

GSA DATA REPOSITORY 2012282

Twentieth-century warming revives the world's northernmost lake

Bianca B. Perren, Alexander P. Wolfe, Colin A. Cooke, Kurt H. Kjær, David Mazzucchi & Eric J. Steig

Detailed Site Description

Kakkeklubben Sø is the northernmost lake on the planet, situated 5 km south of Kaffeklubben Ø, the northernmost landmass (Fig. DR1). The lake occupies low-relief terrain comprising glaciofluvial gravels overlain by postglacial marine sediments (Larsen et al., 2010). Regional bedrock comprises frost-shattered schists, draped with thin tills that incorporate Proterozoic gneisses, granites, and metasediments. The lake basin originated as a kettle depression associated with stagnant glacier ice, and lies at an elevation (45 m asl) close to the local limit of postglacial marine incursion. However, basal minerogenic and organic sediments contain no marine macro- or microfossils, and thus there is no direct evidence that the lake was ever a marine embayment. Instead, it is envisioned that relict glacial ice persisted in the depression that now contains the lake until the mid-Holocene. This interpretation is supported by the presence of collapse features in the glaciofluvial complex immediately south of the lake, which is also attributed to persistent relict glacial ice under perennially cold temperatures (Larsen et al., 2010).

Additional site information includes limnological characteristics and water chemistry (Table DR1). The lake is small (0.48 km²) but relatively deep (>14 m), and characterized by dilute, circumneutral to slightly alkaline, waters. During summer, which represent conditions at the annual peak of lake production, lake-water chemistry has a high N/P molar ratio (82) indicative of pronounced P limitation (Bergström et al., 2005). At this time, the lake also becomes depleted in available silica.

Coring And Chronology of Sediments from Kaffeklubben Sø

Multiple gravity cores were obtained from near the deepest point (~14 m) of Kaffeklubben Sø using a modified Kajak-Brinkhurst system (Glew et al., 2001). The uppermost sediments (20 cm) were extruded at continuous 0.125 to 0.25 cm intervals in the field, whereas the more consolidated basal core increments were extruded at 1.0 cm increments in the Copenhagen laboratory upon return.

Geochronology of the uppermost 5 cm of sediment is based on excess (unsupported) ^{210}Pb activities derived from α -spectroscopic determinations of ^{209}Po , assumed to be in secular equilibrium with ^{210}Pb . The entire unsupported ^{210}Pb inventory is contained within the uppermost 6.0 cm of sediment, yielding an excess ^{210}Pb inventory characterized by declining activities in the uppermost 1.0 cm that indicate acceleration of sedimentation rates in the last decade of deposition (Fig. DR2). The uneven distribution of dates resulted from an incremental sampling scheme, where a coarse resolution initial sample set was augmented with additional samples where needed. The only data that are not shown in Fig. DR2 are the three lower samples (6, 8, and 10 cm) that constrain the supported (*in situ*) ^{210}Pb inventory owed to U-bearing phases in the sediment. The mean value of supported ^{210}Pb activity is $0.048 \pm 0.012 \text{ Bq g}^{-1}$. These ^{210}Pb activities were translated to sediment age using the constant rate of supply (CRS) model (Appleby, 2001).

A detailed series of accelerator mass spectrometry (AMS) ^{14}C dates were obtained from lower sediments. We targeted four intervals for which bryophyte macrofossils, spheroidal *Nostoc* cyanobacterial colonies (Fig. DR1e), and humic acids (Abbott and Stafford, 1996) could be dated from the same stratigraphic levels. Mosses are dominantly represented by the family Amblystegiaceae, including *Calliergon giganteum*, *Drepanocladus latinervis*, *Sarmentypnum sarmentosum* and *S. tundrae*. Additional taxa are also present, such as *Philonotis* sp. (Bartramaceae) and *Pohlia wahlenbergii* (Mniaceae). This represents a relatively diverse wetland moss flora for the latitude of the site, and likely includes forms that lived either at the edge of the lake or the immediate surrounding area. Arctic bryophytes have been shown to equilibrate sensitively to atmospheric $^{14}\text{CO}_2$, and are thus considered a reliable dating target (Wolfe et al., 2004). Accordingly, for each of the four depths where sufficient moss macrofossils were recovered for dating, they consistently produce the youngest dates compared to cyanobacterial and humic acid fractions measured from the same depths.

The absence of ^{14}C targets in the middle of the core is consistent with the inference of protracted ice cover during the least well-dated intervals. We have dated as much of the core by ^{14}C as possible after scrutinizing the core extensively for even minute organic fragments. The single cyanobacterial sample at 23 cm is a mat obtained by sieving freeze-dried material. The sample was too small to generate a $\delta^{13}\text{C}$ value, and so a value of -25‰ was assumed by convention.

Only one of the moss dates is stratigraphically reversed and deemed anomalous, that from 66-67 cm (CU 9809; 2380 Cal yrs BP, Table DR2). Given an average macrofossil-humic acid age offset of 200 Cal yrs from the three remaining paired dates, the predicted age for the 66-67 cm moss is 2730 Cal yr BP. Similarly, the lowermost

humic acid date from 81-82 cm (CU 9812; 3480 Cal yrs BP) is considered a maximum age for incipient organic sedimentation at the site, in the absence of moss macrofossils from the basal organic unit. We note that, with the exception of the anomalous macrofossil result from 66-67 cm (Table DR2), the offsets between macrofossil and humic acid dates (100-380 years) are considerably smaller than those observed in Arctic lakes from lower latitudes, where the humic acid fraction is typically in the range of 600 years older than adjacent plant fossils (Wolfe et al., 2004). We interpret the smaller offsets observed in Kaffeklubben Sø sediments to reflect the absence of significant pools of aged terrestrial dissolved organic carbon in catchment soils, consistent with the lake's setting in an unproductive polar desert catchment. This view is further supported by the observation that, throughout the Kaffeklubben Sø sequence, dates from fossil cyanobacterial colonies are directly comparable to those obtained from humic acid extracts (Table S2). The nostocalean cyanobacteria have thus incorporated a broad range of dissolved carbon species of terrestrial and aquatic origin that, as with the humic acid extracts, are slightly older than the dominantly atmospheric ^{14}C signature captured by the bryophytes.

The age model uses a monotone spline for the ^{210}Pb -dated segment, joined by linear interpolation between radiocarbon dates, using the CLAM (Classical non-Bayesian age modeling) function in R (Blaauw, 2010). Collectively, the ^{210}Pb and ^{14}C geochronology from Kaffeklubben Sø sediments suggests that sediment accumulation rates are higher during intervals for which diatom abundances suggest seasonally open-water, that is, both after ~1960 AD (Fig. DR2) and before ~2400 Cal BP (Fig. DR3). However, sediment accumulation appears to have continued uninterrupted during the intervening interval of greatly reduced production and inferred cold conditions, although only one ^{14}C date could be obtained from this interval (23-24 cm; UCI 80817; 1290 Cal yrs BP).

Diatom Flora

The diatom assemblage from Kaffeklubben Sø is not significantly different from that reported from shallow ponds in Peary Land immediately to the south (Foged, 1955), or a lake in Inglefield Land to the west (Blake et al., 1992), which constitute the only prior reports of freshwater diatoms from north Greenland. Only two centric diatoms were encountered (*Aulacoseira distans* and *Cyclotella antiqua*). Diatom communities are overwhelmingly dominated by small colonial forms of the family Fragilariaceae, including the genera *Pseudostaurosira*, *Staurosira* and *Staurosirella* (Table DR3). In a general sense, the modern diatom assemblage is taxonomically poor even for the High Arctic, consistent with the lake's harsh climatic and limnological regimes. Small and generally alkaliphilous colonial fragilarioid diatoms are able to exploit these conditions

successfully, and are thus widespread in these environments (Paull et al., 2008), as they were during the early postglacial at lower latitudes (Whitehead et al., 1989).

Diatom Preservation

The interval where diatoms are rare or absent requires a careful consideration of the possibility of diatom valve dissolution. We used field-emission scanning electron microscopy (SEM) of slurries prepared in the same manner as those counted, in order to identify telltale indicators of dissolution such as sub-micron pitting and thinning of valves, or loss of fine structures such as spines and alveolae. We are keenly aware of how dissolution presents itself in SEM (Hobbs et al., 2010). Despite occurring at trace abundances in sediments dating between ~2400 Cal yrs BP and the mid-20th century, the diatoms present in these intervals are as well preserved as those in younger and older diatom-rich sediments (Fig. DR4). For example, minute fragilarioids from 9 cm in the gravity core, well below the demise of richer assemblages that characterize recent decades, have preserved linking spines and vestiges of velar occlusions in areolae (Fig. DR4, F-H). The occasional valves are principally fragilarioid taxa, but occasionally cymbelloids or eunotioids, with no relationship to their degree of silicification. Because there is no evidence that dissolution is responsible for the marked changes in diatom abundance in the Kaffeklubben SØ sequence, we are unable to falsify the contention that they represent a primary signature of past algal populations, noting that similar interpretations have been made from other polar lakes where diatoms largely disappear from the record (Antoniades et al., 2007). In these cases, perennial ice cover and attendant light limitation become the leading interpretation for the near-complete absence of diatom in sediments collected from the profundal zone of polar lakes. We appreciate that diatoms do occur in perennially-frozen lakes in Antarctica (Spaulding et al., 1996), but these floras involve endemic taxa that may have evolved adaptations to low-light conditions that are not expressed in the north polar lake assemblages.

Geochemical Record

The complete stratigraphy of measured geochemical variables supports the inference of a fundamentally different limnological regime during the interval where diatoms are rare or absent (Fig. DR5). Although C and N contents are relatively stable, several high C/N excursions are registered in these sediments, suggesting inputs from terrestrial sources. We infer that terrestrial contributions were derived primarily from localized gelifluction of the catchment and possibly aeolian inputs with subsequent melting through the permanent ice pan, similar to the current delivery of sediments to permanently frozen Antarctic lakes (Squyres et al., 1991). Sediment $\delta^{13}\text{C}$ values also rise markedly over this interval (by 4-8‰) and are significantly correlated with sediment C/N

(Fig. DR5 inset). The magnitude and direction of $\delta^{13}\text{C}$ variability is consistent with episodic influxes of isotopically-enriched carbonates derived from the catchment, which accompanied terrestrially-sourced organic matter during the interval of inferred low aquatic production. Finally, we note that sediment $\delta^{15}\text{N}$ values (measured in parallel with $\delta^{13}\text{C}$) are uncorrelated with either %N, C/N, or $\delta^{13}\text{C}$.

Supplemental References Cited

- Abbott, M.B., and Stafford, T.W. Jr., 1996, Radiocarbon geochemistry of modern and ancient arctic lake systems, Baffin Island, Canada: *Quaternary Research*, v. 45, p. 300-311.
- Antoniades, D., Crawley, C., Douglas, M.S.V., Pienitz, R., Andersen, D., Doran, P.T., Hawes, I., Pollard, W., and Vincent, W.F., 2007, Abrupt environmental change in Canada's northernmost lake inferred from fossil diatom and pigment stratigraphy: *Geophysical Research Letters*, v. 34, L18708, doi:10.1029/2007GL030947.
- Appleby, P.G., 2001, Chronostratigraphic techniques in recent sediments, *in* Last, W.M., and Smol, J.P., eds., *Tracking Environmental Change Using Lake Sediments Volume 1: Basin Analysis, Coring, and Chronological Techniques*. Dordrecht: Kluwer, p. 171-203.
- Bergström, A.-K., Blomqvist, P., and Jansson, M., 2005, Effects of nitrogen deposition on nutrient limitation and phytoplankton biomass in unproductive Swedish lakes: *Limnology and Oceanography*, v. 50, p. 987-994.
- Blaauw, M., 2010, Methods and code for 'classical' age-modelling of radiocarbon sequences, *Quat. Geochron.* 5, p.512-518.
- Blake, W., Jr., Boucherle, M.M., Fredskild, B., Janssens, J.A., and Smol, J.P., 1992, The geomorphological setting, glacial history and Holocene development of "Kap Inglefield Sø", Inglefield Land, Northwest Greenland: *Meddelelser om Grønland Geoscience*, v. 27, p. 1-42.
- Foged, N., 1955. Diatoms from Peary Land, North Greenland: *Meddelelser om Grønland*, v. 128, p. 1-90.
- Glew, J.R., Smol, J.P., and Last, W.M., 2001, Sediment core collection and extrusion, *in* Last, W.M., and Smol, J.P., eds., *Tracking Environmental Change Using Lake Sediments Volume 1: Basin Analysis, Coring, and Chronological Techniques*. Dordrecht: Kluwer, p. 73-105.
- Hobbs, W.O., Lalonde, S.V., Vinebrooke, R.D., Konhauser, K.O., Weidman, P.R., Graham, M.D., and Wolfe, A.P., 2010, Algal-silica cycling and pigment diagenesis in recent alpine lake sediments: mechanisms and paleoecological implications: *Journal of Paleolimnology*, v. 44, p. 613-628.
- Larsen, N.K., Kjær, K.H., Funder, S., Möller, P., van der Meer, J.J.M., Schomacker, A., Linge, H., and Darby, D.A., 2010, Late Quaternary glaciation history of northernmost

- Greenland - Evidence of shelf-based ice: *Quaternary Science Reviews*, v. 29, p. 3399-3414.
- Paull, T.M., Hamilton, P.B., Gajewski, K.K., and Leblanc, M., 2008, Numerical analysis of small Arctic diatoms (Bacillariophyceae) representing the *Staurosira* and *Staurosirella* species complexes: *Phycologia*, v. 47, p. 213-224.
- Spaulding, S.A., McKnight, D.M., Stoermer, E.F., and Doran, P.T., 1996, Diatoms in the sediments of Lake Hoare. *Journal of Paleolimnology*, v. 17, p. 403-420.
- Squyres, S.W., Andersen, D.W., Nedell, S.S., and Wharton, R.A., Jr., 1991, Lake Hoare, Antarctica: Sedimentation through a thick perennial ice cover: *Sedimentology*, v. 38, p. 363-379.
- Whitehead, D.R., Charles, D.F., Jackson, S.T., Smol, J.P., and Engstrom, D.R., 1989, The developmental history of Adirondack (N.Y.) lakes: *Journal of Paleolimnology*, v. 2, p. 185-206.
- Wolfe, A.P., Miller, G.H., Olsen, C.A., Forman, S.L., Doran, P.T., and Holmgren, S.U., 2004, Geochronology of high latitude lake sediments, *in* Pienitz, R., Douglas, M.S.V., and Smol, J.P., eds., *Long-Term Environmental Change in Arctic and Antarctic Lakes. Developments in Paleoenvironmental Research* vol. 8. Dordrecht: Springer, p. 19-52.

Supplemental Figures

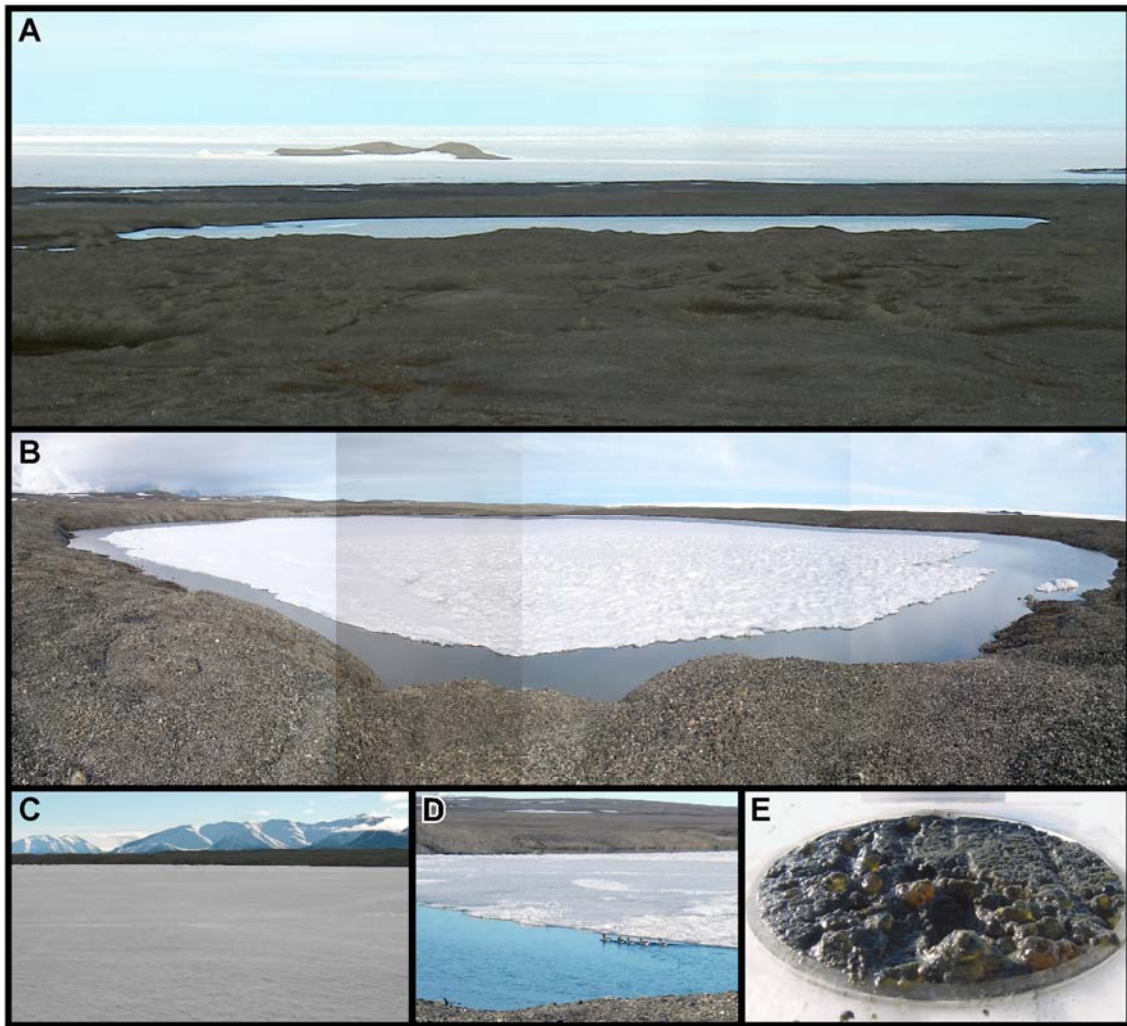


Figure DR1. Photographs of Kaffeklubben Sø and its lake sediments. **A**, View looking north towards the Arctic Ocean with Kaffeklubben Ø in the background. **B**, View to the west of the ice-pan and moat (July, 2006), with mountains of Johannes V. Jensen Land visible to the left. **C**, View across lake ice to the southeast. **D**, Moating of the ice pan on the western shore of Kaffeklubben Sø, with geese. **E**, Spheroidal colonies of *Nostoc* cyanobacteria revealed during extrusion of the intact gravity core. Average colony diameter is 0.5 cm.

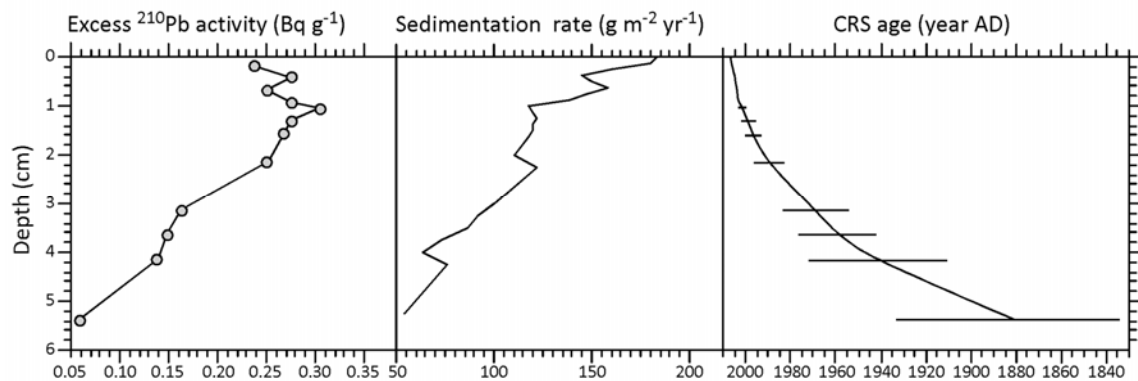


Figure DR2. Excess ^{210}Pb inventory and the CRS chronology of the upper 6 cm of Kaffeklubben SØ sediments.

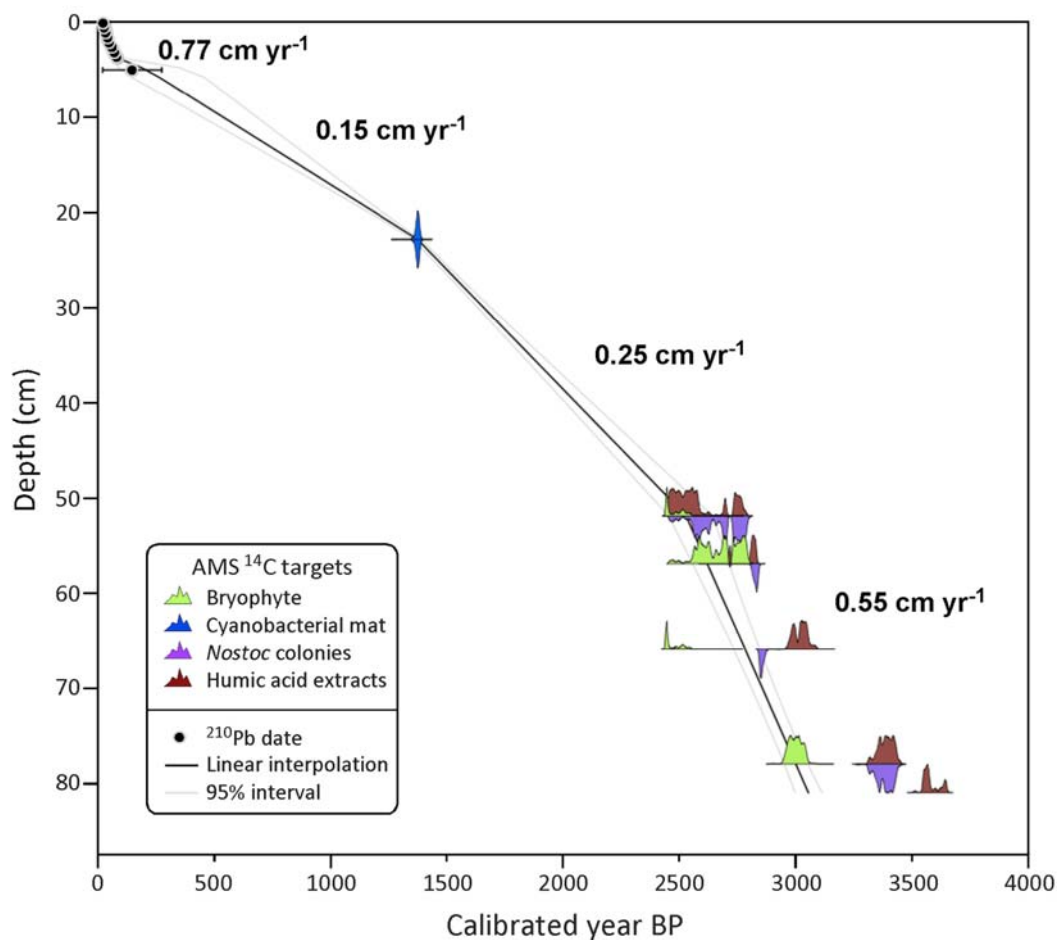


Figure DR3. Accelerator mass spectrometry ^{14}C dates from various organic fractions of Kaffeklubben SØ sediments, with probability distributions of the calibration solutions. Bold numbers are average sediment accumulation rates for the linear segments in the age model.

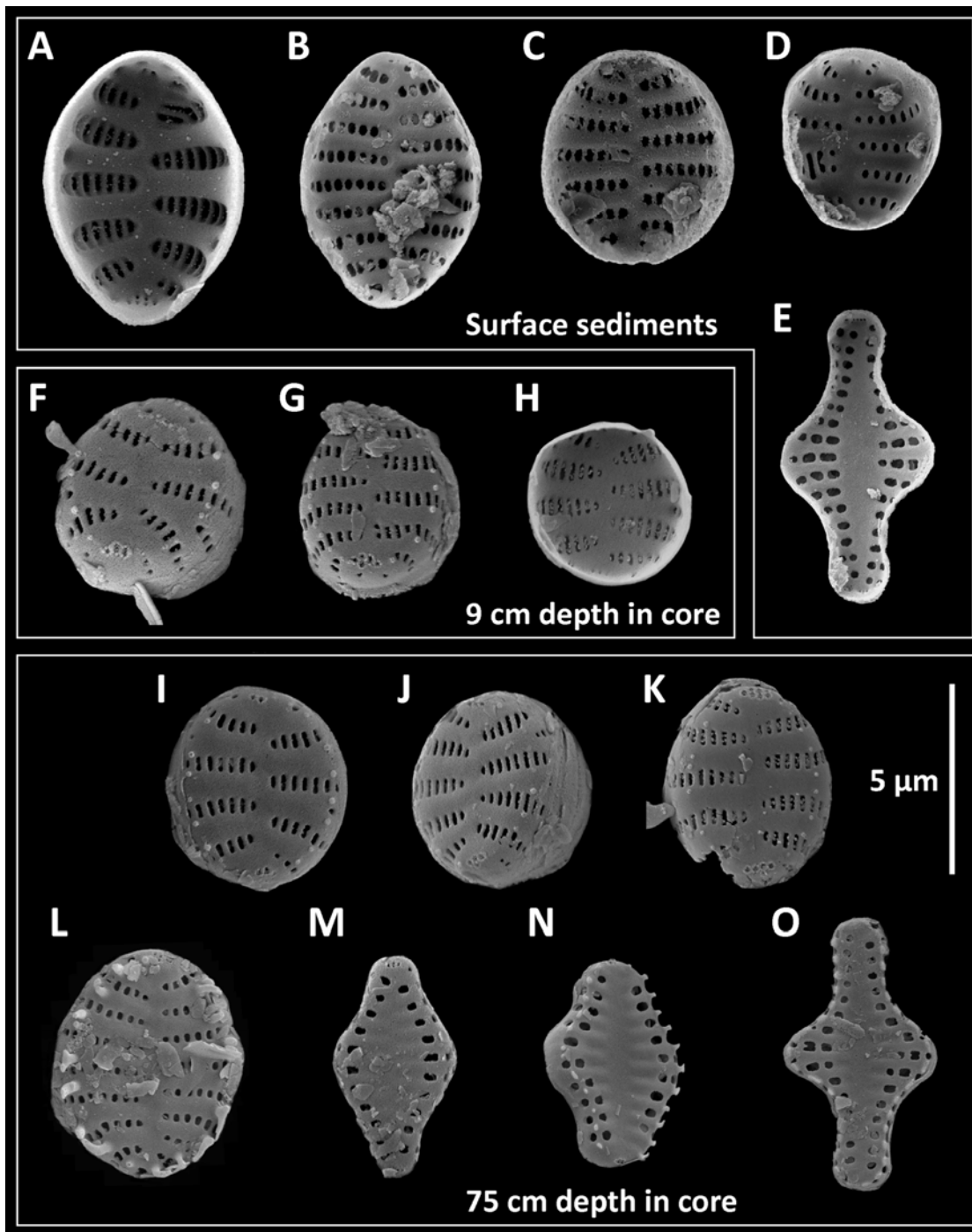


Figure DR4. Evaluation of diatom preservation in Kaffeklubben SØ sediments based on comparative SEM images of various fragilarioid taxa from three depths in the core. (A) *Staurosirella pinnata*; (B-D, L) *Staurosira* spp.; (E, O) *Pseudostaurosira pseudoconstruens*; (F-K) diminutive *Staurosirella* spp.; (M-N) *Pseudostaurosira microstriata*.

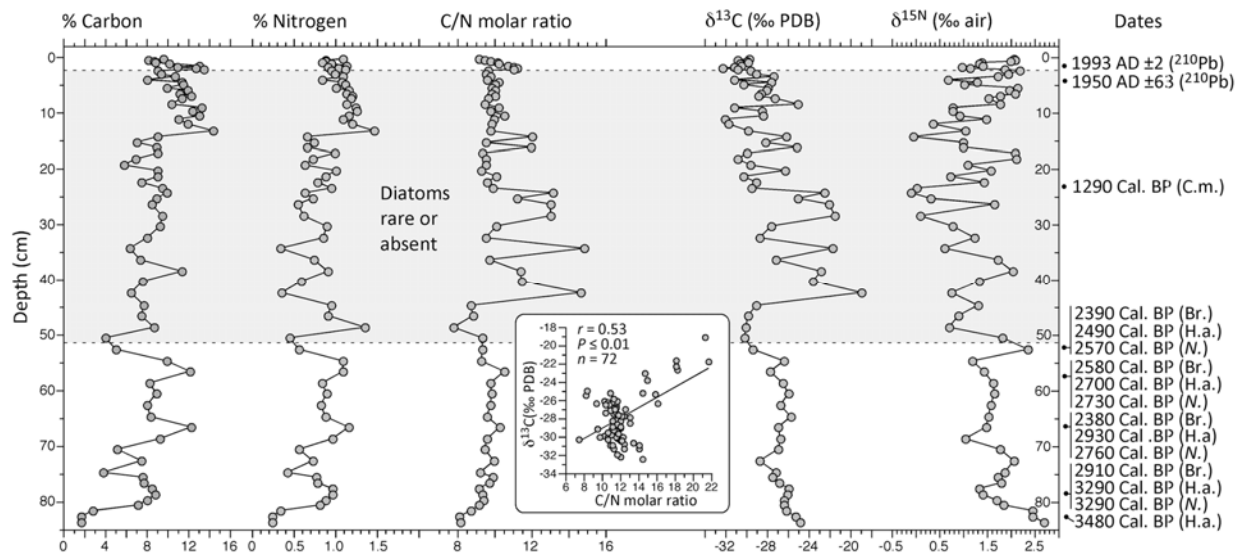


Figure DR5. Stratigraphy of geochemical parameters measured on Kaffeklubben SØ sediments.

Supplementary Tables

Table DR1. Summary location information and limnological properties of Kaffeklubben Sø, Johannes V. Jensen Land, northernmost Greenland.

| Location and morphometry | |
|---------------------------------------------------------------------|-------------|
| Latitude (°N) | 83.6186 |
| Longitude (°W) | 30.7677 |
| Elevation (m asl) | 45 |
| Maximum depth (m) | 14.2 |
| Ice thickness (cm) | 138 |
| Lake area (km ²) | 0.48 |
| Water chemistry (July, 2006) | |
| NH ₄ ⁺ (µg L ⁻¹) | 12.0 |
| NO ₂ +NO ₃ ⁻ (µg L ⁻¹) | 6.0 |
| TN (µg L ⁻¹) | 111.0 |
| TP (µg L ⁻¹) | 3.0 |
| N/P (Mol/Mol) | 82 |
| SO ₄ ²⁻ (mg L ⁻¹) | 4.1 |
| Si (mg L ⁻¹) | d.l. (<0.1) |
| Conductivity (µS cm ⁻¹) | 96 |
| pH | 7.6 |

d.l.= detection limit

Table DR2. Radiocarbon dates from various fractions of Kaffeklubben Sø sediments determined by AMS. Calibration of ¹⁴C results was performed using OxCal 4.0 implemented with the IntCal 4.0 database.

| Depth (cm) | Accession number | Fraction dated | δ ¹³ C (‰ PDB) | Fraction modern and error | Radiocarbon age and error | Mean calibrated age | ±95% Confidence interval |
|------------|------------------|----------------------------------|---------------------------|---------------------------|---------------------------|---------------------|--------------------------|
| 23-24 | UCI-80817 | Cyanobacterial mat | -25.0‰ | 0.8441 ±0.0019 | 1,360 ±20 | 1290 | 1270-1310 |
| 52-53 | CURL-9798 | Bryophytes | -30.6‰ | 0.7437 ±0.0013 | 2,380 ±15 | 2390 | 2350-2460 |
| 52-53 | CURL-9794 | Humic acids | -29.6‰ | 0.7385 ±0.0014 | 2,435 ±20 | 2490 | 2360-2700 |
| 52-53 | CURL-9803 | Spherical <i>Nostoc</i> colonies | -22.3‰ | 0.7359 ±0.0013 | 2,465 ±15 | 2570 | 2370-2710 |
| 57-58 | CURL-9800 | Bryophytes | -26.7‰ | 0.7354 ±0.0014 | 2,470 ±15 | 2580 | 2370-2710 |
| 57-58 | CURL-9814 | Humic acids | -26.7‰ | 0.7282 ±0.0013 | 2,550 ±15 | 2700 | 2550-2750 |
| 57-58 | CURL-9796 | Spherical <i>Nostoc</i> colonies | -24.9‰ | 0.7252 ±0.0014 | 2,580 ±20 | 2730 | 2620-2750 |
| 66-67 | CURL-9809 | Bryophytes | -31.5‰ | 0.7440 ±0.0013 | 2,375 ±15 | 2380 | 2340-2460 |
| 66-67 | CURL-9810 | Humic acids | -30.1‰ | 0.7031 ±0.0012 | 2,830 ±15 | 2930 | 2870-2980 |
| 66-67 | CURL-9813 | Spherical <i>Nostoc</i> colonies | -23.0‰ | 0.7184 ±0.0013 | 2,655 ±15 | 2760 | 2750-2780 |
| 78-79 | CURL-9795 | Bryophytes | -29.9‰ | 0.7051 ±0.0013 | 2,805 ±20 | 2910 | 2860-2960 |
| 78-79 | CURL-9802 | Humic acids | -28.5‰ | 0.6832 ±0.0012 | 3,060 ±15 | 3290 | 3220-3350 |
| 78-79 | CURL-9811 | Spherical <i>Nostoc</i> colonies | -20.6‰ | 0.6838 ±0.0012 | 3,055 ±15 | 3290 | 3220-3340 |
| 81-82 | CURL-9812 | Humic acids | -27.0‰ | 0.6665 ±0.0012 | 3,260 ±15 | 3480 | 3440-3560 |

Table DR3. Diatom taxa encountered in Kaffeklubben SØ sediments, with authorities, number of samples in which each was represented (of the 45 diatom-rich samples), and maximum percent representative to the summed valves counted.

| Taxon and authority | Number of samples present | Maximum relative % |
|------------------------------------------------------------------------------|------------------------------|-----------------------|
| <i>Achnantheidium minutissimum</i> (Kützing) Czarnecki | 27 | 9 |
| <i>Achnanthes pinnata</i> Hustedt | 4 | 1 |
| <i>Amphora inariensis</i> Krammer | 3 | <1 |
| <i>Aulacoseira distans</i> (Ehrenberg) Simonsen | 1 | <1 |
| <i>Brachysira brebissonii</i> Ross in Hartley | 1 | <1 |
| <i>Caloneis bacillum</i> (Grunow) Cleve | 2 | 1 |
| <i>Cavinula variostrata</i> (Krasske) Mann ex Round et al. | 8 | <1 |
| <i>Cyclotella antiqua</i> W.Smith | 2 | <1 |
| <i>Cymbella arctica</i> (Lagerstedt) Schmidt | 1 | <1 |
| <i>Cymbella incerta</i> Grunow | 1 | <1 |
| <i>Cymbella subcuspidata</i> Krammer | 2 | <1 |
| <i>Diademesis contenta</i> (Grunow ex Van Heurck) Mann | 5 | 2 |
| <i>Diatoma elongatum</i> (Lyngbye) Agardh | 3 | <1 |
| <i>Encyonema minutum</i> (Hilse in Rabenhorst) Mann | 38 | 3 |
| <i>Encyonema silesiacum</i> (Bleisch in Rabenhorst) Mann | 25 | 12 |
| <i>Eunotia arcus</i> Ehrenberg | 6 | <1 |
| <i>Eunotia exigua</i> (Brébisson ex Kützing) Rabenhorst | 1 | <1 |
| <i>Eunotia faba</i> (Ehrenberg) Grunow | 1 | <1 |
| <i>Fragilaria capucina</i> Desmazières | 4 | 1 |
| <i>Fragilaria tenera</i> (W.Smith) | 3 | <1 |
| <i>Frustulia rhomboides</i> (Ehrenberg) de Toni | 1 | <1 |
| <i>Navicula digitulus</i> Hustedt | 14 | 1 |
| <i>Navicula modica</i> Hustedt | 6 | 1 |
| <i>Navicula radiosa</i> Kützing | 1 | 1 |
| <i>Neidium affine</i> (Ehrenberg) Pfizer | 1 | <1 |
| <i>Nitzschia fonticola</i> (Grunow) Grunow | 6 | 1 |
| <i>Nitzschia perminuta</i> (Grunow) Peragallo | 8 | <1 |
| <i>Pinnularia balfouriana</i> Grunow ex Cleve | 2 | <1 |
| <i>Pinnularia interrupta</i> W.Smith | 15 | 3 |
| <i>Pseudostaurosira brevistriata</i> (Grunow in Van Heurck) Williams & Round | 39 | 7 |
| <i>Pseudostaurosira pseudoconstruens</i> (Marciniak) Williams & Round | 45 | 72 |
| <i>Rosithidium pusillum</i> (Grunow) Round & Bukhtiyarova | 20 | 3 |
| <i>Stauroneis anceps</i> Ehrenberg | 1 | <1 |
| <i>Stauroneis phoenicentron</i> Ehrenberg | 15 | 1 |
| <i>Staurosira construens</i> var. <i>venter</i> (Ehrenberg) Hamilton | 40 | 16 |
| <i>Staurosira elliptica</i> (Schumann) Williams & Round | 23 | 3 |
| <i>Staurosirella pinnata</i> (Ehrenberg) Williams & Round | 45 | 89 |