



## Abrupt environmental change in Canada's northernmost lake inferred from fossil diatom and pigment stratigraphy

Dermot Antoniades,<sup>1</sup> Catherine Crawley,<sup>2</sup> Marianne S. V. Douglas,<sup>2,3</sup> Reinhard Pienitz,<sup>1</sup> Dale Andersen,<sup>4</sup> Peter T. Doran,<sup>5</sup> Ian Hawes,<sup>6</sup> Wayne Pollard,<sup>7</sup> and Warwick F. Vincent<sup>1</sup>

Received 13 June 2007; revised 8 August 2007; accepted 22 August 2007; published 28 September 2007.

[1] An analysis of diatoms and fossil pigments in a sediment core from perennially ice-covered Ward Hunt Lake at latitude 83°N in Nunavut, Canada revealed striking changes in diatom communities and sedimentary pigment concentrations during the last two centuries. Diatoms were found only in the upper 2.5 cm of the sedimentary record, and where present, diatom assemblages were composed almost entirely of *Staurisirella pinnata*. Photosynthetic pigments were present in low concentrations throughout the sedimentary profile, consistent with the ultra-oligotrophic nutrient status of the lake. Pigment concentrations varied slightly in the lower sections of the core, and began to increase gradually at the 4 cm horizon followed by an increase of two orders of magnitude in the uppermost 2.5 cm. The changes observed in the sedimentary record of Ward Hunt Lake had similar trajectories to those observed post-1850 elsewhere in the circumpolar Arctic, and imply that aquatic communities even in the most extreme northern lakes have been strongly impacted by recent climate warming. **Citation:** Antoniades, D., C. Crawley, M. S. V. Douglas, R. Pienitz, D. Andersen, P. T. Doran, I. Hawes, W. Pollard, and W. F. Vincent (2007), Abrupt environmental change in Canada's northernmost lake inferred from fossil diatom and pigment stratigraphy, *Geophys. Res. Lett.*, 34, L18708, doi:10.1029/2007GL030947.

### 1. Introduction

[2] The amplification of recent climatic change in Arctic regions has had pronounced effects on freshwater ecosystems [*Arctic Climate Impact Assessment*, 2005]. Paleolimnological studies have also demonstrated that past limnological changes, as recorded by proxy indicators, have increased in magnitude with increasing latitude [*Smol et al.*, 2005]. These changes have been attributed to decreased duration of ice cover and the increased length of growing season for aquatic biota [*Douglas and Smol*, 1999]. Climate

models predict that global warming will continue to be magnified at high latitudes, and that Arctic systems will experience further large-scale changes over the course of this century [*McCarthy et al.*, 2001; *Holland et al.*, 2006]. Observations at far northern latitudes may therefore provide an early indication of the effects of climate change.

[3] Ward Hunt Lake is situated in one of the most ice-dominated regions of the northern hemisphere. Ward Hunt Island is surrounded by the Ward Hunt Ice Shelf, which recently fractured leading to the loss of an epishelf lake in nearby Disraeli Fiord [*Mueller et al.*, 2003]. Ward Hunt Lake is also the northernmost lake in Canada, and thereby represents an end-member in terms of latitude and the severity of ice and climate conditions. Our objective was to investigate using paleolimnological techniques the environmental history of Ward Hunt Lake, and to reconstruct patterns of past climate variability using diatoms and fossil pigments.

### 2. Site Location and Methods

[4] Ward Hunt Lake is located on Ward Hunt Island, off the northern coast of Ellesmere Island at the northern limit of North America (83°05'N, 74°10'W; Figure 1). The lake is 0.37 km<sup>2</sup>, of which the majority is shallow (i.e., <2 m), with a maximum depth of 5 m. Ward Hunt Lake is perennially ice-covered, and has 100% ice cover for at least nine months per year. Ice thickness ranged from 4.0–4.1 m when measured in May 1998 and August 2003, with a moat of open water that develops over the littoral zone of the lake in late summer. The lake water is ultra-oligotrophic (<0.5 μg chlorophyll *a* · L<sup>-1</sup> [*Villeneuve et al.*, 2001]), but nutrient-replete cyanobacterial mats extend over the sediments of the shallow littoral zone, as in many high latitude lakes [*Bonilla et al.*, 2005]. However, these mats do not appear to have colonized the sediments beneath the thick ice cover. A 19 cm sediment core was extracted from Ward Hunt Lake on August 10, 2003 by scuba divers below the ice who manually pushed a core tube into the sediment. The core was frozen immediately, and stored frozen until analysis.

[5] Diatom samples were prepared using the following steps. First, carbonates were removed by digestion in 10% HCl for 24 hours, after which samples were washed with distilled water to return them to circumneutral pH. Organic material was then oxidized by addition of 30% H<sub>2</sub>O<sub>2</sub> in 1 ml increments, after which the reaction was allowed to continue for 24 hours, and samples were again washed with distilled water until they reached circumneutral pH. Diatom slurries were dried on glass cover slips in a dust-free environment, and mounted using ZRax<sup>®</sup>. Three hundred diatom valves were enumerated per sample, and following the enumeration

<sup>1</sup>Centre d'Études Nordiques, Université Laval, Québec, Québec, Canada.

<sup>2</sup>Department of Geology, University of Toronto, Toronto, Ontario, Canada.

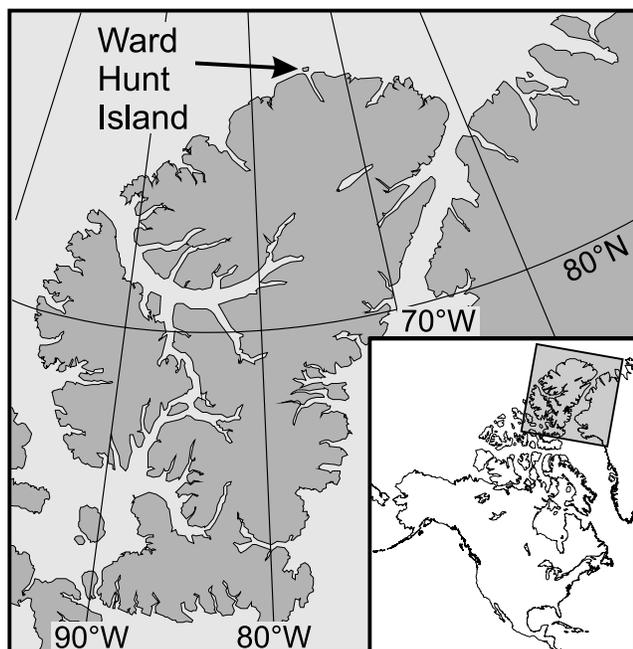
<sup>3</sup>Now at Canadian Circumpolar Institute, Edmonton, Alberta, Canada.

<sup>4</sup>Center for the Study of Life in the Universe, Search for Extraterrestrial Intelligence Institute, Mountain View, California, USA.

<sup>5</sup>Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, Illinois, USA.

<sup>6</sup>National Institute of Water and Atmospheric Research, Christchurch, New Zealand.

<sup>7</sup>Department of Geography, McGill University, Montreal, Québec, Canada.



**Figure 1.** Location map of Ward Hunt Island in the Canadian High Arctic.

of each slide several further transects were examined to determine whether additional taxa were present.

[6] Samples were prepared for pigment analysis by adding 2 ml of 100% acetone and sonicating for one minute. Samples were placed under argon and the extraction was allowed to continue for 24 h at  $-20^{\circ}\text{C}$ . Extracts were separated by centrifuging and then filtered through  $2\ \mu\text{m}$  PTFE filters; serial extractions were prepared to ensure that our methods were extracting all available pigments.  $100\ \mu\text{L}$  of each sample were injected into a Varian ProStar high performance liquid chromatography (HPLC) system, and the pigments were analyzed using a reverse-phase protocol. The instrument was equipped with a Symmetry C8 column ( $3.5\ \mu\text{m}$  pore size), a photodiode array (PDA) and a programmable fluorescence detector. HPLC analyses followed the solvent protocol of Zapata *et al.* [2000], but using a flow rate of  $0.8\ \text{ml}\cdot\text{min}^{-1}$  and a total run time of 60 mins per sample. Pigments were identified by comparison with reference standards where available (i.e., chlorophylls *a* and *b*,  $\beta$ -carotene, diadinoxanthin, echinenone, fucoxanthin and lutein) or by comparison with absorption spectra from literature [Jeffrey *et al.*, 1997]. Where identifications were not confirmed with standards the pigment names are designated “-like” (e.g., pheophytin *a*-like). Sedimentary pigment concentrations were calibrated relative to organic matter (OM), and values presented here are expressed relative to organic matter content ( $\text{ng}\cdot\text{g}^{-1}$  OM). The mass ratio of chlorophylls to degradational pheopigments in each sample was calculated as an index of pigment diagenesis; these values are expressed as molar ratios.

[7] Organic matter content was estimated by loss-on-ignition (LOI) [Dean, 1974] to investigate changes in sediment content as well as to calibrate pigment concentrations. Sediment samples were taken throughout the core, weighed, and heated to  $550^{\circ}\text{C}$  for four hours. Mass differ-

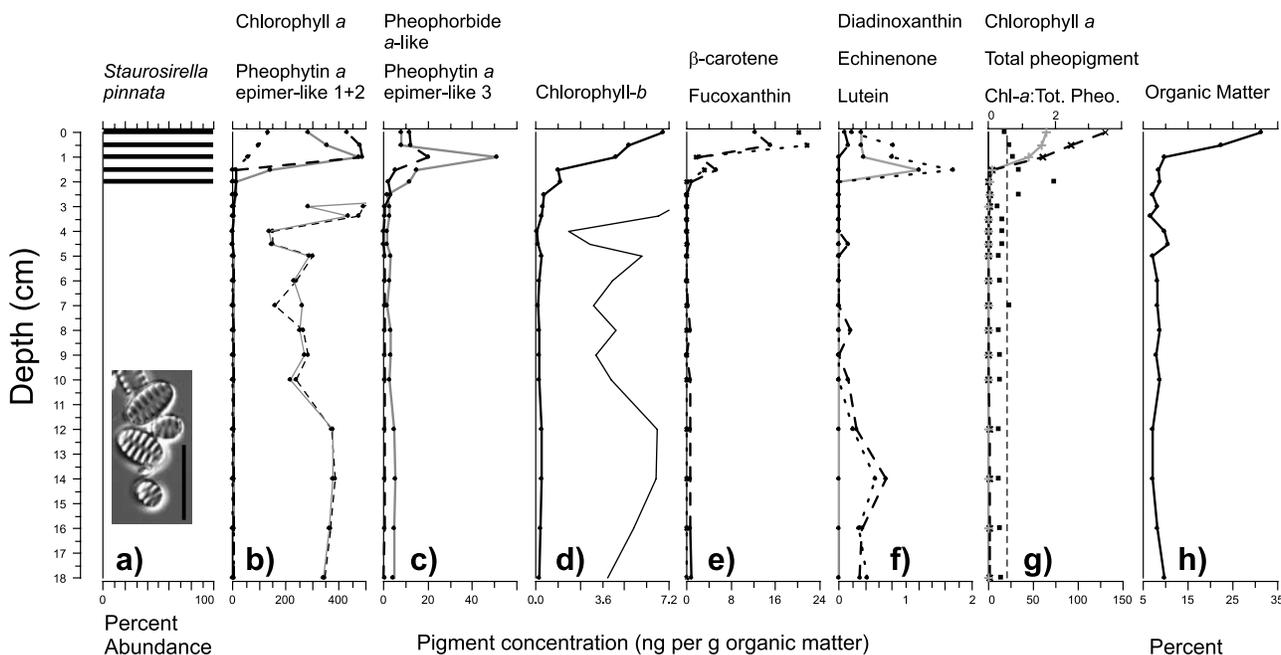
ences were calculated in order to determine the organic matter content of each sample [Dean, 1974]. Fourteen subsamples were also taken from the core and analyzed using alpha spectrometry at Mycore Scientific Inc. (Deep River, ON, Canada) to determine their  $^{210}\text{Pb}$  activities. Ten samples were analyzed for  $^{137}\text{Cs}$  by gamma spectrometry at the Paleocological Environmental Assessment and Research Laboratory (Queen’s University, Kingston, ON, Canada). One sample from the base of the core was dated with AMS  $^{14}\text{C}$  at the Beta Analytic Radiocarbon Laboratory (Miami, FL, USA). Radiocarbon ages were calibrated using the program CALIB (version 5.0) [Stuiver and Reimer, 1993] using both terrestrial and marine radiocarbon age calibration datasets [Reimer *et al.*, 2004; Hughen *et al.*, 2004], in order to encompass the maximum possible range of uncertainty given the age of the core.

### 3. Results

[8] Sediment organic matter was low throughout most of the core (6.5–10.5%) relative to the upper centimetre, where it increased to a maximum of 31% in the surface 0.5 cm (Figure 2). Only two diatom taxa were identified in the sediment core – *Staurosirella pinnata* (Ehrenberg) Williams & Round (Figure 2), and a single frustule of *Amphora copulata* (Kützing) Schoeman & Archibald. Diatoms were present only in the upper 2.5 cm of the stratigraphy, and were qualitatively much more abundant in the top 1.5 cm. During enumeration, diatom assemblages consisted of 100% *S. pinnata* valves in all intervals where diatoms were present (Figure 2).

[9] Changes in pigment concentrations were also striking. Concentrations of chlorophyll *a*, *b*, and degradation products were low below the 3 cm horizon (i.e.,  $<5.4\ \text{ng}\cdot\text{g}^{-1}$  OM; Figure 2). Some variation was measured in pigment concentrations in this section of the core, however these were dwarfed by subsequent increases and so are presented with an exaggerated secondary scale in Figure 2. Above the 3 cm horizon, an increase in pigment concentrations was observed that reached two orders of magnitude (i.e., max. chl-*a*  $474\ \text{ng}\cdot\text{g}^{-1}$  OM). As the organic content of sediments increased concurrently with pigment concentrations in the upper strata, absolute concentrations of most major pigments actually increased by three orders of magnitude prior to calibration relative to organic matter. Increases of this scale were measured for chlorophylls *a* and *b*, pheophytin *a*-like, and pheophorbide *a*-like pigments.  $\beta$ -carotene, echinenone and lutein also increased markedly above this horizon, while fucoxanthin and diadinoxanthin were identified only in sediments of the upper 2 cm. Mass ratios of chlorophylls to degradational pheopigments were relatively stable throughout the core, although there was a slight increase above the 3 cm mark, and a peak in the 2–2.5 cm sample (Figure 2g).

[10] Alpha spectrometry of sediment samples indicated that  $^{210}\text{Pb}$  activities were extremely low, ranging from 0.025 to  $0.031\ \text{Bq}\cdot\text{g}^{-1}$ , and that there was no increase in activities in the upper sediment horizons. Unsurprisingly, activities of  $^{137}\text{Cs}$  in the sediments were also very low. A weak  $^{137}\text{Cs}$  peak was present in the 0.25–0.5 cm core section, with an activity of  $0.21\ \text{dissolutions}\ \text{min}^{-1}\ \text{g}^{-1}$ . This was the only sample in which  $^{137}\text{Cs}$  activities exceeded the 99% confi-



**Figure 2.** Ward Hunt Lake diatom and pigment profiles. (a) Diatom stratigraphy. Inset Photomicrograph of valves of *Staurosirella pinnata* (scale bar =  $10\mu\text{m}$ ). (b) Chl-*a*, solid grey line; Pheophytin *a* epimer-like 1, dashed line; Pheophytin *a* epimer-like 2, dotted line. The lines at right represent the same pigments with horizontal scale exaggerated 80x to show trends dwarfed by the magnitude of the scale of recent changes. (c) Pheophorbide *a*-like, solid line; Pheophytin *a* epimer-like 3, dashed line. (d) Chl-*b*, with 10x exaggerated horizontal scale at right. (e)  $\beta$ -carotene, dashed line; Fucoxanthin, dotted line. (f) Diadinoxanthin, solid line; lutein, dashed line; echinenone, dotted line. (g) Total chl-*a* (grey line, crosses) and total pheopigments (dashed black line, x-symbols) expressed as molar concentrations and not corrected for organic matter content; black squares represent the molar ratio of chl-*a*:total pheopigment, and the vertical line the mean ratio. (h) Percent organic matter determined by LOI.

dence interval for the mean value (the detector background error). This suggests that the upper 0.5 cm of sediment contain the last 50 years of sediment deposition and that the rate of sediment accumulation is extremely low. Analysis of  $^{14}\text{C}$  indicated the base of the sediment core to be 8450 calibrated years BP (8299–8601), reinforcing the extreme paucity of sediment deposition.

#### 4. Discussion

[11] With perennial ice cover and a narrow moat of open water present for only several weeks per year, the modern aquatic environment of Ward Hunt Lake is extreme. However, our data suggest that current conditions may be considerably less severe than those in the past. The sharp increase in chlorophyll *a* and  $\beta$ -carotene concentrations suggests that there has been a marked recent increase in productivity in Ward Hunt Lake, while the decrease in pigment concentrations and the complete absence of diatoms below 2.5 cm raise the possibility that the lake may until recently have remained almost completely frozen to its base throughout the year. The changes that we observed in the sedimentary record are consistent with those expected with longer melt seasons in a warming climate. Similar stratigraphic profiles showing post-1850 changes have been recorded in sediment cores from around the circumpolar Arctic using diatoms, chironomids, chrysophytes and cladocera [Smol *et al.*, 2005], although such records from the Arctic using fossil pigments are rare [Leavitt *et al.*, 2003; Michelutti *et al.*, 2005].

[12] The striking increases in pigment concentrations included general indicators of algal standing crop (chl-*a*,  $\beta$ -carotene, see Guilizzoni *et al.* [1983]) as well as those indicative of more specific algal groups (fucoxanthin, diadinoxanthin, echinenone, lutein; see Leavitt and Hodgson [2001]), implying that these changes were caused by environmental factors and likely not by internal shifts in Ward Hunt Lake's algal dynamics. There was a slight increase in the mass ratio of chlorophylls to degradational pheopigments in the upper horizons of the core (i.e., mean above 2 cm, 0.70; overall mean, 0.55; Figure 2g). The peak in the 2–2.5 cm sample was likely caused by analytical differences, as very little sediment was available from this horizon for HPLC analysis. Several pheopigments were at or below the limits of detection of our PDA in this sample, and therefore the high Chl:pheopigment ratio, which resulted from an inordinately low pheopigment concentration (rather than a high Chl concentration), may result from the inability of our HPLC system to quantify the extremely low concentration of pheopigments in this sample. Given the roughly 500-fold increase in pigment concentrations and the similarity of the Chl:pheopigment mass ratios above and below this shift, it is highly likely that the observed increases represent changes in algal communities and are not the result of post-depositional alteration.

[13] *Staurosirella pinnata*, the only diatom enumerated from our core, is the most common taxon reported in paleolimnological studies from dominantly ice-covered Arctic sites [Douglas *et al.*, 1994; Michelutti *et al.*, 2003; Perren *et al.*, 2003] and its presence in Ward Hunt Lake was

therefore to be expected. However, to our knowledge, it has never before been recorded in such overwhelming relative abundances throughout a sedimentary sequence, an observation that is indicative of the extremity of conditions in Ward Hunt Lake. *Bonilla et al.* [2005] reported “*Navicula* spp.” in ice-marginal phytoplankton samples from Ward Hunt Lake, however we found no *Navicula* taxa in the sediments. Given the limited opportunity for the development of phytoplankton (due to ice cover), the overshadowing in our sediment samples of such taxa by benthic diatoms is unsurprising. *Hodgson et al.* [2005] observed a monospecific assemblage of *Stauriforma inermis* in an Antarctic lake during the Last Glacial Maximum, and inferred the lack of diversity to be indicative of perennial ice cover and colder conditions. The similarity of the diatom assemblage found in Ward Hunt Lake under such extreme perennial ice conditions may support this hypothesis.

[14] In Ward Hunt Lake, diatom valves appeared to be well-preserved, and there is no evidence to support that dissolution, rather than environmental change, was responsible for the disappearance of diatoms in the sedimentary record. Moreover, the synchronous appearance of diatoms, fucoxanthin and diadinoxanthin in the sedimentary record strongly suggests that the absence of diatoms below 2.5 cm does not result from preservation issues. These carotenoids were also identified from recent phytoplankton communities in Ward Hunt Lake, where they were associated with the dominant Chrysophyceae as well as with diatoms [*Bonilla et al.*, 2005]. A similar disappearance of diatoms was also observed from a lake near Alert, approximately 160 km to the east on Ellesmere Island [*Doubleday et al.*, 1995]. In a study from a second lake near Alert, diatoms (dominantly *S. pinnata*) were present throughout the sedimentary profile, however a modest increase in the number of species began in the 1920s and a pronounced shift toward higher diversity assemblages was observed only in the last 20 years [*Antoniades et al.*, 2005].

[15] Despite the absence of diatoms below the 2.5 cm horizon, the record of sedimentary pigments and changes in their concentrations indicate that some level of photosynthesis and algal growth was ongoing throughout the history of Ward Hunt Lake. Echinenone and lutein were identified throughout the core, and increased slightly in the bottom 6 cm. This suggests that the benthic communities of cyanobacteria and chlorophytes observed in the modern littoral zone of Ward Hunt Lake [*Bonilla et al.*, 2005] have been present in the lake throughout its history, and have varied in response to environmental change.

[16] The extremely low  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  activities measured in Ward Hunt Lake’s sediments are not unusual in high Arctic profiles, and levels are often too low to calculate reliable geochronologies. Given the thick, perennial ice cover (4 m), the extremely short melt season (approximately 8 weeks), and the low precipitation (mean 154 mm yr $^{-1}$ , Alert weather station, ~160 km to the east), it is plausible that there is little to no atmospheric deposition of unsupported  $^{210}\text{Pb}$  to the sediments of Ward Hunt Lake. The position of the  $^{137}\text{Cs}$  peak in the 0.25–0.5 cm interval implies that the last 50 years of sediment deposition are encompassed within the upper 0.5 cm. If roughly uniform sedimentation rates are assumed, the dramatic changes that we observed in the diatom and sedimentary pigment

assemblages would have occurred within the last two centuries. This is consistent with the extremely low sedimentation rate implied by the  $^{14}\text{C}$  age at the base of the core (8450 cal yr BP).

[17] There is a well-documented pattern of pronounced shifts in Arctic aquatic communities during the last 150 years [see *Smol et al.*, 2005], and recent paleolimnological changes recorded from nearby Alert, Ellesmere Island showed marked changes in the last 20 years [*Antoniades et al.*, 2005]. The changes that occurred in Ward Hunt Lake within the last 200 years are consistent with this overall pattern of change, although the onset of biotic change in Ward Hunt Lake predates that observed from Alert. Furthermore, the period of relative stability throughout much of our sediment core prior to the diatom and pigment shifts suggests that Ward Hunt Lake’s aquatic biota have been affected more by environmental change during the last two centuries than at any point during the preceding eight millennia.

[18] The increase in pigment concentrations in the Ward Hunt Lake sediments predated the appearance of diatoms in the record. This indicates that changes in algal communities occurred before they were recorded in the diatom stratigraphy, and suggests that fossil pigments may provide important, sensitive records of Arctic limnological change especially in the absence of diatoms. However, the shifts in both diatom and pigment records were similarly striking, and suggest marked ecosystem shifts in Ward Hunt Lake in the last two centuries. Due to the extremity of latitude, ice and climate conditions of Ward Hunt Lake, this implies that even the most ice-bound aquatic ecosystems in the northern hemisphere have already been strongly impacted by recent environmental change.

[19] **Acknowledgments.** This research was funded by Natural Sciences and Engineering Research Council of Canada (NSERC), the Networks of Centres of Excellence program ArcticNet, and the Canada Research Chair program. Thanks to John Smol and Chris Grooms for expediting the  $^{137}\text{Cs}$  analyses. We are grateful to the Polar Continental Shelf Project (PCSP) for logistical support. This is PCSP contribution 03107. We also thank two anonymous reviewers whose comments greatly improved this manuscript.

## References

- Antoniades, D., M. S. V. Douglas, and J. P. Smol (2005), Quantitative estimates of recent environmental changes in the Canadian High Arctic inferred from diatoms in lake and pond sediments, *J. Paleolimnol.*, **33**, 349–360.
- Arctic Climate Impact Assessment (2005), *Arctic Climate Impact Assessment Scientific Report*, Cambridge Univ. Press, Cambridge, U. K.
- Bonilla, S., V. Villeneuve, and W. F. Vincent (2005), Benthic and planktonic algal communities in a high Arctic lake: Pigment structure and contrasting responses to nutrient enrichment, *J. Phycol.*, **41**, 1120–1130.
- Dean, W. E. (1974), Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods, *J. Sediment. Petrol.*, **44**, 242–248.
- Doubleday, N. C., M. S. V. Douglas, and J. P. Smol (1995), Paleoenvironmental studies of black carbon deposition in the High Arctic: A case study from Northern Ellesmere Island, *Sci. Total Environ.*, **160**(161), 661–668.
- Douglas, M. S. V., and J. P. Smol (1999), Freshwater diatoms as indicators of environmental change in the High Arctic, in *The Diatoms: Applications for the Environmental and Earth Sciences*, edited by E. F. Stoermer and J. P. Smol, pp. 227–244, Cambridge Univ. Press, Cambridge, U. K.
- Douglas, M. S. V., J. P. Smol, and W. Blake Jr. (1994), Marked post-18th century environmental change in high-Arctic ecosystems, *Science*, **266**, 416–419.
- Guilizzoni, P., G. Bonomi, G. Galanti, and D. Ruggiu (1983), Relationship between sedimentary pigments and primary production: Evidence from core analyses of twelve Italian lakes, *Hydrobiologia*, **103**, 103–106.

- Hodgson, D. A., E. Verleyen, K. Sabbe, A. H. Squier, B. J. Keely, M. J. Leng, K. M. Saunders, and W. Vyverman (2005), Late Quaternary climate-driven environmental change in the Larsemann Hills, East Antarctica, multi-proxy evidence from a lake sediment core, *Quat. Res.*, *64*, 83–99.
- Holland, M. M., C. M. Bitz, and B. Tremblay (2006), Future abrupt reductions in the summer Arctic sea ice, *Geophys. Res. Lett.*, *33*, L23503, doi:10.1029/2006GL028024.
- Hughen, K. A., et al. (2004), Marine04 Marine radiocarbon age calibration, 26–0 ka BP, *Radiocarbon*, *46*, 1059–1086.
- Jeffrey, S. W., R. F. C. Mantoura, and S. W. Wright (Eds.) (1997), *Phytoplankton Pigments in Oceanography*, 661 pp., UNESCO, Paris.
- Leavitt, P., and D. Hodgson (2001), Sedimentary pigments, in *Tracking Environmental Change Using Lake Sediments*, vol. 3, *Terrestrial, Algal and Siliceous Indicators*, edited by J. P. Smol, H. J. B. Birks, and W. M. Last, pp. 295–325, Kluwer, Dordrecht, Netherlands.
- Leavitt, P. R., D. A. Hodgson, and R. Pienitz (2003), Past UVR environments and impacts in lakes, in *UV Effects in Aquatic Organisms and Ecosystems, Comprehensive Ser. Photochem. Photobiol.*, vol. 1, edited by E. W. Helbling and H. Zagarese, pp. 509–545, R. Soc. of Chem., Cambridge, U. K.
- McCarthy, J. J., O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White (Eds.) (2001), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, 1032 pp., Cambridge Univ. Press, Cambridge, U. K.
- Michelutti, N., M. S. V. Douglas, and J. P. Smol (2003), Diatom response to recent climatic change in a high arctic lake (Char Lake Cornwallis Island, Nunavut), *Global Planet. Change*, *38*, 257–271.
- Michelutti, N., A. P. Wolfe, R. D. Vinebrooke, B. Rivard, and J. P. Briner (2005), Recent primary production increases in arctic lakes, *Geophys. Res. Lett.*, *32*, L19715, doi:10.1029/2005GL023693.
- Mueller, D. R., W. F. Vincent, and M. O. Jeffries (2003), Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake, *Geophys. Res. Lett.*, *30*(20), 2031, doi:10.1029/2003GL017931.
- Perren, B. B., R. S. Bradley, and P. Francus (2003), Rapid lacustrine response to recent high arctic warming: A diatom record from Sawtooth Lake, Ellesmere Island, Nunavut, *Arct. Antarct. Alp. Res.*, *35*, 271–278.
- Reimer, P. J., et al. (2004), IntCal04 Terrestrial radiocarbon age calibration, 26–0 ka BP, *Radiocarbon*, *46*, 1029–1058.
- Smol, J. P., et al. (2005), Climate-driven regime shifts in the biological communities of arctic lakes, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 4397–4402.
- Stuiver, M., and P. J. Reimer (1993), Extended <sup>14</sup>C database and revised CALIB radiocarbon calibration program, *Radiocarbon*, *35*, 215–230.
- Villeneuve, V., W. F. Vincent, and J. Komárek (2001), Community structure and microhabitat characteristics of cyanobacterial mats in an extreme high Arctic environment: Ward Hunt Lake, *Nova Hedwigia*, *123*, 199–224.
- Zapata, M., F. Rodriguez, and J. L. Garrido (2000), Separation of chlorophylls and carotenoids from marine phytoplankton: A new HPLC method using a reversed phase C8 column and pyridine containing mobile phases, *Mar. Ecol. Prog. Ser.*, *195*, 29–45.
- 
- D. Andersen, Center for the Study of Life in the Universe, Search for Extraterrestrial Intelligence Institute, 55 N. Whisman Road, Mountain View, CA 94043, USA.
- D. Antoniadès, R. Pienitz, and W. F. Vincent, Centre d'Études Nordiques, Université Laval, Québec, QC, Canada G1K 7P4. (dermot.antoniadès@cen.ulaval.ca)
- C. Crawley, Department of Geology, University of Toronto, 22 Russell Street, Toronto, ON, Canada M5S 3B1.
- P. T. Doran, Department of Earth and Environmental Sciences, University of Illinois at Chicago, 845 W. Taylor Street, MC 186, Chicago, IL 60607, USA.
- M. S. V. Douglas, Canadian Circumpolar Institute, Edmonton, AB, Canada T6G 0H1.
- I. Hawes, National Institute of Water and Atmospheric Research, P.O. Box 8602, Christchurch, New Zealand.
- W. Pollard, Department of Geography, McGill University, Montreal, QC, Canada H3A 2K6.