



Inferring Past Climatic Changes in Canada Using Paleolimnological Techniques

John P. Smol, Brian F. Cumming,
Marianne S. V. Douglas¹ and
Reinhard Pienitz²

*Paleoecological Environmental
Assessment and Research Lab
Department of Biology
Queen's University
Kingston, Ontario K7L 3N6*

SUMMARY

Paleolimnological approaches have considerable potential for providing paleoclimate proxy data. Indicators such as diatom valves, chrysophyte scales and cysts, and chironomid head capsules may provide both direct and indirect inferences of lakewater temperature and related variables. For example, quantitative transfer functions are now available for certain regions that can infer lakewater temperature from chironomids and diatoms. Meanwhile, the paleolimnological record from closed-basin lakes in arid and semi-arid regions of western Canada can be used to track past climatic/hydrologic changes, as transfer functions have been developed for diatom, chrysophyte and chironomid indicators that can provide quantitative inferences of past lakewater salinity. Other climate-related variables that can be tracked include dissolved organic carbon concentrations that can be related to past changes in arctic treeline, and past ice-cover in high-arctic regions.

¹ presently Department of Geology
University of Toronto, 22 Russell Street
Toronto, Ontario M5S 3B1

² presently Centre d'études nordiques et
dép. de géographie
Université Laval
Sainte-Foy, Québec G1K 7P4

RÉSUMÉ

L'approche paléolimnologique a du grand potentiel pour fournir des données paléo-écologiques quantitatives. Des indicateurs comme les valves de diatomées, les écailles et kystes de chrysophycées, ainsi que les parties chitineuses de chironomides peuvent fournir non seulement des inférences directs, mais aussi indirects de la température de l'eau ainsi que d'autres variables reliés à la température. Par exemple, des fonctions de transfert quantitatives sont maintenant disponibles pour certaines régions qui peuvent être utilisées pour reconstituer la paléotempérature des lacs à partir de fossiles de chironomides et de diatomées. En même temps, les données paléolimnologiques de lacs salés de régions arides et semi-arides de l'ouest du Canada nous permettent de reconstituer les changements climatiques et hydrologiques survenus dans le passé. Ces derniers sont préservés de façon indirecte dans les séquences sédimentologiques lacustres et peuvent être identifiés à partir de variations de la composition spécifique des assemblages fossiles causés par les fluctuations de paléosalinité. Des fonctions de transfert ont été développées pour des reconstitutions quantitatives de paléosalinité à partir de fossiles de diatomées, chrysophycées et chironomides. De plus, la teneur en carbone organique dissous (COD) de l'eau représente une autre variable influencée par les changements de la limite des arbres et la couverture de glace en région arctique, et qui est donc utile pour des reconstitutions indirectes du paléoclimat.

INTRODUCTION

The integrative science of paleolimnology has experienced considerable advances in recent years, with important developments in the amount and quality of environmental information that can be retrieved from sedimentary profiles (for example, see reviews by Charles *et al.*, 1994; Charles and Smol, 1994; Dixit *et al.*, 1992; Smol, 1987, 1990a,b, 1992, 1995; Anderson, 1993). Much of this progress has been related to applied aspects of lake management, such as studies of lake acidification (*e.g.*, Battarbee and Renberg, 1990; Charles and Smol, 1990), but many of these advancements can be readily transferred to studies of past climatic change (*e.g.*, Smol *et al.*, 1991).

Lake sediments preserve a large suite of biological indicators (see Warner, 1990 for a compilation of many of the indicators that are especially relevant to Canadian

studies), many of which can be used to assist interpretations of past climates (Smol *et al.*, 1991). The short generation times of many limnological indicators may make them especially useful in high-resolution paleoclimatic studies.

Although a large number of paleolimnological indicators can potentially be used to infer climatic trends, we restrict our present discussion to diatom valves, chrysophyte scales and cysts, and chironomid head capsules. Other biological indicators, such as ostracods, also hold considerable potential for paleolimnological studies, but these indicators are discussed elsewhere (*e.g.*, Forester, 1987; De Deckker *et al.*, 1988; Delorme, 1989; Smith, 1993).

Much of the paleolimnological literature dealing with climatic change is published in biological and limnological journals. Consequently, an overall goal of this short review is to summarize these diverse studies, focussing on Canadian applications, so that this information may be more readily available to the geoscience community.

CALIBRATION OR TRAINING SETS

Before biological assemblages can be used to infer environmental conditions, the limnological variables that are highly correlated to species distributions must be estimated. The use of surface sediment "calibration" or "training" sets is a powerful method for determining these species-environmental relationships (reviewed in Charles and Smol, 1994). In summary, the basic approach is to choose a suite of study lakes that span the limnological gradients of interest. From each study lake, the biological remains preserved in the lakes' surface sediments (*e.g.*, usually the top 1 cm, which represents the last few years of sediment accumulation) are identified and enumerated. These sediments provide an integrated sample, in both space and time, of the taxa that have accumulated over the previous few years. From each study lake, environmental data consisting of present-day physical, chemical and biological variables that are thought to be ecologically important are measured. A number of statistical techniques can then be used to determine which environmental variables are most highly related to the assemblages under consideration. Variables that account for a high and significant proportion of variation in the species data may result in strong reconstruction models. However, the applicability of inference

models should be judged on their appropriateness (*e.g.*, Birks *et al.*, 1990; Hall and Smol, 1993) and predictive ability.

There are several approaches that can be used to develop quantitative inference models ranging from fairly simple to very complex methods. All these techniques involve two steps: 1. the regression step where taxon parameters (*e.g.*, environmental optima, tolerances to particular environmental variables) are estimated based on the distribution of taxa in the "training" set; and 2. a calibration step where the environmental variables are predicted from the species composition. In order to avoid the circularity inherent in the above approach, computer intensive resampling procedures such as jackknifing and bootstrapping and/or independent val-

idation datasets are used to determine predictive abilities associated with the inference models (reviewed in Charles and Smol, 1994).

PALEOCLIMATIC INFERENCES

Our work on paleoclimatic reconstructions in Canada can be broadly divided into four major limnological regions (Fig. 1): temperate dilute lakes; semi-arid region lakes; northern boreal forest-tree-line lakes; and high-arctic lakes and ponds. In each of these regions, different environmental constraints determine the composition of the algal and invertebrate communities. Fortunately, many of these environmental variables are climate-related, and so paleolimnological investigations can be used to interpret past climatic conditions. Al-

though there is some overlap between studies, we treat each of these regions separately.

In general, two major types of inferences can be used: direct inferences (using the temperature optima and tolerances of various taxa); and indirect inferences (relying on the interpretation of phenomena that are indirectly related to climate, such as habitat alteration, chemical assimilation, *etc.*).

Temperate Dilute Lakes

In some ways, the most challenging sites for Canadian paleolimnological reconstructions of climate may be the many dilute lakes that characterize much of south-eastern Canada, as well as other regions (Fig. 1). Climate-related environmental gradients tend to

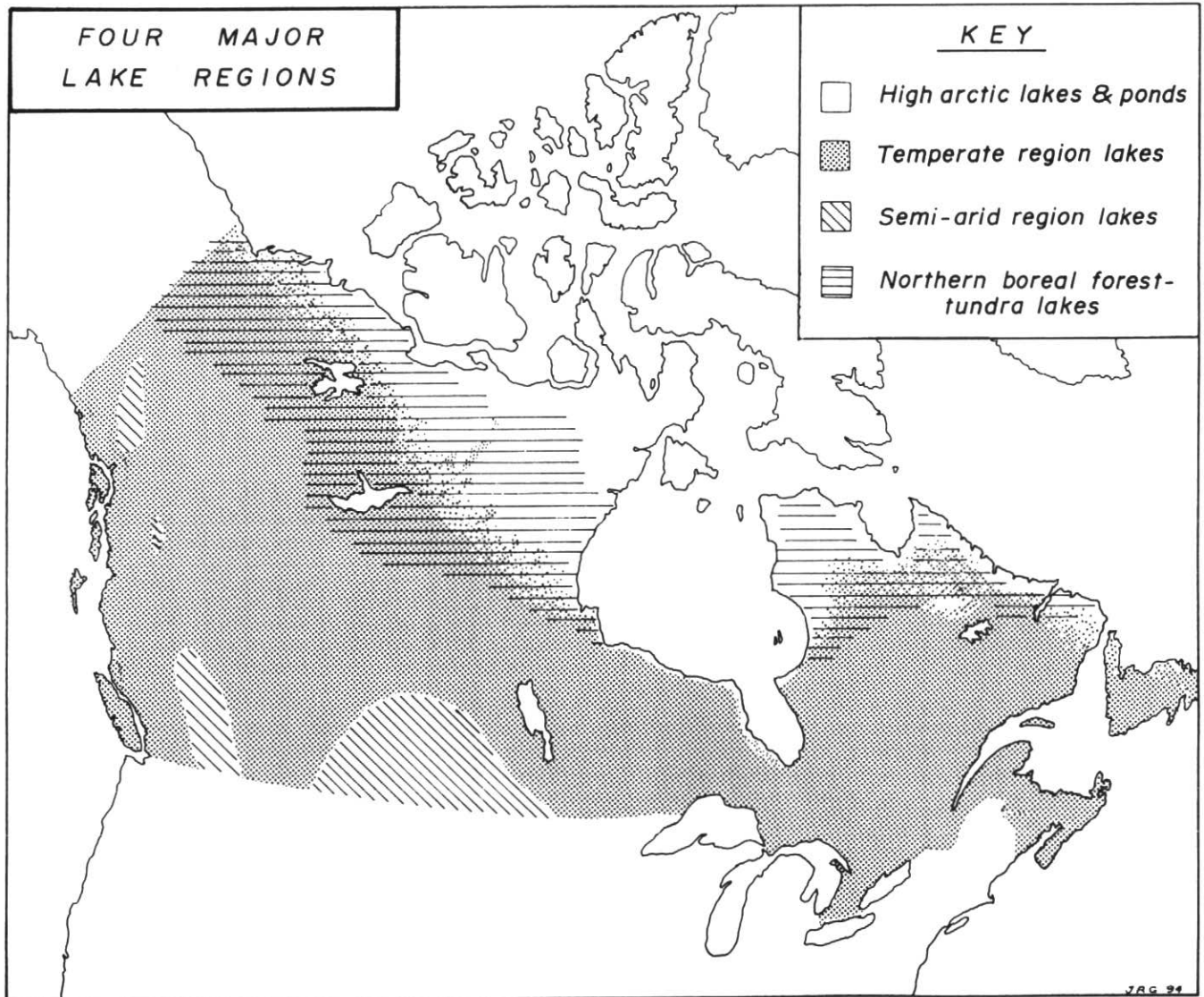


Figure 1 Map showing the approximate boundaries of the four broad lake regions discussed in this paper. There is considerable overlap between regions.

be shorter in these dilute lakes (at least based on the work completed to date). For some paleo-indicators, such as chironomid (midge fly larvae) head capsules, statistical relationships (*i.e.*, transfer functions) that directly relate temperature to taxa distributions have been developed (Walker *et al.*, 1991a), although this has elicited some controversy (*e.g.*, Hann *et al.*, 1992; Walker *et al.*, 1992). Chironomid-based reconstructions of past lake temperatures have been made, with a focus on the Younger Dryas interval, for lakes in the Maritimes (*e.g.*, Walker *et al.*, 1991b; Wilson *et al.*, 1993; Levesque *et al.*, 1993).

Other limnetic indicators, such as diatoms, have also been studied with respect to the Younger Dryas interval (*e.g.*, Rawlence, 1988, 1992; Rawlence and Senior, 1988; Wilson *et al.*, 1993; Wolfe and Butler, 1994). Although changes in species composition have been noted, direct inferences of temperature are as yet unavailable, and inferences are qualitative and tentative. It is generally implied that organisms such as diatoms are responding to climate-related variables in these dilute lakes (*e.g.*, stratification patterns, ice-cover, *etc.*).

Chrysophyte indicators (*i.e.*, siliceous body scales and bristles, as well as chrysophyte resting stages, or stomatocysts), although not yet fully exploited in these studies, may provide additional data. For example, the siliceous scales of chrysophytes belonging to the Synurophyceae and some Chrysophyceae, are species-specific and are well preserved in lake sediments, and species may potentially be used to infer lakewater temperatures (Siver, 1991).

Semi-Arid Region Lakes

Closed-basin saline lakes, such as those that characterize much of the western plains and inter-montane regions of British Columbia, potentially contain high-resolution records of past climates and hydrological regimes. In closed-basin lakes, brine concentrations and lake levels are governed, to a large extent, by the balance between precipitation and evaporation (Gasse, 1994). Because lakewater salinity concentration and composition are often highly related to the distribution of organisms, past climatic/hydrologic conditions can be reconstructed indirectly

from the algal and invertebrate micro- and macrofossils available from the paleolimnological record. Biological techniques have been developed to infer past changes in lakewater salinity and associated changes in water level in North America (*e.g.*, Radle *et al.*, 1989; Fritz 1990; Fritz *et al.*, 1991, 1993, 1994; Hickman and Schweger 1993). For example, Fritz (1990) showed that salinity reconstructions from diatom assemblages faithfully tracked post-1900 measured variations in lake-water salinity from Devils Lake, North Dakota. Recent advances include quantitative salinity inferences based on the species composition of diatoms (*e.g.*, Fritz *et al.*, 1991; Cumming and Smol 1993; Wilson *et al.*, 1994), chrysophyte cysts and scales (Cumming *et al.*, 1993; Zeeb and Smol, *in press*), and chironomids (Walker *et al.*, 1995). Efforts are currently underway to develop international inference models of salinity and other variables (*e.g.*, Juggins *et al.*, 1994). Studies that combine inferences from multiple proxies should provide the most robust reconstructions.

Northern Boreal Forest-Treeline Lakes

Paleoclimatic studies in high-latitude regions are receiving considerable attention (*e.g.*, Andrews and Brubaker, 1994), as long-term instrumental data are generally lacking, and high-latitude regions are believed to be especially sensitive to climatic change. The use of algal and invertebrate taxa as paleoclimatic indicators is of special interest in high latitudes because other paleoecological methods are, at times, of limited usefulness in these environments (*e.g.*, low diversity of plants, *etc.*). One such region receiving considerable attention is the vast northern boreal forest of Canada, and especially lakes in the vicinity of the treeline. Reconstructing the past position of treeline has important paleoclimatic implications, as tree-line roughly follows the mean summer position of the Arctic Front (Bryson, 1966). In addition, lakes and ponds located along latitudinal transects that include steep climatic and vegetational gradients show some dramatic changes in water chemistry across treeline (Pienitz, 1993). Pollen is, of course, useful in treeline reconstructions, but paleoclimatic reconstructions based on several different types of indicators are more robust (MacDonald *et al.*, 1993).

The results of our diatom work in the western subarctic have been encouraging, as we believe we can reconstruct lakewater temperature and other climate-related variables. Two major gradients appear to emerge: the concentration of lakewater dissolved organic carbon (DOC, which is related to the position of treeline), and surface-water temperature.

Pienitz and Smol (1993), working on a surface-sediment lake calibration set across the boreal forest-tundra ecotone near Yellowknife, found that dissolved inorganic carbon (DIC) and DOC concentrations in lakewater accounted for additional statistically significant proportions of the variation in the distribution of the diatoms. Weighted-averaging regression and calibration were used to develop transfer functions relating diatom distributions to measured DIC and DOC concentrations. Because lakewater DOC closely tracks the abundance of coniferous trees in a drainage basin, diatom-based reconstructions of DOC in dated sediment cores can be used to infer the past position of northern treeline (Pienitz, 1993).

A second surface-sediment calibration set that spanned 59 sites between Whitehorse and the Tuktoyaktuk Peninsula revealed that lake depth and summer surface-water temperature were the two environmental variables that accounted for most of the variance in the diatom data (Pienitz *et al.*, 1995). Using these data, transfer functions were developed to infer lakewater temperatures from diatoms. The inclusion of an altitudinal gradient in this calibration set of lakes revealed some similarities between alpine lakes and those located in arctic tundra regions, indicating the potential usefulness of diatoms as paleoclimate proxies in alpine regions (Pienitz, 1993). Similar approaches may prove useful in other regions with strong elevation gradients.

We are now completing several other calibration sets for different subarctic regions using diatoms, as well as other algal and invertebrate indicators. The results are encouraging and suggest that many of these inference models can be used in different geographic regions (*e.g.*, Lapland, Pienitz *et al.*, *in press*; Norman Wells, Pienitz and Smol, *unpub. data*; Siberia, Laing *et al.*, *unpub. data*).

Analogous to the approach described in the above section on semi-arid region

lakes, changes in lake level can be tracked in closed-basin lakes located in high latitudes. Such lakes are believed to be rare in arctic regions (Pienitz *et al.*, 1992). Analysis of a long sediment record from one such saline lake in the central Yukon Territory revealed shifts in diatom assemblage composition from freshwater to saline taxa (Pienitz *et al.*, unpub. data), which may be related to short-lived climatic and related hydrological changes. Detailed paleoclimate inferences in this region are especially important, as the anticipated greenhouse warming is expected to be enhanced at high latitudes.

High-arctic Lakes and Ponds

High-arctic regions have been consistently identified as important regions for paleoclimatic reconstructions, but paleoclimatic data are notoriously difficult to attain in these extreme environments, as many of the standard paleoclimatic approaches are fraught with difficulties (e.g., the very low numbers of flowering plants, *etc.*). Also, given the absence of trees, other variables, such as DOC in the lakewater, will not have a significant effect on diatom distributions. Nonetheless, high-arctic lakes and ponds provide important opportunities and challenges to paleolimnologists. Thus far, most climatic inferences that paleolimnologists proposed from high-arctic regions have been more qualitative than the models presently developed for more southerly regions.

In deeper high- and mid-arctic sites, the extent of snow and ice-cover on a lake may have profound influences on the distribution of algae and invertebrates (Smol, 1983, 1988). For example, during cold years, some lakes may remain permanently ice-covered, or have only a very small "moat" of open water along their perimeters (Smol, 1988). In such cases, shallow water and aerophilic (*i.e.*, those organisms that can survive periodic drying) taxa are relatively more abundant. During warmer periods, more ice will melt, and a larger proportion of the lake will be more hospitable to growth. For example, algal taxa characteristic of deeper-water or planktonic habitats may be more abundant. Much of this work was developed from studies on Ellesmere Island, but similar patterns may occur on more southern locations, such as Baffin Island (Lemmen *et al.*, 1988; Wolfe, 1994).

In addition to affecting species com-

position, the extent of ice cover will also influence overall algal production, which can provide additional paleoclimatic inferences (Smol, 1983, 1988; Williams, 1990). Total siliceous algal production can be estimated using biogenic silica analyses as well.

A characteristic feature of most arctic regions is the abundance of shallow ponds. In many respects, the limnological characteristics of these shallow ponds are different from the deep lakes (Douglas and Smol, 1994), and the ponds support characteristic diatom (Douglas and Smol, 1993, 1995a) and chrysophyte cyst (Duff *et al.*, 1992; Douglas and Smol, 1995b) floras. Despite their shallow nature, several independent lines of evidence clearly show that their sediments are not markedly disturbed by turbation processes (Douglas, 1993), and that these ponds may be especially sensitive bellwethers of environmental change. For example, Douglas *et al.* (1994) completed paleolimnological reconstructions of several ponds on Cape Herschel, Ellesmere Island, which showed that diatom floras were relatively stable over several millennia, but then experienced unparalleled changes beginning in the 19th century. These changes would be consistent with an interpretation of recent climatic warming (e.g., more diverse diatom floras, increases in moss epiphytes, *etc.*). Pondwater pH and conductivity, as well as other chemical variables, may also be tracking climatic changes (Douglas and Smol, unpub. data), and diatoms and other indicators can potentially be used to infer these variables as well.

Some of the paleolimnological techniques we applied to lake and pond sediments can also be used to help interpret arctic fossil peat deposits. For example, Brown *et al.* (1994) described the diatoms, chrysophyte cysts, and siliceous protozoan plates preserved in a high-arctic peat deposit on an island near the northwestern coast of Greenland. The peat accumulated over the approximate period of 6 300 to 4 000 BP. The siliceous microfossils exhibited interesting stratigraphic changes that could potentially be indicating climate-related variables, and could be used to supplement paleo-peat analyses (Brown *et al.*, 1994).

CONCLUSIONS

We have limited our discussion pri-

marily to paleolimnological studies that Paleocological Environmental Assessment and Research Lab (PEARL) scientists have been involved with. Many of these studies are ongoing, but the opportunities are many, and the initial results are promising. Clearly, more work is required on defining the climate-related environmental optima and tolerances of the many indicators available. To this end, we are currently completing many surface sediment calibration sets across Canada and other parts of the world (e.g., Siberia). Combined profiles, using proxy information from many sources of paleoclimate data, will undoubtedly result in the most robust inferences of past climate. Such data will be essential to define natural variability, to distinguish long-term trends from short-term noise, and to provide much needed data for model evaluations (e.g., GCM hindcasts).

ACKNOWLEDGEMENTS

This work has largely been supported by various research and strategic grants from the Natural Sciences and Engineering Research Council of Canada. In addition, research in the Arctic was made possible by logistic support provided by the Polar Continental Shelf Project, Northern Studies Training Program, and the Geological Survey of Canada (GSC). Much of our early work on Cape Herschel would not have been possible without the support of Dr. W. Blake, Jr. (GSC).

REFERENCES

- Anderson, N.J., 1993, Natural versus anthropogenic change in lakes: The role of the sediment record: *Trends in Ecology and Evolution*, v. 10, p. 356-361.
- Andrews, J. and Brubaker, L., 1994, The Paleoclimates of Arctic Lakes and Estuaries (PALE): Goals and rationale of an international research program: *Journal of Paleolimnology*, v. 10, p. 163-166.
- Battarbee, R.W. and Renberg, I., 1990, The Surface Water Acidification Project (SWAP) palaeolimnology programme: *Philosophical Transactions of the Royal Society of London, B.*, v. 327, p. 227-232.
- Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C., and ter Braak, C.J.F., 1990, Diatoms and pH reconstructions: *Philosophical Transactions of the Royal Society of London, B.*, v. 327, p. 301-311.
- Brown, K. M., Douglas, M.S.V., and Smol, J.P., 1994, Siliceous microfossils in a Holocene, high arctic peat deposit: *Canadian Journal of Botany*, v. 72, p. 208-216.

- Bryson, R.A., 1966, Air masses, streamlines, and the boreal forest: *Geographical Bulletin*, v. 8, p. 228-269.
- Charles, D.F. and Smol, J.P., 1990, The PIRLA II project: regional assessment of lake acidification trends: *Verhandlungen der Internationalen Vereinigung von Limnologen*, v. 24, p. 474-480.
- Charles, D.F. and Smol, J.P., 1994, Long-term chemical changes in lakes: Quantitative inferences using biotic remains in the sediment record, in Baker, L., ed., *Environmental Chemistry of Lakes and Reservoirs: Advances in Chemistry, Series 237*, American Chemical Society, Washington D.C., p. 3-31.
- Charles, D.F., Smol, J.P. and Engstrom, D.R., 1994, Paleolimnological approaches to biomonitoring, in Loeb, S. and Spacie, D., eds., *Biological Monitoring of Aquatic Systems*: Lewis Press, Ann Arbor, p. 233-293.
- Cumming, B.F. and Smol, J.P., 1993, Development of diatom-based salinity models for paleoclimatic research from lakes in British Columbia (Canada): *Hydrobiologia*, v. 269/270, p. 179-196.
- Cumming, B.F., Wilson, S.E. and Smol, J.P., 1993, Paleolimnological potential of chrysophyte cysts and scales, and sponge spicules as indicators of lakewater salinity: *International Journal of Salt Lake Research*, v. 2(1), p. 87-92.
- De Deckker, P., Colin, J.P. and Peypouquet, J.-P., eds., 1988, *Ostracoda in the Earth Sciences*: Elsevier, Amsterdam, 302 p.
- Delorme, L. D., 1989, Methods in Quaternary ecology: Freshwater ostracodes: *Geoscience Canada*, v. 16, p. 85-90.
- Dixit, S.S., Smol, J.P., Kingston, J.C. and Charles, D.F., 1992, Diatoms: Powerful indicators of environmental change: *Environmental Science and Technology*, v. 26, p. 22-33.
- Douglas, M.S.V., 1993, Diatom ecology and paleolimnology of high arctic ponds: Ph.D. thesis, Queen's University, 164 p.
- Douglas, M.S.V. and Smol, J.P., 1993, Freshwater diatoms from high arctic ponds (Cape Herschel, Ellesmere Island, N.W.T.): *Nova Hedwigia*, v. 57, p. 511-552.
- Douglas, M.S.V. and Smol, J.P., 1994, Limnology of high arctic ponds (Cape Herschel, Ellesmere Island, N.W.T.): *Archiv für Hydrobiologie*, v. 131, p. 401-434.
- Douglas, M.S.V. and Smol, J.P., 1995a, Periphytic diatom assemblages from high Arctic ponds: *Journal of Phycology*, v. 31, p. 60-69.
- Douglas, M.S.V. and Smol, J.P., 1995b, Paleolimnological significance of observed distribution patterns of chrysophyte cysts in arctic pond environments: *Journal of Paleolimnology*, v. 13, p. 79-83.
- Douglas, M.S.V., Smol, J.P. and Blake, W., Jr., 1994, Marked post-18th century environmental change in high arctic ecosystems: *Science*, v. 266, p. 416-419.
- Duff, K., Douglas, M.S.V. and Smol, J.P., 1992, Chrysophyte cysts from 36 high arctic ponds: *Nordic Journal of Botany*, v. 12, p. 471-499.
- Forester, R.M., 1987, Late Quaternary paleoclimate records from lacustrine ostracodes, in Ruddiman, W.F. and Wright, Jr., H.E., eds., *North America and adjacent oceans during the last deglaciation*: Geological Society of America, The Geology of North America, p. 261-276.
- Fritz, S.C., 1990, Twentieth-century salinity and water-level fluctuations in Devils Lake, North Dakota: Test of a diatom-based transfer function: *Limnology and Oceanography*, v. 35, p. 1771-1781.
- Fritz, S.C., Juggins, S. and Battarbee, R.W., 1993, Diatom assemblages and ionic characterization of freshwater and saline lakes of the northern Great Plains, N.A.: a tool for reconstructing past salinity and climate fluctuations: *Canadian Journal of Fisheries and Aquatic Sciences*, v. 50, p. 1844-1856.
- Fritz, S.C., Engstrom, D.R. and Haskell, B.J., 1994, "Little Ice Age" aridity in the North American Great Plains: a high-resolution reconstruction of salinity fluctuations from Devils Lake, North Dakota, USA: *The Holocene*, v. 4, p. 69-73.
- Fritz, S.C., Juggins, S., Battarbee, R.W. and Engstrom, D.R., 1991, Reconstruction of past changes in salinity and climate using a diatom-based transfer function: *Nature*, v. 352, p. 706-708.
- Gasse, F., 1994, Lacustrine diatoms for reconstructing past hydrology and climate, in Duplessy, J.-C. and Spyridakis, M.-T., eds., *Long-Term Climatic Variations*: NATO ASI Series, v. 122, p. 335-369.
- Hall, R.I. and Smol, J.P., 1993, A weighted-averaging regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes: *Freshwater Biology*, v. 27, p. 417-434.
- Hann, B.J., Warner, B. and Warwick, W., 1992, Aquatic insects and climate change: A comment on Walker *et al.* (1991): *Canadian Journal of Fisheries and Aquatic Sciences*, v. 49, p. 1274-1276.
- Hickman, M. and Schweger, C., 1993, Late glacial-early Holocene paleosalinity in Alberta, Canada - climate implications: *Journal of Paleolimnology*, v. 8, p. 149-161.
- Juggins, S., Battarbee, R., Fritz, S. and Gasse, F., 1994, The CASPIA Project: diatoms, salt lakes and environmental change: *Journal of Paleolimnology*, v. 12, p. 191-196.
- Lemmen, D.S., Gilbert, R., Smol, J.P. and Hall, R.I., 1988, Holocene sedimentation in glacial Tasikutaq Lake, Baffin Island: *Canadian Journal of Earth Sciences*, v. 25, p. 810-823.
- Levesque, A.J., Mayle, F.E., Walker, I.R. and Cwynar, L.C., 1993, A previously unrecognized late-glacial cold event in eastern North America: *Nature*, v. 361, p. 623-626.
- MacDonald, G., Edwards, T., Moser, K., Pienitz, R. and Smol, J.P., 1993, Rapid response of treeline vegetation and lakes to past climate warming: *Nature*, v. 361, p. 243-246.
- Pienitz, R., 1993, Paleoclimate proxy data inferred from freshwater diatoms from the Yukon and the Northwest Territories: Ph.D. thesis, Queen's University, 218 p.
- Pienitz, R. and Smol, J.P., 1993, Diatom assemblages and their relationship to environmental variables in lakes near Yellowknife (N.W.T., Canada): *Hydrobiologia*, v. 269/270, p. 391-404.
- Pienitz, R., Walker, I. R., Zeeb, B.A., Smol, J.P. and Leavitt, P.R., 1992, Biomonitoring past salinity changes in an athalassic sub-arctic lake: *International Journal of Salt Lake Research*, v. 1(2), p. 91-123.
- Pienitz, R., Douglas, M.S.V., Smol, J.P., Huttenen, P. and Meriläinen, J., in press, Diatom, chrysophyte, and protozoan distributions along a latitudinal transect in Fennoscandia: *EcoGraphy*, in press.
- Pienitz, R., Smol, J.P. and Birks, H.J., 1995, Assessment of freshwater diatoms as quantitative indicators of past climatic change in the Yukon and Northwest Territories, Canada: *Journal of Paleolimnology*, v. 13, p. 21-49.
- Radle, N., Keister, C.M. and Battarbee, R.W., 1989, Diatom, pollen, and geochemical evidence for the palaeosalinity of Medicine Lake, S. Dakota, during the Late Wisconsin and early Holocene: *Journal of Paleolimnology*, v. 2, p. 159-172.
- Rawlence, D.J., 1988, The postglacial diatom history of Splan Lake, New Brunswick: *Journal of Paleolimnology*, v. 1, p. 55-60.
- Rawlence, D.J., 1992, Paleophycology of Long Lake, Saint John County, New Brunswick, Canada, based on diatom distribution in sediments: *Canadian Journal of Botany*, v. 70, p. 229-239.
- Rawlence, D.J. and Senior, A., 1988, A late-glacial diatom and pigment history of Little Lake, New Brunswick with particular reference to the Younger Dryas climatic oscillation: *Journal of Paleolimnology*, v. 1, p. 163-177.
- Siver, P.A., 1991, *The Biology of Mallomonas*: Kluwer Academic Publishers, Dordrecht, 230 p.
- Smith, A. J., 1993, Lacustrine ostracodes as hydrochemical indicators in lakes of the north-central United States: *Journal of Paleolimnology*, v. 8, p. 121-134.
- Smol, J.P., 1983, Paleophycology of a high arctic lake near Cape Herschel, Ellesmere Island: *Canadian Journal of Botany*, v. 61, p. 2195-2204.

- Smol, J.P., 1987, Methods in Quaternary ecology—freshwater algae: *Geoscience Canada*, v. 14, p. 208-217.
- Smol, J.P., 1988, Paleoclimate proxy data from freshwater arctic diatoms: *Verhandlungen der Internationalen Vereinigung von Limnologen*, v. 23, p. 837-844.
- Smol, J.P., 1990a, Paleolimnology – Recent advances and future challenges: *Memoire dell'Istituto Italiano di Idrobiologia*, v. 47, p. 253-276.
- Smol, J.P., 1990b, Are we building enough bridges between paleolimnology and aquatic ecology?: *Hydrobiologia*, v. 214, p. 201-206.
- Smol, J.P., 1992, Paleolimnology: An important tool for effective ecosystem management: *Journal of Aquatic Ecosystem Health*, v. 1, p. 49-58.
- Smol, J.P., 1995, Application of chrysophytes to problems in paleoecology, in Sandgren, C., Smol, J. and Kristiansen, J., eds., *Chrysophyte Algae: Ecology, Phylogeny and Development*: Cambridge University Press, Cambridge, p. 303-329.
- Smol, J.P., Walker, I.R. and Leavitt, P.R., 1991, Paleolimnology and hindcasting climatic trends: *Verhandlungen der Internationalen Vereinigung von Limnologen*, v. 24, p. 1240-1246.
- Walker, I.R., Smol, J.P., Engstrom, D.R. and Birks, H.J.B., 1991a, An assessment of Chironomidae as quantitative indicators of past climatic change: *Canadian Journal of Fisheries and Aquatic Sciences*, v. 48, p. 975-987.
- Walker, I.R., Mott, R.J. and Smol, J.P., 1991b, Allerod/Younger Dryas temperatures from midge fossils in Atlantic Canada: *Science*, v. 253, p. 1010-1012.
- Walker, I.R., Smol, J.P., Engstrom, D.R. and Birks, H.J.B., 1992, Aquatic invertebrates, climate, scale, and statistical hypothesis testing: A response to Hann, Warner, and Warwick: *Canadian Journal of Fisheries and Aquatic Sciences*, v. 49, p. 1276-1280.
- Walker, I.R., Wilson, S.E. and Smol, J.P., in press, Chironomidae (Diptera): Quantitative palaeosalinity indicators for lakes in Western Canada: *Canadian Journal of Fisheries and Aquatic Sciences*, v. 52, in press.
- Warner, B.G., ed., 1990, *Methods in Quaternary Ecology*: Geological Association of Canada, St. John's, Newfoundland, 170 p.
- Williams, K.M., 1990, Paleolimnology of three Jackman Sound lakes, Southern Baffin Island, based on down-core diatom analyses: *Journal of Paleolimnology*, v. 4, p. 203-217.
- Wilson, S.E., Walker, I.R., Mott, R. and Smol, J.P., 1993, Climatic and limnological changes associated with the Younger Dryas in Atlantic Canada: *Climate Dynamics*, v. 8, p. 177-187.
- Wilson, S.E., Cumming, B.F. and Smol, J.P., 1994, Diatom-salinity relationships in 111 lakes from the Interior Plateau of British Columbia, Canada: The development of diatom-based models for paleosalinity and paleoclimatic reconstructions: *Journal of Paleolimnology*, v. 12, p. 197-221.
- Wolfe, A., 1994, Late Wisconsinan and Holocene diatom stratigraphy from Amarak Lake, Baffin Island, N.W.T., Canada: *Journal of Paleolimnology*, v. 10, p. 129-139.
- Wolfe, A. P. and Butler, D. L., 1994, Late-glacial and early Holocene environments at Pine Hill Pond, Newfoundland, Canada: evidence from pollen and diatoms: *Boreas*, v. 23, p. 53-65.
- Zeeb, B. A. and Smol, J.P., in press, A weighted-averaging regression and calibration model for inferring lakewater salinity using chrysophycean stomatocysts from western Canadian lakes: *International Journal of Salt Lake Research*, in press.

Accepted, as revised, 30 June 1995.