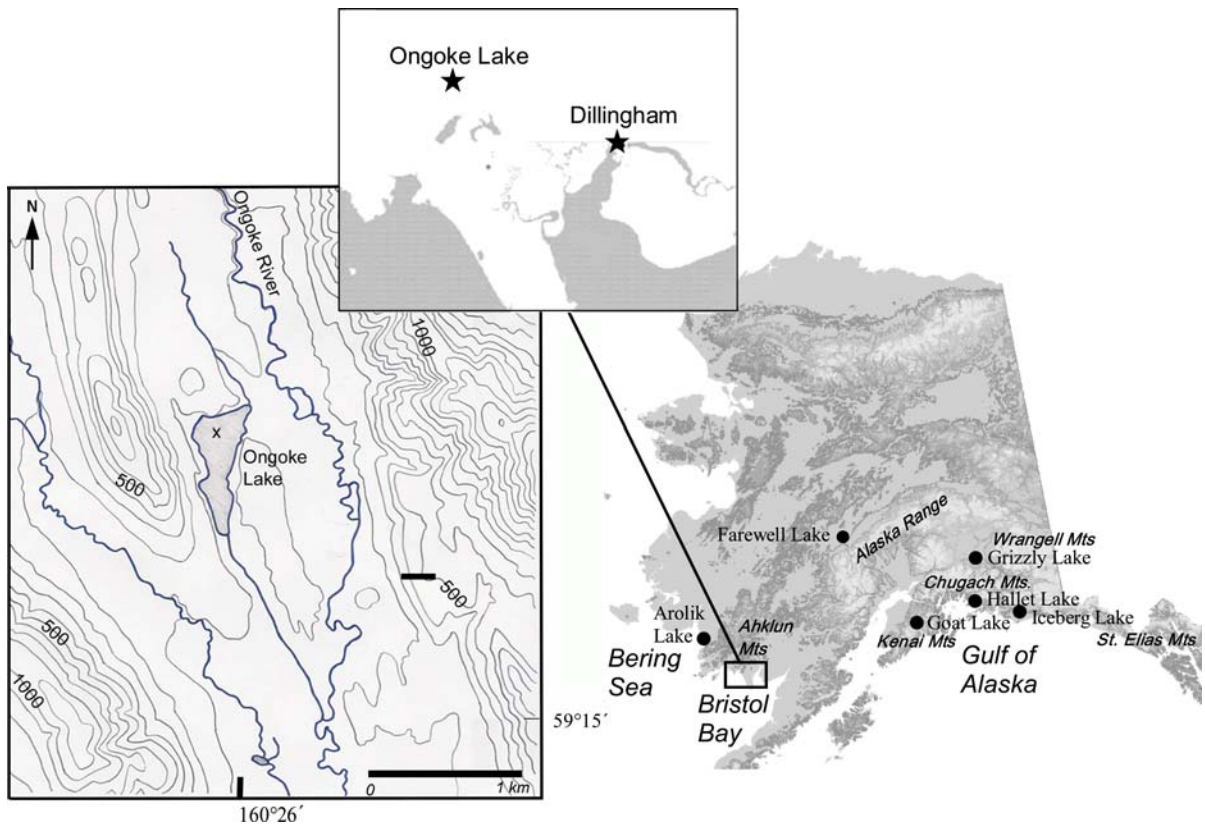
**Fig. 1** Maps showing locations of Dillingham and Ongoke Lake in Alaska. Base map from National Atlas, Department of the Interior and the Alaska Department of Natural Resources. (×) marks the core site. Locations of other sites mentioned in the text are also shown

Lake currently does not receive inflow from the Ongoke River, which is located ∼0.3–0.7 km east of the lake. The outlet streams did not have discernable flow in June 2004, indicating the lake level may be sensitive to effective-moisture fluctuations. Near the surface of the lake, water pH was 8.3, conductivity 33.8 μs, and temperature 15°C. Temperature, conductivity, and $O_2$ measurements of the water column all indicate that the lake was well mixed from the surface to ∼4 m (data not shown). From ∼4 m to the maximum depth, temperature declined from 15 to 9.1°C, indicating thermal stratification. Modern vegetation surrounding the lake is shrub tundra dominated by birch (*Betula nana* and *Betula glandulosa*). A few small trees of white spruce *(Picea glauca)* and several groves of balsam poplar *(Populus balsamifer*a) trees are present within the lake watershed.

## Methods

### Core retrieval and processing

In June 2004, we obtained two sediment cores using a modified Livingstone piston corer. We chose our core sites in an extensive flat area of Ongoke Lake at a water depth of 5.9 m, instead of at the deepest part of the lake, to accommodate the goals of other analyses (especially chironomids) of the same sediments. The core sites were ∼1 m apart, and the cores were stratigraphically overlapping. An additional core with an intact sediment-water interface was retrieved using a polycarbonate tube fitted with a piston. This core was extruded in the field at 0.5–1 cm intervals. In the laboratory, magnetic susceptibility was measured at 1-cm intervals using a Barrington Instruments MS2 meter and MS2B sensor (data not presented in this

paper). Changes in magnetic susceptibility, bulk density, BSi, and chironomid assemblages were used to correlate the cores (data not presented).

## $^{210}$Pb and $^{14}$C dating

For $^{210}$Pb analysis, 35 consecutive sediment samples (0–26 cm core depth) were processed following the method of Eakins and Morrison (1978) (Table 1). The $^{210}$Pb activity was measured with an Ortec OctêtePlus alpha spectrometer. Numerous sediment samples (1–3 cm$^3$ each) were sieved through a 212 μm mesh to obtain terrestrial plant macrofossils for radiocarbon dating. The samples were treated using an acid-base-acid method (Oswald et al. 2005) and submitted to Lawrence Livermore National Laboratory for $^{14}$C analysis. Nine AMS $^{14}$C ages were obtained and calibrated to years before present (BP = before 1950 AD) using CALIB 5.01 and the IntCal 04 dataset (Stuiver and Reimer 1993; Reimer et al. 2004) (Table 2). The median probability of each calibrated age was used to develop the age-depth models (Table 2). We used loess regression (Cleveland et al. 1992) in the modreg library of R2 to develop an age-depth model. We also developed an alternative age-depth model using a cubic smoothing spline in Matlab (following Higuera et al. 2008).

## Chemical, diatom-assemblage, and numerical analyses

Sediment subsamples were analyzed for bulk density and the percentages of organic matter, organic carbon, organic nitrogen, biogenic silica (BSi), and carbonate. Bulk density was obtained for every 0.5–1 cm of the core by freeze-drying 1 cm$^3$ of sediment and weighing immediately after drying. BSi was extracted at this same resolution using a 10% $Na_2CO_3$ solution (modified after Mortlock and Froelich 1989). BSi concentration (mg $SiO_2$ $g^{-1}$ dry sediment mass) was measured on a Spectronic Genesys 5 spectrophotometer. Loss-on-ignition at 550°C for 4 h and 950°C for 2 h was performed at 10 cm intervals to measure organic-matter and carbonate percentages, respectively. Carbon and nitrogen percentages were measured on a Costech Analytical Technologies® ECS4010 CHN analyzer at various intervals (∼20 year resolution from 0 to

**Table 1** $^{210}$Pb activity and ages from Ongoke Lake sediment core

| Depth (cm) | $^{210}$Pb activity (dpm/g) | $^{210}$Pb age (AD) | $2\sigma$ error (years) |
|---|---|---|---|
| 0–1 | 31.10 | 2003.3 | 0.27 |
| 1–1.5 | 31.03 | 2002.4 | 0.27 |
| 1.5–2 | 28.98 | 2001.3 | 0.27 |
| 2–2.5 | 31.50 | 1999.9 | 0.28 |
| 2.5–3 | 31.82 | 1998.4 | 0.28 |
| 3–3.5 | 31.62 | 1997.0 | 0.28 |
| 3.5–4 | 30.10 | 1994.9 | 0.28 |
| 4–4.5 | 27.33 | 1992.6 | 0.29 |
| 4.5–5 | 26.63 | 1990.5 | 0.28 |
| 5–5.5 | 25.98 | 1988.5 | 0.27 |
| 5.5–6 | 25.18 | 1986.3 | 0.28 |
| 6–6.5 | 26.61 | 1984.6 | 0.27 |
| 6.5–7 | 24.86 | 1982.2 | 0.28 |
| 7–7.5 | 25.67 | 1979.6 | 0.28 |
| 7.5–8 | 24.61 | 1976.9 | 0.28 |
| 8–8.5 | 23.76 | 1973.8 | 0.29 |
| 8.5–9 | 23.87 | 1970.2 | 0.30 |
| 9–9.5 | 22.62 | 1966.6 | 0.30 |
| 9.5–10 | 19.82 | 1963.2 | 0.27 |
| 10–11 | 16.31 | 1956.6 | 0.39 |
| 11–12 | 11.18 | 1950.7 | 0.38 |
| 12–13 | 8.53 | 1947.0 | 0.32 |
| 13–14 | 7.75 | 1942.8 | 0.36 |
| 14–15 | 8.38 | 1935.5 | 0.54 |
| 15–16 | 5.30 | 1931.0 | 0.48 |
| 16–17 | 6.11 | 1923.1 | 0.63 |
| 17–18 | 5.79 | 1914.4 | 0.72 |
| 18–19 | 5.12 | 1903.0 | 1.13 |
| 19–20 | 3.91 | 1892.6 | 1.21 |
| 20–21 | 2.74 | 1885.1 | 1.56 |
| 21–22 | 2.19 | 1878.5 | 2.71 |
| 22–23 | 2.64 | 1864.3 | 4.98 |
| 23–24 | 1.51 | Estimated background = 1.46 dpm/g | |
| 24–25 | 1.36 | | |
| 25–26 | 1.52 | | |

700 years ago, sub-centennial for rest of core), and used to calculate the C/N mass ratio of the sediment.

The average resolution of diatom analysis was ∼7 years for 1700–2004 AD and ∼35 years for the remainder of the past two millennia. Diatoms were extracted by soaking ∼0.5 g of sediment from each depth in 30% hydrogen peroxide at 60–75°C for

**Table 2** AMS ^{14}C ages from Ongoke Lake sediment core

| Lab ID (CAMS #) | Material | Depth (cm) | [14]C age (year BP) | ±Error | Calibrated age | 2σ Calibrated age range |
|---|---|---|---|---|---|---|
| 110411 | Small twigs | 48* | 685 | 40 | 1303 AD | 1247–1359 AD |
| 115586 | Wood | 79* | 660 | 35 | 1338 AD | 1276–1400 AD |
| 112155 | Leaves and wood | 87* | 715 | 40 | 1282 AD | 1223–1341 AD |
| 111250 | Wood | 108.5* | 700 | 35 | 1289 AD | 1237–1341 AD |
| 136550 | Grass | 124.5 | 1360 | 60 | 669 AD | 561–777 AD |
| 136551 | Leaves | 131.5 | 1295 | 35 | 716 AD | 659–773 AD |
| 111251 | Wood | 145.5 | 1595 | 35 | 479 AD | 377–581 AD |
| 122355 | Wood | 170.5 | 1960 | 60 | 40 AD | 151 BC–231 AD |
| 112156 | Wood | 214 | 3350 | 40 | 1636 BC | 1743–1529 BC |

Four statistically indistinguishable dates are indicated by (*); see main text for additional description

3 days (Renberg 1990). Frustules were mounted in a Naphrax® medium and counted and identified at 1000× magnification on a Nikon® Eclipse E600 microscope with phase contrast. Approximately 400 diatom valves were counted per sample, and identification followed Krammer and Lange-Bertalot (1986, 1988, 1991a, b). Diatom concentrations ($10^8$ diatom frustules $g^{-1}$ dry sediment) were estimated by adding microspheres to the samples (Battarbee and Kneen 1982). Chrysophyte cysts were also tallied and are expressed as the percentage of diatom valves enumerated.

Stratigraphic zones were determined with CONISS in the TILIA program (Grimm 1987), and all diatom taxa with >2% of the diatom sum in any one sample were included for the zonation. CONISS uses an algorithm of stratigraphically constrained chord-distance clustering and square-root transformation of the percent data. To summarize diatom-assemblage variation, we used CANOCO v 4.53 (ter Braak and Šmilauer 1998) to run principal components analysis (PCA). Species counts were transformed to percentages and only species >2% in any one sample were used in the analysis in order to remove the effect of the rare species. Percentage data were then log-transformed in order to reduce the dominance of abundant species (in particular, cosmopolitan *Fragilaria*) over species with smaller percentages (Digby and Kempton 1987). We also applied detrended correspondence analysis (DCA) to the same data. The DCA results show that the length of the first axis was 0.92 standard deviation units, indicating that PCA should be used (ter Braak and Prentice 1988). The

P/B ratio was calculated by dividing the total number of planktonic and tychoplanktonic diatoms by the total number of benthic diatoms at each depth.

We used a water-depth transfer function to estimate lake levels and infer effective-moisture (precipitation minus evaporation) variation from the diatom record of Ongoke Lake. The transfer function is based on a training set composed of modern (i.e. surface-sediment) diatom assemblages and associated environmental measurements from a north-south transect in Alaska (Gregory-Eaves et al. 1999). Although this training set does not include lakes from southwestern Alaska, its dominant species were similar to those found at Ongoke Lake, with benthic *Fragilaria* and *Achnanthes* spp. in highest abundance and with *Cyclotella* spp. and *Fragilaria capucina* var. *gracilis* as the most abundant planktonic taxa (Gregory-Eaves et al. 1999). Canonical correspondence analysis indicated that water depth was one of the most important variables in driving the variation in this training set. A weighted-averaging model using classical deshrinking was found to produce the most robust model, resulting in a bootstrapped coefficient ($r^2_{boot}$) of 0.53 and a root-mean squared error of prediction (RMSEP$_{boot}$) of 0.31 with a RMSE of 1.7 m for the observed versus inferred depths (Gregory-Eaves et al. 1999). Fossil diatom identification was harmonized to the modern training set by careful comparison of nomenclature and associated species descriptions from various sources. *Tabellaria flocculosa* III and *T. flocculosa* IV (after Koppen 1975) were combined in the training set as the fossil *T. flocculosa* counts were not split at this taxonomic

level. The difference in the $r^2_{boot}$, RMSEP$_{boot}$, and RMSE between the initial transfer function and this revised one is minimal ($\leq 0.001$ for all), and the water-depth reconstruction is not affected by combining these taxa. We used the modern analogue technique (MAT) to obtain square-chord measures of dissimilarity between fossil and modern assemblages (Birks 1995) in order to evaluate the potential of the fossil dataset for water-depth reconstruction.

Select samples were prepared for chironomid analysis following a modified version of the procedures described by Walker (1988). Subsampled sediment (0.5 cm$^3$) was heated in 10% KOH for 10 min and rinsed through a sieve of 90 μm mesh. Washing in HCl was omitted because the sediments contained no carbonate. Head capsules of *Corynocera* sp. and *Sergentia* sp. were identified under a dissecting microscope and the total number of head capsules tallied for each sample.

## Results [1]

### Chronology

Background $^{210}$Pb levels were reached at 21 cm, and an age-depth relationship was developed for the past 125 years (Fig. 2 inset and Table 1) using a constant-rate-of-supply model (modified after Oldfield et al. 1977). Four of the nine $^{14}$C ages are statistically indistinguishable with a mean of $\sim$1300 AD, even though they span 60.5 cm (48–108.5 cm; Table 2) of the sediment core. One interpretation of these ages is that this sediment section represents an instantaneous deposition event. Several lines of evidence argue against this interpretation. The sediment is unsorted and has no visible lithological features that would suggest a turbidite. The diatom taxa also showed no apparent sorting by size through this interval. In addition, all of the sediment chemical indicators we analyzed display stratigraphic variation within this interval (Figs. 3, 4). Finally, the dominant chironomid taxon in the sediments of this interval is *Sergentia*, a profundal taxon at Ongoke Lake,
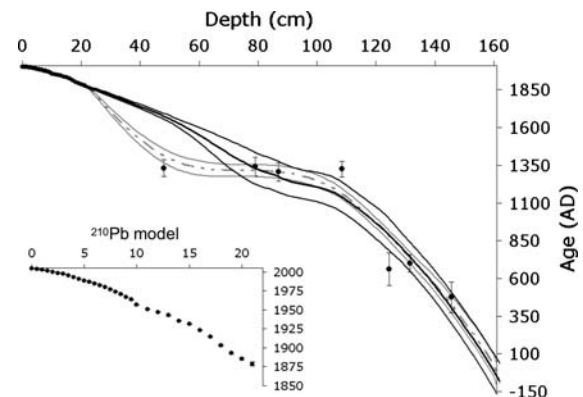


Fig. 2 Age-depth relationships based on $^{14}$C and $^{210}$Pb dating. Black line = loess model with associated $2\sigma$ errors. Dashed line = spline model with associated $2\sigma$ confidence intervals. Inset shows the $^{210}$Pb profile. Errors are $2\sigma$ calibrated age ranges

indicating that the sediments did not derive from redeposition from shallow areas in the lake. It is possible that the Ongoke River may have discharged into the lake during this interval, resulting in a period of increased sediment accumulation compared to the rest of the record.

Previous studies in arcto-boreal regions (e.g. Oswald et al. 2005; Tinner et al. 2008) also show that $^{14}$C dating of this time interval commonly yield results that are difficult to interpret, even when the dated materials are carefully selected terrestrial plant macrofossils. Rather than choosing $^{14}$C ages to eliminate from our record, we applied two conservative approaches for age-depth modeling. First, we fitted a loess smooth function (span = 14/16) using all nine $^{14}$C ages and the oldest $^{210}$Pb date (Fig. 2). With this model, the $^{14}$C age of 685 $\pm$ 40 BP at 48 cm stands out as anomalously old, possibly because the dated twigs had resided in the watershed for a long period before deposition in the lake. The alternative age-model (Fig. 2 dashed line), which uses a cubic smoothing spline, gave more weight to the extreme upper and lower dates in the interval from 48 and 108 cm. This model assumes that none of the $^{14}$C ages are erroneous and that the sediments deposited rapidly but not instantaneously in the interval with the four indistinguishable ages.

The two age models diverge between the core depths of 23–79 cm, but they are nearly identical for the remainder of the record. Between 23 and 79 cm, the two models have an average difference of 164 years and a maximal difference of 265 years.

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[1] All data presented in this paper are available on-line at the World Data Center for Paleoclimatology: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/northamerica/usa/alaska/ongoke2008.txt.
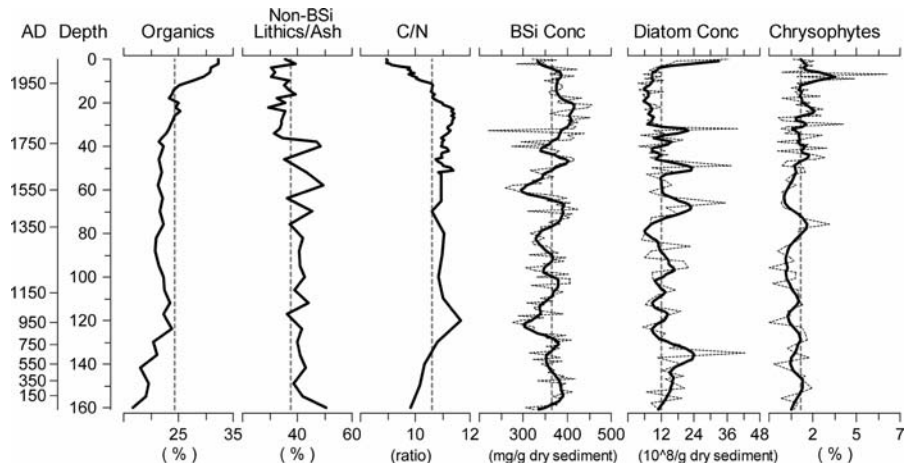
**Fig. 3** Sediment chemical composition. Organic matter content (LOI (%) 550°C), non-BSi lithics and ash (LOI (%) 950°C minus BSi concentration), C/N ratio, biogenic silica (BSi) content, diatom concentration, and percent chrysophyte cysts.

Bold curves for BSi concentration, diatom concentration, and percent chrysophytes are loess smoothed data (span = 0.1). Vertical dashed lines indicate mean values of the last 1000 years

We use the loess model throughout this paper but report the ages from the alternative model at relevant places. Because of the age-model uncertainties, caution is warranted when interpreting temporal trends from our proxy records. We also chose not to interpret accumulation rate data, which are highly sensitive to chronological errors. Furthermore, comparison with other regional proxy records must be approached with caution as a result of chronological errors at Ongoke Lake or at other sites.

### Sediment geochemistry

Sediment chemical composition of Ongoke Lake varies substantially over the 2000 year record (Fig. 3). Organic matter increases from minimal values of $\sim 16.7\% \sim 2000$ years ago to 32% at present, with the highest values over the last 100 years. $CaCO_3$ is consistently <2.5%, which is within the range of analytical errors of LOI. The C/N mass ratio ranges from 8.9 to 11.7, with a mean of 10.6 over the last 2000 years. The ratio increases from 9.8 to 11.6 between 50 BC and 970 AD, displays relatively high values ($\sim 11.1$) from $\sim 970$ to 1860 AD, and declines to a minimal value of 8.9 at present.

BSi concentrations fluctuate around the mean value of 370 mg $g^{-1}$ from 50 BC through $\sim 1740$ AD, with minimal values centered at 950, 1320,

1560, and 1740 AD. BSi increases to peak values ($\sim 450$ mg $g^{-1}$) between 1740 and 1880 AD, followed by a decrease to 320 mg $g^{-1}$ at 2004 AD.

### Fossil diatoms

#### Concentration stratigraphy

Diatom concentrations (unit: $10^8$ diatom frustules $g^{-1}$ dry sediment) fluctuate between 3.8 and 42.2 with a mean value of 12.7 over the 2000 year record (Fig. 3). The values increase from a minimum at 50 BC to a peak at 670 AD, followed by a decrease to a mean of 6.2 from 670 to 1430 AD. Peaks occur around 1480, 1670, and 1800 AD, and low values are centered at 1630 and 1730 AD. The period of 1820–1985 AD is characterized by low values of $\sim 4.0$, after which diatom concentration increases steadily until present. With the exception of opposite stratigraphic patterns from 1815 AD to present, the diatom-concentration and BSi-concentration (Fig. 3) records are similar in terms of major peaks and troughs throughout the past 2000 years.

#### Assemblage zones

We identified 278 different diatom taxa at Ongoke Lake. Benthic species account for 60.8–85.5% of the assemblages throughout the record (Fig. 4a).
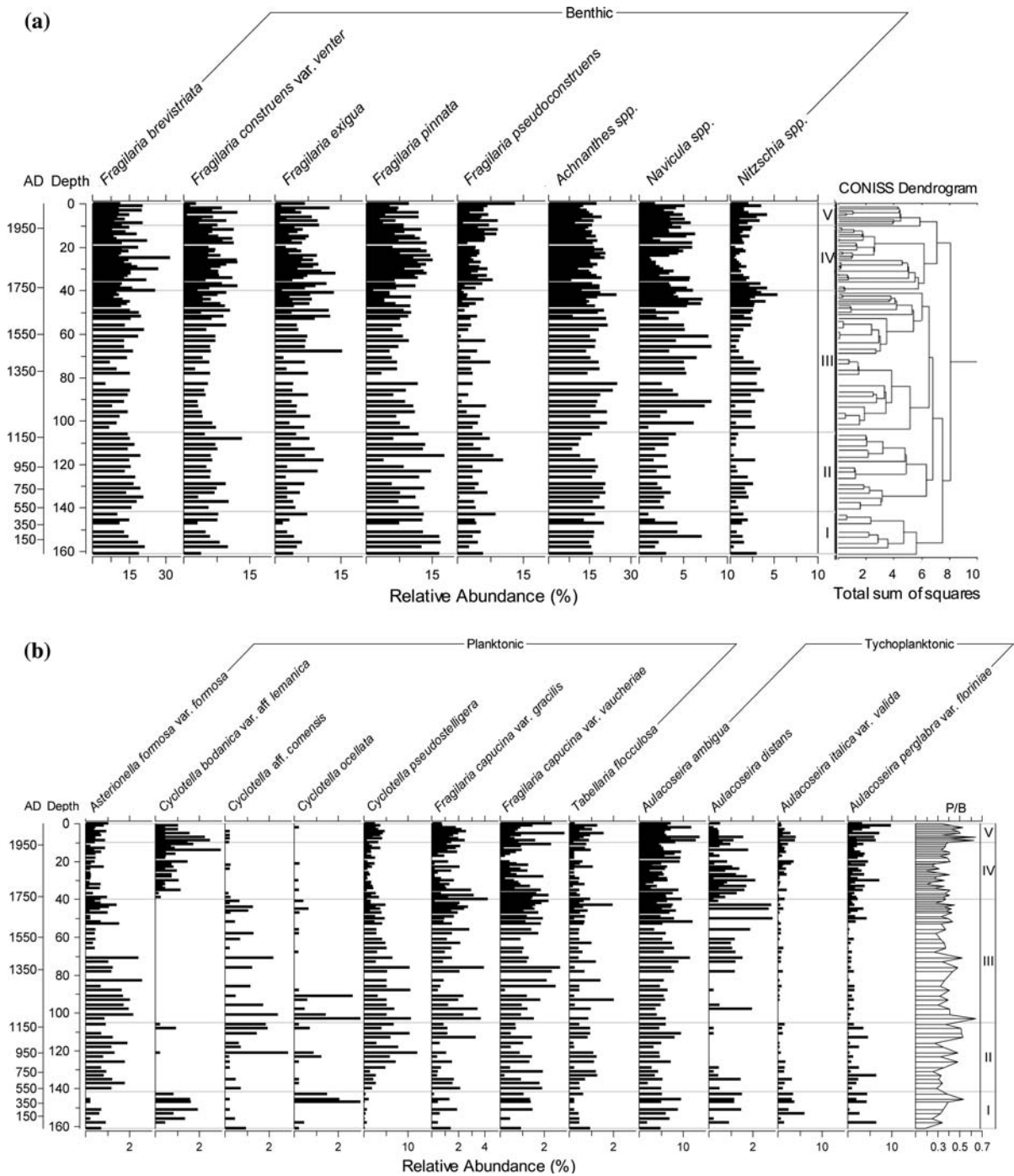
Fig. 4 Diatom assemblages from Ongoke Lake. **a** Percentages of the dominant benthic diatom taxa (species occurring at >10% in any one sample are shown, and *Navicula*, *Achnanthes*, and *Nitzschia* species are combined into each genus); **b** Percentages of the dominant planktonic and tychoplanktonic diatom taxa (species occurring at >2.5% in any one sample are shown)

*Fragilaria brevistriata*, *Fragilaria exigua*, and *Fragilaria pinnata* dominate the assemblages, representing 19.1–48.9% of the total abundance in any one sample. Planktonic species fluctuate between 8.9–31.6% of the diatom assemblages and are dominated by *Cyclotella pseudostelligera* (Fig. 4b). Tychoplanktonic species account for 3.7–25.8%, with the range mostly reflecting fluctuations in *Aulacoseria* spp. (Fig. 4b).

Five diatom zones were identified using CONISS (see dendrogram in Fig. 4a). Zone I (141–161 cm, ∼50 BC-520 AD) is characterized by low proportions of most of the planktonic species, except for noticeable peaks of *Cyclotella bodanica* var. aff. *lemanica* and *Cyclotella ocellata*. Tychoplanktonic species increase overall in abundance, and benthic *Fragilaria* species are high throughout this zone, especially *F. pinnata*. The P/B ratio is overall low in this zone compared to the rest of the record (Fig. 4b), but generally increases.

In zone II (105–141 cm, 520–1170 AD), tychoplanktonic species are less abundant than in zone I, with *Aulacoseira distans* reaching the lowest values of the record. *C. pseudostelligera* steadily increases over this interval, and *Cyclotella* aff. *comensis* reaches peak values. Benthic *Fragilaria* species remain high. Benthic *Achnanthes* and *Nitzschia* species exhibit decreased values near the end of the zone. The P/B ratio remains overall low, but increases in the latter part of this zone.

Benthic *Fragilaria pseudoconstruens*, *Fragilaria construens* var. *venter*, *F. brevistriata*, and *F. pinnata* generally decrease to minimum values over zone III (40–105 cm, 1170–1740 AD). In contrast, *Achnanthes*, *Navicula*, and *Nitzschia* species reach the highest values of the record during this interval. Planktonic *Asterionella formosa*, *T. flocculosa*, *F. capucina* var. *gracilis* and several *Cyclotella* species reach peak values in the early part of this zone. Tychoplanktonic species have relatively high percentages over this zone, with *A. distans* reaching peak values in the latter part of the interval. P/B is steady at median values, reflecting the increases in both planktonic and benthic species.

Zone IV (10–40 cm, 1740–1955 AD) highlights a decrease in all *Cyclotella* species, with the exception of *C. bodanica* var. aff. *lemanica*. *Aulacoseira* species remain abundant except for an overall decrease in *A. ambigua*. The percentages of several

benthic *Fragilaria* species increase over this zone with peak values in *F. exigua* and *F. brevistriata*. These species shifts correspond to lower P/B values, especially near the end of the zone.

Zone V (0–10 cm, 1955–2004 AD) is characterized by dramatic increases in the tychoplanktonic species, with *Aulacoseira perglabra* var. *floriniae* and *A. ambigua* reaching peak percentage values of the entire record. Planktonic species also have higher values than in the previous zone, with *F. capucina* var. *vaucheriae* and *C. bodanica* var. aff. *lemanica* exhibiting the highest values of the record. Most benthic species exhibit overall lower values compared to zone IV. Corresponding to these assemblage changes, the P/B ratio displays an overall increasing trend, reaching peak values ∼7–9 cm (∼1966–1980AD).

*Principal component analysis*

Diatom PCA axes 1 and 2 (PCA1, PCA2) explain 16.3% and 11.2% of the total variance in the diatom record, respectively. PCA1 is driven primarily by tychoplanktonic *Aulacoseira* species and some benthic *Fragilaria* species on the positive end, and by several planktonic species (*Cyclotella* and *Asterionella*) and benthic *Achnanthes* species on the negative end (Fig. 5). PCA2 separates several benthic *Fragilaria* species on the negative end from several planktonic, tychoplanktonic, and epiphytic benthic species (e.g. *Navicula* and *Nitzschia* species) on the positive end (Fig. 5).

PCA1 exhibits lowest values from ∼500 to 1740 AD (zones II and III) and higher values between ∼50 BC and 500 AD (zone I) and ∼1740 to present (zones IV and V) (Fig. 6). The lower values in zones II and III are driven primarily by increases in *Asterionella formosa*, *C.* aff. *comensis*, and *C. pseudostelligera* while *C. bodanica* var. aff. *lemanica* and the *Aulacoseira* species decrease (with the exception of an increase in *Aulacoseira distans* over zone III). The higher PCA1 values over the remaining intervals are driven by the opposite trends in these species.

PCA2 exhibits overall low values ∼50 BC to 1140 AD (zones I–II) and the lowest values between 1740 and 1840 AD (zone IV) (Fig. 6). These low values reflect the dramatic decrease in the abundance of most of tychoplanktonic, planktonic, and epiphytic benthic species while benthic *Fragilaria* species

**Fig. 5** Principal component analysis (PCA) of the diatom record from Ongoke Lake. Select species are shown as arrows and sample scores as points. Only the most influential species (eigenvalues >0.35 or <−0.35) are included in the plot. Abbreviations of diatom genera = F.—*Fragilaria*, C.—*Cyclotella*, Au.—*Aulacoseira*, Ac.—*Achnanthes*, Ast.—*Asterionella*, N.—*Navicula*, Nz.—*Nitzschia*
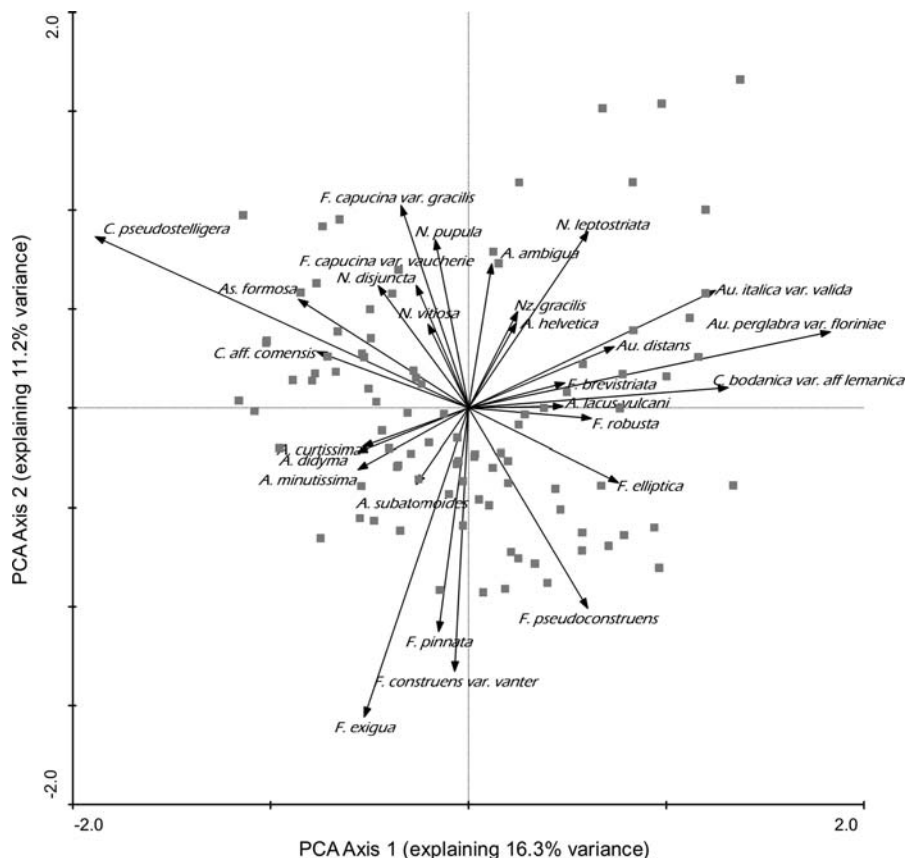


**Fig. 6** Diatom principal component analysis (PCA) axis 1 and axis 2 scores, diatom P/B ratio, and water-depth reconstruction. Vertical dashed lines indicate mean values of the last 1000 years. Asterisks and triangles on the right indicate samples that have poor and no modern analogues, respectively. Bold curves are loess smoothed data (span = 0.1). Reconstructed water depths are shown with error envelope
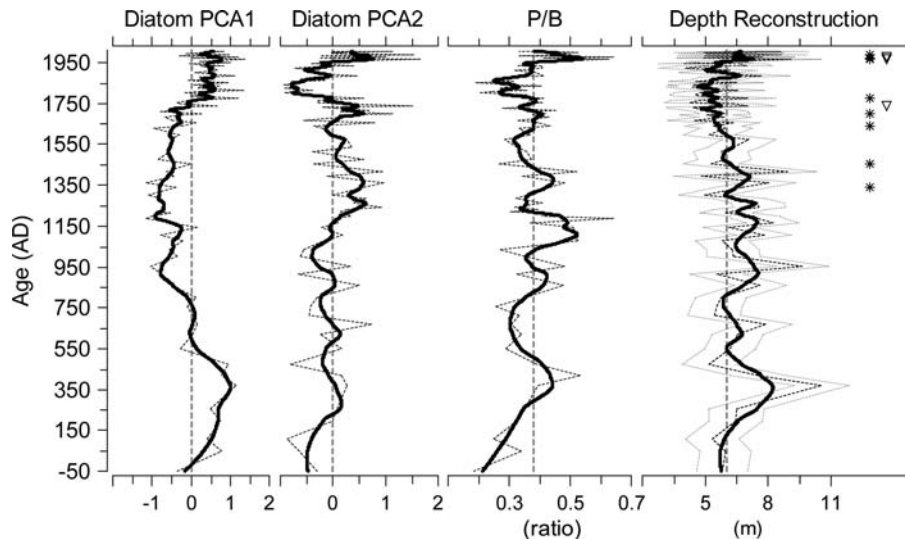


remain overall high (Fig. 4a, b). PCA2 values are higher between ∼1180 and 1740 AD (zone III) and increase steadily to the highest values of the record between 1840 and present (part of zone IV plus zone V), reflecting the opposite trends in species abundance.

*Lake-level estimates*

Comparison of harmonized fossil and modern diatom counts show that on average, 74% of all species in each fossil sample are represented in the modern training set of Gregory-Eaves et al. (1999). Based on the square-chord dissimilarity coefficients of the modern samples from the MAT analysis, we classified the upper tenth and twentieth percentiles as "no" and "poor" modern-analogue samples in the fossil record, respectively. These conservative cut-off values yield only three and eight of the 93 fossil diatom samples with no and poor modern analogues, respectively (denoted in Fig. 6).

Applying the transfer function (Gregory-Eaves et al. 1999) to the surface-sediment diatom assemblage yields a water depth of 5.8 m (Fig. 6). This estimate is similar to the depth of 5.9 m at the core site and the maximum depth of 7 m in 2004, despite large error bars associated with the water-depth model. Over the past 2000 years, our results show that water depths were generally higher around 350 AD, 850–1500 AD, and after 1850 AD (with a minimum centered ∼1820 AD) than during other periods of the record.

## Data interpretation

Sediment geochemistry

Organic matter with C/N values between 4 and 12 has primarily aquatic origins whereas values of greater than 20 indicate terrestrial sources (Hutchinson 1957; Meyers and Lallier-Vergès 1999). Thus the C/N range of 8.9–11.7 suggests that sedimentary organic matter in Ongoke Lake represents accumulation from predominately autochthonous sources, such as diatom and chrysophyte production within the water column. Consistent with this interpretation, BSi concentrations are high (221.9–455.7 mg BSi g$^{-1}$ dry sediment) at Ongoke Lake compared to data from other Alaskan sites (Hu et al. 2001b, 2003; McKay et al. 2008).

Despite its numerous controlling factors, some of which are unrelated to climate, BSi has proved to be a sensitive proxy indicator of past climatic change at certain lakes (e.g. Colman et al. 1995; Hu et al. 2003). For example, BSi is strongly correlated with oxygen and hydrogen isotopes as well as with pollen

assemblages at Arolik Lake (Hu et al. 2003). Furthermore, at millennial and multi-centennial time scales, spatial coherency exists across widely distributed sites (including Ongoke Lake) in Alaska (F. S. Hu, unpublished data). A plausible cause for strong BSi-climate relationships is that BSi production is determined by nutrient availability, which is in turn affected by lake (e.g. water mixing and internal nutrient loadings) or watershed (e.g. soil decomposition and nutrient leaching) processes that are related to climatic conditions. However, climatic interpretations of BSi data may be more complicated at some sites and at high temporal resolution, and a careful evaluation of BSi as a climatic proxy indicator is warranted at each individual site.

At Ongoke Lake, neither BSi concentration nor flux is significantly correlated ($r < 0.48$, $P > 0.025$, $n = 21$) with any climatic variables in the instrumental weather record of Dillingham (Chipman 2007). This result might be explained by diagenetic processes in the near-surface sediments of Ongoke Lake, such as rapid degradation of organic matter and diatom dissolution in the oxygenated microzone (e.g. Ryves et al. 2006). For the same reason, inferring twentieth-century warming from BSi presents a major challenge. At Ongoke Lake, BSi displays an overall declining trend in the twentieth century, which suggests the possibility of decreasing diatom productivity. In contrast, C/N decreases and diatom concentrations increase during the same period, arguing for the possibility of increasing aquatic productivity. The BSi decrease mirrors a marked increase in organic matter during the same period, and the high organic-matter content most likely indicates that the near-surface sedimentary organic matter has not been subjected to extensive microbial degradation. Thus the twentieth-century BSi decrease likely results from dilution by organic matter, instead of indicating decreased aquatic productivity related to climatic change. BSi accumulation rates during this interval (based on $^{210}$Pb dates) confirm this interpretation.

At centennial time scales, the BSi profile displays some overall similarities to the diatom-concentration stratigraphy at Ongoke Lake (Fig. 3). For example, both have low values prior to 300 AD, and there are common peaks and troughs between 600 and 1700 AD. A conspicuous exception is the period of 1800–2004 AD, during which BSi and diatom concentration diverge. A number of factors may lead

to discrepancies between BSi and diatom concentrations. For example, diatom sizes (i.e. biovolume) differ with different species composition, and other siliceous organisms, such as chrysophytes, may contribute to BSi but not to diatom concentration (Newberry and Schelske 1986). At Ongoke Lake, the latter may be important after 1800 AD when chrysophyte counts are higher than during previous intervals (Fig. 3). Additionally, highly silicified tychoplanktonic diatom species increased during the nineteenth and twentieth centuries (Fig. 4b), and BSi and the total percentages of tychoplanktonic taxa exhibit similar stratigraphic patterns during several time intervals of the past 2000 years. These species incorporate greater amounts of silica into their cell walls than smaller and less-silicified species, potentially elevating BSi values (Schelske 1999). Because of these complications and the lack of significant correlation with instrumental climate data, we chose not to rely on our BSi or diatom-concentration data for climatic inferences.

Diatom assemblages

Diatom assemblages are influenced by a number of inter-related limnological factors, including nutrients, pH, dissolved organic carbon (DOC), timing and duration of ice cover and thermal stratification, and water depth (Smol and Cumming 2000). Some of these factors in turn respond to climatic variables, such as temperature, rainfall, snow/ice cover, and windiness (Anderson 2000; Smol and Cumming 2000). For example, temperature fluctuations may alter diatom composition through changes in the duration of ice cover and strength of lake stratification (e.g. Anderson 2000; Lotter and Bigler 2000; Rühland and Smol 2005). Changes in terrestrial vegetation may also exert controls over nutrient availability and DOC content in lake water that can affect diatom assemblages. In southwestern Alaska, the abundance of N-fixer *Alnus viridis* in the watershed plays a key role in a lake's nitrogen budget (Hu et al. 2001b; Devotta 2008). However, pollen data from Ongoke Lake reveal only minor vegetation variation over the last 2000 years (F. S. Hu, unpublished), in contrast to pronounced vegetation changes near the treelines in the boreal ecosystems of south-central Alaska over this time period (e.g., Tinner et al. 2008).

In this section, we first lay out the rationale for climatic and limnological inferences from our diatom record and then describe patterns of change over the past 2000 years. These inferences are based upon lake-level estimates using a regional diatom training set (Gregory-Eaves et al. 1999), and on the autecologies of the dominant diatom taxa driving the first two PCA axes of our diatom record. Wherever possible we substantiate these inferences with additional lines of evidence.

*Inferences of lake stratification and ice cover*

The dominant diatom species along PCA1 suggest that this axis reflects the strength of lake thermal stratification and duration of ice cover, which may be related to temperature. However, our inferences of these limnological variables are more speculative than those of effective moisture discussed below. PCA1 is characterized by (1) tychoplanktonic *Aulacoseira* and several benthic *Fragilaria* species on the positive end, and (2) planktonic *Cyclotella* and *A. formosa* species and benthic *Achnanthes* species on the negative end (Fig. 5). Tychoplanktonic species are heavily silicified, and they tend to thrive in lakes that experience deep mixing of the water column and overall turbulent conditions. In contrast, planktonic diatoms flourish in clear and calm water, and they thrive during extended periods of lake thermal stratification (e.g. Sorvari et al. 2002; Rühland and Smol 2005). *Aulacoseira* spp. have high affinity for high silica to light ratios, which increase with deep-water mixing, compared to moderate and low requirements by planktonic *A. formosa* and *Cyclotella* species, respectively (Makulla and Sommer 1993). Strengthened thermal stratification during the summer may decrease wind-induced turbulence, facilitating the decline of tychoplanktonic species (Rühland and Smol 2005; Rühland et al. 2008).

Variation in species abundances along PCA1 may also be linked to changes in ice-cover duration. Most diatom species bloom during intense spring mixing in response to nutrient release from bottom waters and to increased light as ice cover disappears (Wetzel 2001). The *Cyclotella* species with low PCA1 scores at Ongoke Lake are known to increase with annual temperature and a prolonged growing season as a result of delayed onset of ice cover and early ice-out (e.g. Smol 1988; Lotter and Bigler 2000; Batterbee

et al. 2002; Sorvari et al. 2002; Karst-Riddoch et al. 2005). In response to climatic warming over the past 150 years, many lakes experienced increases in these planktonic species at the expense of benthic taxa (e.g. *Fragilaria*) in the Arctic (Smol et al. 2005) and other regions of the Northern Hemisphere (Rühland et al. 2008). In contrast, species more tolerant of low temperature and low light may thrive for extended periods of ice cover under cold conditions (e.g. Douglas et al. 1994). For example, the benthic *Fragilaria* species, several of which have high PCA1 scores in our diatom record, are opportunistic diatoms that can survive in shallow moats on the littoral lake edge during the ice-cover season (Karst-Riddoch et al. 2005; Lotter and Bigler 2000; Smol 1988; Lim et al. 2001).

We cannot unambiguously separate changes in the strength of lake stratification and the duration of ice cover, or assess the role of wind-driven mixing in stratification and nutrient supplies. Some of these limnological variables are often related. For example, early ice-out resulting from climatic warming can facilitate the development of summer stratification. Thus diatom variation along PCA1 may be indicative of their combined effects in response to temperature. Taken together, the downcore variation of PCA1 suggests that the duration of ice cover was long and the lake stratification weak from 50 BC to ∼500 AD, relative to other periods of the record. Ice-cover duration decreased and stratification strengthened between ∼500 and 950 AD, and these conditions were sustained through ca. 1740 AD. From ca.1740 AD through the present, ice cover expanded and thermal stratification diminished. The inferred changes at ∼1740 AD may have occurred at ∼1530 AD if the alternative age model is used (Fig. 2).

Other evidence also supports our interpretation of strengthened lake stratification between ∼550 and 1740 AD. During this period, *C. bodanica* var. aff. *lemanica* largely disappears from the record. In the PCA, *C. bodanica* var. aff. *lemanica* is associated with *Aulacoseira* species and negatively correlated with all other *Cyclotella* taxa (Fig. 5). This *Cyclotella* variety requires much higher concentrations of phosphorus than other *Cyclotella* taxa (Wunsam et al. 1995). Its abundance may have decreased as P was progressively lost to the sediment and the internal loading of P lessened as a result of lake stratification (Levine et al. 1986; Cole and Pace 1995).

Preliminary analysis of chironomid head capsules in the sediments of Ongoke Lake also reveals assemblage changes that may be related to enhanced lake stratification and diminished oxygen availability in the hypolimnion. Specifically, *Sergentia coracina*-type increased abruptly around 1120 AD and remained dominant until 1750 AD (Fig. 7). This change occurred at the expense of *Corynocera* sp. (mostly *C. ambigua*, with both *C. oliveri* and *C.* nr. *ambigua* sensu Barley et al. 2006 as minor components). *Sergentia* is a profundal taxon found in temperate to Low Arctic lakes, and it is tolerant of lower $O_2$ concentrations (Brundin 1949; Brodersen et al. 2008) than *Corynocera* (Brodin 1986). Thus this dominant-species shift suggests the development of a hypolimnion and supports the interpretation of decreased deep-water mixing. Conversely, these preliminary chironomid data suggest weaker stratification and greater water mixing during other periods, including the second half of the twentieth century when storm activity might have been stronger (see section "Discussion"). However, reduced sediment stability associated with increased sedimentation rate (Fig. 2) may have also contributed to the lower abundance of *Corynocera* sp. (Brodersen and Lindegaard 1999) during 1120–1750 AD than during the remainder of the record.
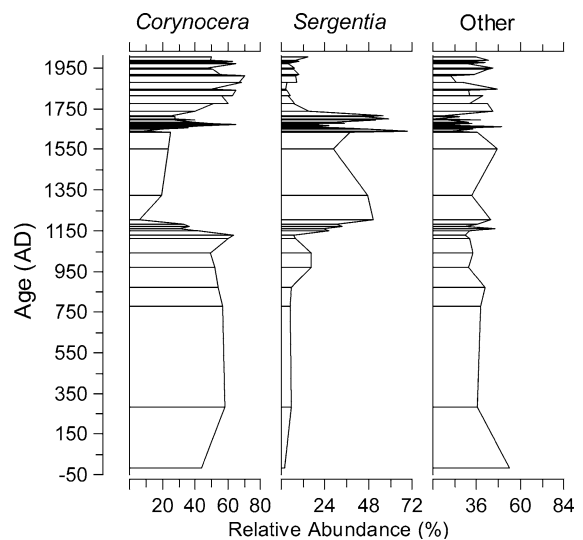


**Fig. 7** Percentages of chironomid head-capsules showing two select taxa

### Water-depth estimates

The water-depth transfer function of Gregory-Eaves et al. (1999) has a moderate strength of prediction (WA regression $- r^2_{boot} = 0.53$) and has been previously applied to infer water-depth changes at an Alaskan lake over the past 700 years (Tinner et al. 2008). Water-depth reconstructions, however, are comprised by the covariance of depth with other variables known to influence diatom assemblages (e.g. light penetration or nutrient concentration) (Wolin and Duthie 1999). Ongoke Lake presently reaches the overflow level with a maximum depth of 7 m, and sediment infill of the basin over the last 2000 years accounts for $\sim 1.6$ m. As such, the maximum water depth has probably not exceeded much over 8.6 m during the last 2000 years. The median depth estimates generated from the application of the transfer function show that this maximum depth of 8.6 m was exceeded at only a few stratigraphic levels (Fig. 6). Like most transfer functions, however, the transfer function of Gregory-Eaves et al. (1999) has significant bias, where greater depths are underestimated and shallower depths overestimated. We consider the overall trends in our water-depth estimates qualitatively reliable even though they may be quantitatively skewed.

Diatom PCA2 is significantly correlated with the water-depth reconstruction ($r = 0.68$, $P < 0.001$, $n = 92$), which lends further support for our lake-level estimates and offers additional limnological information. In the Ongoke Lake PCA ordination, many planktonic and tychoplanktonic as well as epiphytic benthic species have positive PCA2 scores, whereas the benthic *Fragilaria* species have low scores. Planktonic *Cyclotella* and tychoplanktonic *Aulacoseira* species prosper in deeper lakes in arctic tundra and forest-tundra ecozones (Pienitz and Smol 1993; Gregory-Eaves et al. 1999; Rühland and Smol 2002; Rühland et al. 2003). Many epiphytic benthic diatoms (e.g. *Navicula* and *Nitzschia* species) increase in abundance when lake levels are lower and shallow-water habitats more abundant (Wolin and Duthie 1999). However, unlike the adnate *Fragilaria* species, which adhere to the substrate, these species are motile diatoms that can move along a substrate to adjust to changes in the photic zone (Hill 1996; Hay et al. 2000).

The P/B ratio also displays temporal patterns similar to the water-depth estimates over much of the record, although no statistically significant correlation exists between this ratio and inferred water depth or PCA2. The P/B ratio may indicate water depth because most planktonic and tychoplanktonic diatoms increase in abundance when lake levels are high, whereas benthic species are more competitive under lowered lake levels (Batterbee 1986; Wolin and Duthie 1999).

Taken together, our lake-level estimates along with the PCA2 and P/B profiles suggest that effective moisture increased steadily prior to $\sim 350$ AD, followed by a decrease to the lower values of 550–750 AD. From 750 to 1450 AD, estimated water depths indicate relatively moist conditions. Effective moisture decreased from $\sim 1450$ to 1850 AD with some fluctuations; the alternative age model (Fig. 2) places this interval between $\sim 1315$ and 1840 AD. The past 150 years are marked by an increasing trend in effective moisture with variation, and the estimated water depth reached peak values in the second half of the twentieth century.

### Discussion

Several previous studies in Alaska reported tree-ring and lake-sediment evidence of climatic variation over the past 2000 years (Hu et al. 2001a; Wiles et al. 2004; Loso et al. 2006; McKay et al. 2008). Our data from Ongoke Lake contributes to this growing dataset by offering the first proxy record at centennial time scales from southwestern Alaska. Here we compare this record with existing temperature reconstructions, the focus of all previous paleoclimate studies of the last two millennia in the region, and discuss changes in the moisture regime. We emphasize that this comparison may be compromised by chronological uncertainties at various sites, especially around the interval of the four statistically indistinguishable ^{14}C ages at Ongoke Lake (Table 2, Fig. 2).

The diatom data from Ongoke Lake suggest changes in the strength of thermal stratification and duration of ice cover that may be related to temperature variation. These changes exhibit both similarities to and major differences from several distinct climatic events in other areas of Alaska. For example, extended ice cover and reduced
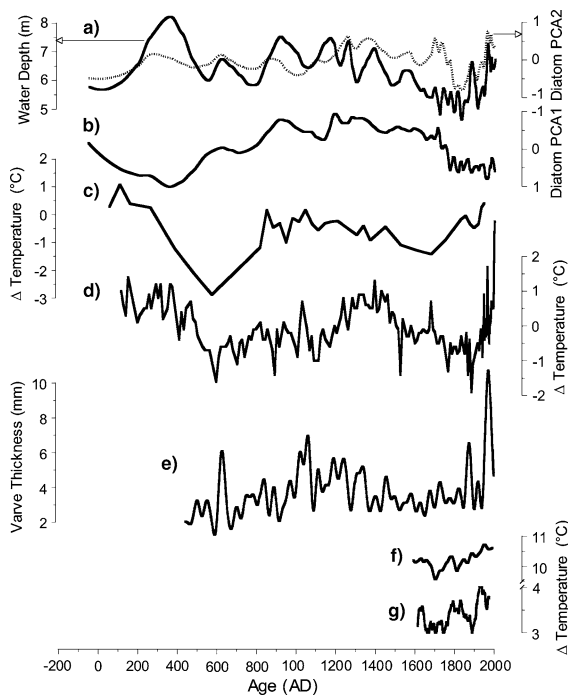
**Fig. 8** Comparison of the Ongoke Lake record with temperature reconstructions from other sites in Alaska. **a** Diatom principal component analysis (PCA) axis 2 (dashed) and reconstructed water depth (solid) from Ongoke Lake. **b** Diatom PCA axis 1 from Ongoke Lake. **c** Warm-season temperature anomaly estimated from oxygen-isotope composition at Farewell Lake (Hu et al. 2001a). **d** Summer (JJA) temperature anomaly inferred from biogenic silica at Hallet Lake (McKay et al. 2008). **e** Varve thickness from Iceberg Lake (Loso et al. 2006; updated 2007), with thicker varves indicating warmer climate. **f** Warm-season temperature inferred from tree-ring records from the Wrangell Mountains (Davi et al. 2006). **g** Warm-season temperature inferred from tree-ring records from areas around the Gulf of Alaska (Wiles et al. 1999)

stratification suggest a cold interval around 400 AD (Fig. 8b). This cold interval may be related to the FMC event, described as the coldest period in the last 2000 years (Wiles et al. 2004). Glaciers advanced in southern Alaska during the FMC (Wiles and Calkin 1994; Reyes et al. 2006; Wiles et al. 2008). The exact timing of these advances differs among the sites: around 200–320 AD in the Wrangell Mountains and ~430–700 AD in the Kenai, Chugach, and St. Elias Mountains. Cold conditions have also been documented at Farewell Lake on the northwestern foothills of the Alaska Range, where maximal cooling and increased moisture occurred around 600 AD (Hu et al. 2001a) (Fig. 8c). Similarly, maximal cooling was found in south-central Alaska around this

time, as suggested by BSi at Hallet Lake (McKay et al. 2008), and in varve thickness at Iceberg Lake (Loso et al. 2006) (Fig. 8d, e).

At Ongoke Lake, the longest interval of warm climate, inferred from decreased ice cover and enhanced stratification, occurred between ~950 and 1700 AD. This interval encompasses the MCA, which appears to be one of the warmest periods of the last two millennia at several Alaskan sites (Hu et al. 2001a; Wiles et al. 2004; Loso et al. 2006; McKay et al. 2008). However, this warm interval extends into the LIA period at Ongoke Lake according to our loess age model. This pattern stands in stark contrast with results from other Alaskan sites where the LIA was characterized by marked cooling. Hu et al. (2001) estimated that warm-season temperatures were up to 1.7°C colder than today at the height of the LIA on the basis of oxygen-isotope data from Farewell Lake. Evidence of LIA cooling in Alaska has also come from glacial advances (Wiles et al. 2008), pollen-inferred treeline declines (Tinner et al. 2008), and tree-ring reconstructions (Wiles et al. 1998; Davi et al. 2006) (Fig. 8f, g). At Ongoke Lake, diatom-inferred changes in ice cover and stratification suggest a climatic cooling beginning around 1740 AD. Our alternative age model places the onset of this cooling at 1530 AD, which is similar to the onset time of LIA cooling at other Alaskan sites.

In terms of understanding the climatic impacts of anthropogenic greenhouse gases, it is essential to put the twentieth-century climate in the context of natural variability. Extreme shifts in diatom species composition over the past 150 years have been found in some Arctic lakes, highlighting that anthropogenic climatic change greatly altered aquatic ecosystems (e.g. Douglas et al. 1994; Smol et al. 2005). At Ongoke Lake, several *Cyclotella* species began to increase ~1840 AD, a pattern similar to that reported from other sites of the Northern Hemisphere and interpreted as a response to climatic warming (e.g. Sorvari et al. 2002; Perren et al. 2003; Karst-Riddoch et al. 2005; Rühland and Smol 2005; Smol et al. 2005; Rühland et al. 2008). However, the abundance of *Cyclotella* is relatively low over the past 150 years compared to the period of 800–1700 AD at our site, where the past 150 years appear to be a part of a prolonged cold interval starting at ~1740 AD. Chronological errors alone cannot account for the

lack of a warmer signal for the twentieth-century at Ongoke Lake because our ^{210}Pb profile provides a solid chronology through the past 125 years (Fig. 2). We do not know the reasons for this major discrepancy between Ongoke Lake and these areas. A possible explanation is that the temperature history of the Ongoke Lake area differs from those of other regions of Alaska. However, Levy et al. (2004) reported evidence of glacial advance during the LIA in the Ahklun Mountains, which suggests other areas of southwestern Alaska experienced climatic cooling at this time.

In contrast to the growing body of evidence for temperature variation over the past 2000 years, little is known about moisture-regime changes that may have accompanied the temperature changes. The diatom record from Ongoke Lake provides information on the history of effective moisture, as inferred from estimated lake water depths, dominant species along PCA2, and P/B ratio. This record suggests effective-moisture variation that coincides with periods of distinct temperature anomalies documented at other Alaskan sites. For example, the Ongoke Lake area was dry during the LIA and wetter during the MCA. In the Copper River Basin of Alaska, pollen and diatom data from Grizzly Lake also indicate a dry LIA (Tinner et al. 2008). Likewise, Daigle and Kaufman (2008) inferred a drier LIA in south-central Alaska based on combined glacier and lacustrine evidence from Goat Lake in the Kenai Mountains. However, comparing the Ongoke Lake reconstruction to other climatic records illustrates spatial variability in the moisture regime within Alaska. For example, oxygen-isotope and trace-element data from Farewell Lake suggest a wet LIA and a dry MCA (Hu et al. 2001a).

Spatial variability in effective moisture is not surprising in Alaska given the topographic complexity and differences in proximity to the ocean. The instrumental weather records of the past 40 years also display striking spatial contrasts in precipitation (Mock et al. 1998). A strengthened and eastward shift of the Aleutian low (AL) results in increased precipitation from the south, causing large positive winter-precipitation anomalies in the Gulf of Alaska and large negative anomalies in the interior. The response of southwestern Alaska is intermediate between these two extremes (Mock et al. 1998). In contrast to the spatial heterogeneity in precipitation, the shift between a weakened/westerly AL and a

strengthened/easterly AL results in virtually identical patterns of temperature response for most of Alaska (Mock et al. 1998). A network of paleorecords of moisture change are needed to help define the spatial variability and to elucidate how ocean-atmospheric circulation patterns are realized at the sub-regional scale.

Our diatom data from Ongoke Lake suggest that effective moisture was among the highest during the second half of the twentieth century in the 2000 year record. This wet period may have been a result of enhanced regional storm activity. For example, several tychoplanktonic *Aulacoseira* species reached the highest values of the record over the twentieth century. These species are found in relatively deep lakes in tundra ecosystems (Pienitz and Smol 1993; Gregory-Eaves et al. 1999; Rühland and Smol 2002; Rühland et al. 2003). They require turbulent water conditions to maintain their position in the photic zone of the water column (e.g. Rühland et al. 2003; Wilson et al. 1993), and increases in their abundance have been attributed to increased wind-induced turbulence (e.g. Korhola et al. 1996). Because the region around Ongoke Lake is highly sensitive to maritime storm tracks, it is possible that increased storm activity may have increased lake water depth and water turbulence, which would have favored these tychoplanktonic species. Enhanced storm activity has been suggested as a possible result of anthropogenic warming in northern high latitudes (IPCC 2007). We speculate that the diatom record from Ongoke Lake shows a trajectory of assemblage changes that may be related to anthropogenic impacts on atmospheric circulation. Evaluating this hypothesis requires additional paleoclimate records from the region.

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