Geoscience Canada

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Volume 21, numéro 3, september 1994

URI : https://id.erudit.org/iderudit/geocan21_3art02

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Éditeur(s)

The Geological Association of Canada

ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

Découvrir la revue

Citer cet article

Smol, J. P., Cumming, B. F., Douglas, M. S. & Pienitz, R. (1994). Inferring Past Climatic Changes in Canada Using Paleolimnological Techniques. *Geoscience Canada*, *21*(3), 113–118.

Résumé de l'article

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Inferring Past Climatic Changes in Canada Using Paleolimnological Techniques

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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.

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RÉSUMÉ

L'approche paléolimnologique a du grand potentiel pour fournir des données paléoécologiques quantitatives. Des indicateurs comme les valves de diatomées, les écailles et kystes de chrysophycées, ainsi que les partes chitneuses 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 transfer 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 préservées 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 transfer 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 validation 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-treeline 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. Although 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

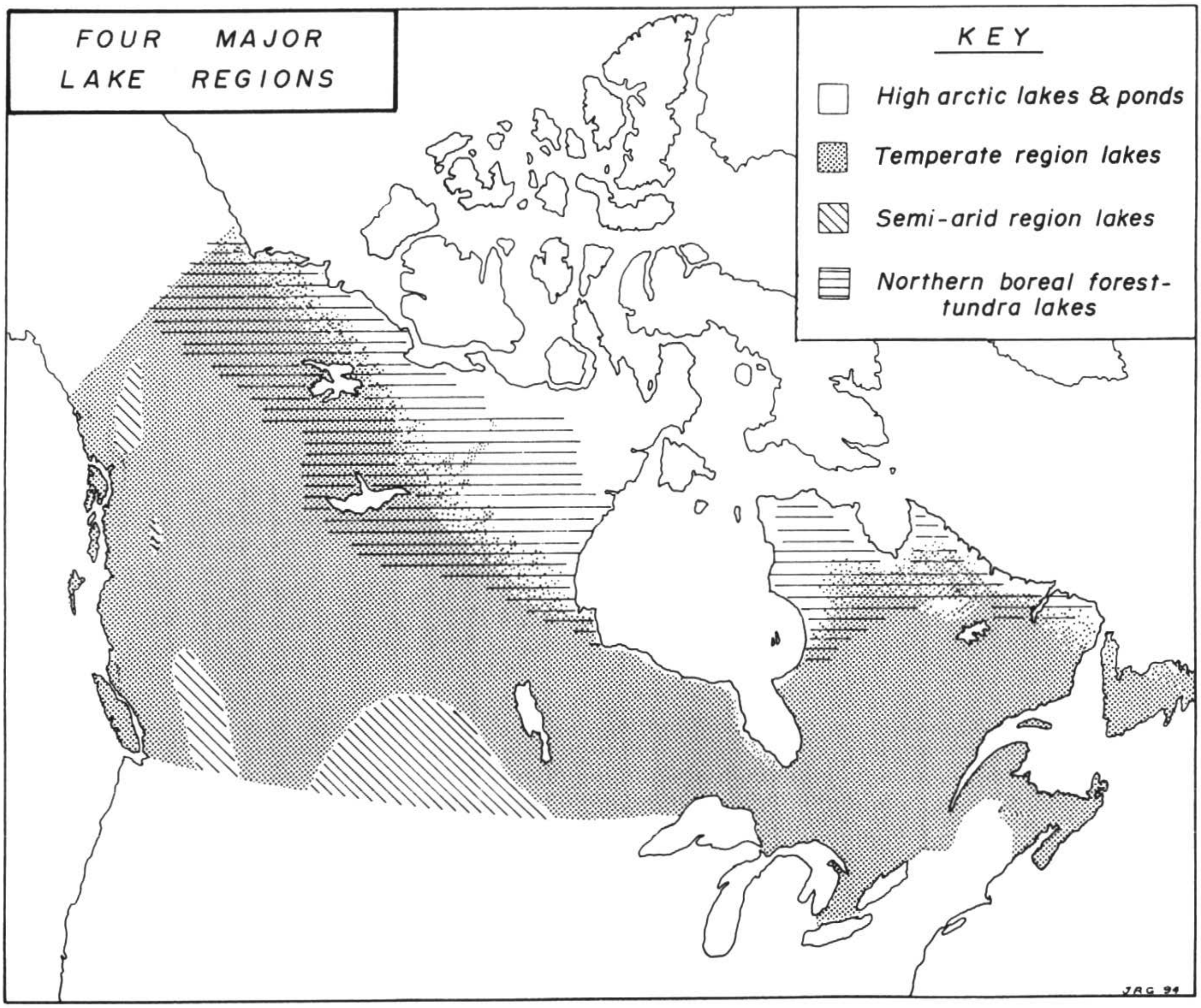

Figure 1 *Map showing the approximate boundaries of the four broad lake regions discussed in this paper. There is considerable overlap between regions.*

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 treeline 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 composition, 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 primarily to paleolimnological studies that Paleoecological 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).

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Accepted, as revised, 30 June 1995.