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Essai: Is Arctic Palynology a "Blunt Instrument"?
La palynologie de l'arctique est-elle un « instrument grossier » ?

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Article abstract

For nearly forty years, palynologists and other scientists studying the Quaternary have claimed that palynology, when applied in the Arctic, is a "blunt instrument" for analysing environmental change in this region. In this essay, the author explains why this expression should be laid to rest. Limits to palynological resolution are spatial, temporal and taxonomic. These are discussed and examples are shown where both the temporal and spatial resolution of pollen analyses is far higher than previously thought possible. The supposed "bluntness" of Arctic palynology is due to the way this tool has been applied in Arctic environments rather than inherent limits of palynology in Arctic ecosystems.

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ESSAI

IS ARCTIC PALYNOLOGY A "BLUNT INSTRUMENT"?

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ABSTRACT For nearly forty years, palynologists and other scientists studying the Quaternary have claimed that palynology, when applied in the Arctic, is a "blunt instrument" for analysing environmental change in this region. In this essay, the author explains why this expression should be laid to rest. Limits to palynological resolution are spatial, temporal and taxonomic. These are discussed and examples are shown where both the temporal and spatial resolution of pollen analyses is far higher than previously thought possible. The supposed "bluntness" of Arctic palynology is due to the way this tool has been applied in Arctic environments rather than inherent limits of palynology in Arctic ecosystems.

RÉSUMÉ *La palynologie de l'arctique est-elle un « instrument grossier » ?* Depuis une quarantaine d'années, de nombreux palynologues et d'autres chercheurs étudiant le quaternaire affirment que la palynologie, lorsque appliquée à l'arctique, est un « instrument grossier » pour l'étude des changements environnementaux dans cette région. Dans cet essai, l'auteur explique pourquoi cette expression devrait être mise de côté. Les limites de la résolution palynologique sont spatiales, temporelles et taxonomiques. Celles-ci sont discutées et des exemples sont montrés, où la résolution temporelle et spatiale des analyses polliniques s'avère bien plus élevée qu'on le croyait. Les limites de la palynologie arctique sont dues à la manière dont cet outil est utilisé dans les environnements arctiques plutôt qu'aux propriétés inhérentes de la palynologie appliquée aux écosystèmes arctiques.

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INTRODUCTION

Many years ago, Colinvaux (1967) summarized his first pollen diagrams from Alaska. At the conclusion of the study, he characterized Arctic palynology as a “blunt instrument” for interpreting tundra environments. This was based on several characteristics of the Arctic pollen assemblages in diagrams available at that time: low taxonomic resolution, the presence of tree pollen in tundra sediments, and low pollen representation of many Arctic plants. The “blunt instrument” metaphor has stuck, is still used today, and is apparently being taught in paleoecology courses, in spite of nearly 40 years of research that have improved our understanding of Arctic palynology. In a recent thesis comprehensive, the author heard it brought up again and it is used as the basis for rejection of grant proposals dealing with Arctic palynology. The interpretation of this phrase is that palynology applied in the Arctic is of limited use in dealing with some important paleoenvironmental questions, including paleoclimatic reconstructions (Larocque *et al.,* 2001; Walker *et al.,* 2003; Wooller *et al.,* 2004). The expression was recently picked up again by Birks and Birks (2000); Birks (2001, 2005), among others, also emphasized the limitations of pollen analysis in Arctic environments. The title of our review of Arctic palynology (Gajewski *et al.,* 1995), apparently contributed to this idea although the text demonstrated the opposite.

In this paper, the author wishes to lay to rest this out-of-date idea. In fact, pollen analysis today provides the best source of information about terrestrial vegetation and paleoclimates from the Arctic. The author will review some recent work illustrating the use of palynology in Arctic environments, emphasizing the North American literature in this discussion. Improvements in methodology and new data from several areas of the Arctic indicate that the potential of palynology to inform about past environments is far greater than commonly assumed. Furthermore, the collection of pollen data into publicly available databases permits regional-scale analyses not possible using other proxy-climate records. However, this thinking appears not to have entered the consciousness of the Quaternary Studies community (Larocque *et al.,* 2001; Walker *et al.,* 2003; Wooller *et al.,* 2004).

The limitations in the use of pollen in interpreting past conditions are based on several observations (Anderson *et al.,* 1994; Gajewski *et al.,* 1995; Ritchie, 1995). First, since some pollen grains are carried by the wind and mixed in the atmosphere, they are transported away from the source plant, in some cases for very long distances. This may make it difficult to confirm the local presence of plant populations by pollen assemblages alone, or to estimate population size of the source plant in the surrounding landscape. Next, various processes involved in pollen transport and lake sedimentation may compromise the temporal resolution of pollen diagrams. Finally, most pollen grains are not identifiable to species level, thereby limiting the ecological inferences that may be made. None of these are particular to the Arctic, but, as will be discussed below, they may appear to represent more significant limitations in this region.

The resolution of a paleoenvironmental “sensor” can be improved or compromised on any of three axes of the paleoecological matrix (Webb *et al.,* 1978): spatial, temporal and taxonomic (Ritchie, 1995). By developing new methods or approaches, by better understanding our data or our tools, or by simply obtaining more and better data, we can increase the resolution of the results that we can interpret from these data. Serving to decrease the resolution on any of these axes are systematic and random variations, discussed below, which can obscure the relation between the pollen and vegetation or pollen and environment. The author will provide recent examples to argue that the resolution of Arctic pollen analysis on these axes is greater than commonly thought and therefore Arctic palynology should be considered no less blunt than when applied in any other region nor less blunt than any other proxy-climate method currently used to reconstruct past Arctic environments.

SPATIAL RESOLUTION

One of the striking aspects of pollen grains is how well they are dispersed and preserved, and indeed, this is the basis of palynology and what makes pollen the most important fossil used in paleoecology (Birks and Birks, 1980). The study of this dispersibility has raised two central issues in palynology. The first is the transport of pollen grains from the source, sometimes to very long distances. The second is the relation of pollen assemblages in sediments to the vegetation immediately surrounding the site and the spatial resolution of the landscape pattern we can interpret. In recent years, we have learned much about both of these processes.

Recent analyses of pollen grains in snow and ice from across the Arctic have provided valuable quantitative data on long-distance transport of pollen in the Arctic. Bourgeois *et al.* (2001) analysed pollen from snow samples across the Canadian Arctic Archipelago and sea ice, from the continent to the North Pole. Because of the sampling method, each assemblage consisted of pollen deposition from one season. The results were quite informative.

The pollen assemblages extracted from snow and ice from the Arctic Ocean resembled those of the nearest landmass and subtle latitudinal and longitudinal differences in the pollen assemblages reflected spatial vegetation differences. For example, taxa such as Saxifragaceae and *Oxyria* were more abundant in High Arctic pollen samples, and shrub taxa more important in Low- and Middle Arctic assemblages. Tree pollen were found in abundance, but even these showed geographic patterns explainable by the distribution of the tree populations and wind transport. The distribution pattern of individual taxa can also be mapped and the source area inferred.

Tree pollen grains comprise a significant proportion of the pollen in Arctic sediments. Aerobiological studies by, for example, Rousseau *et al.* (2004) have used tree pollen grains from pollen traps to interpret air mass movements. Together, these spatial analyses, along with some time series studies discussed below suggest that air mass movements can be recorded by pollen records, as suggested years ago (Nichols *et al.,* 1978). That is, the transport of the pollen grains can be traced back to the source because pollen grains do not simply diffuse in a random individualistic manner in the atmosphere, but rather are transported in air masses, the pollen grains of the constituent taxa remaining as coherent assemblages. Using a spatial or spatio-temporal analysis, source regions and populations centres can in this way be established. The presence of tree pollen in tundra sediments must be accounted for, but (a) tree pollen provide information about air mass movements and (b) their presence can be dealt with in many instances by choice of an appropriate pollen sum.

The results from snow and ice samples accord with studies of the modern pollen deposition in sediments of Arctic lakes. Gajewski (1995) found a clear association between the pollen concentration of sediments and the transition between the High-Arctic and Middle-Arctic vegetation zones. Pollen percentages are also related to the spatial distribution of the vegetation, coherently enough that numerical methods can distinguish the different regions of the Canadian Arctic (Gajewski, 2002).

At present, only the broadest-scale vegetation patterns can be distinguished due to the sparse array of modern pollen data. However, the studies of Oswald *et al.* (2003a, 2003b), for example, demonstrated a close relation between pollen and vegetation at a regional and landscape scale in Alaska, providing every indication that higher spatial resolution results may be possible with more samples in a denser array.

Part of the confusion about this point arises simply due to the low numbers of available data. If only one pollen diagram is analysed, in isolation from all others, it is difficult to determine the source of the pollen grains arriving in the sediment. To distinguish the long-distance component of a particular pollen sample, a quantitative spatio-temporal analysis is needed. A network of sites is needed for any paleoclimatic or paleoenvironmental study, and the questions that can be investigated depend on the spatial resolution of the data. Thus, at present, the only terrestrial or freshwater proxy currently available for paleoclimatic study is pollen, as there are no spatial databases available for other proxies.

Pollen analysis can successfully be used, and is still the best way to determine treeline position. Tree-ring analysis of the recent past can provide supplemental information, particularly of processes causing populations to respond to environmental changes, but pollen diagrams are almost approaching the resolution obtainable from tree ring analysis with the added advantage of providing a regional picture of the vegetation (Gajewski, 2000). To reconstruct the large-scale movements of treeline, pollen analysis remains the only way. Modern pollen assemblages closely reflect the vegetation differences across treeline, if a sufficient number of samples are obtained. Several treeline studies (Lichti Federovich and Ritchie, 1968; Ritchie, 1974; Anderson and Brubaker, 1986; Gajewski, 1991) clearly indicated that the different zones that comprise the forest-tundra boundary can be distinguished using pollen assemblages from lake sediments. Treeline movements of several scales can be identified, when a sufficient number of detailed diagrams are prepared (Gajewski and Garralla, 1992; Gajewski *et al.,* 1993, 1996; Gajewski, 2000). The use of pollen accumulation rates has proven successful in delimiting species limits, reviewed by Seppä and Hicks (2006). The idea that pollen analysis cannot be used to reconstruct treeline history or provides misleading results (Birks and Birks, 2000) ignores the past two decades of literature and the success in reconstructing regional and continental-scale changes in treeline position and structure through time (*e.g.* from North America: Ritchie, 1984; MacDonald and Gajewski, 1992; Gajewski *et al.,* 1993; Gajewski and MacDonald, 2004).

The author would argue that we have not fully exploited pollen records because of this perception of the limits of pollen analysis. An example comes from the northern portion of the lichen woodland in northern Québec (Gajewski *et al.,* 1993). A pollen diagram from the region of the Grande Rivière de la Baleine records only small percentages in *Pinus* (diploxylon) pollen, that increase slightly in the past 3000 years. Based on continental modern pine pollen maps and response surfaces (Anderson *et al.,* 1991), these values would be considered too low to reflect the presence of pine trees in the region; comparable percentages could be found to the north of the species limit. However, analysis of charcoal from sand dunes in the river valley records the presence of pine populations, concordant with the pollen record (Desponts, 1990). In other words, the pollen record does track the arrival of pine in the region, in spite of the low percentages. This is shown by comparing pine pollen increases in any one pollen diagram to those at other sites (Gajewski *et al.,* 1993). If we assume pollen analysis is a blunt instrument, we would simply ignore these data and make no conclusions about the arrival of pine in the region. We would thereby be ignoring this migration event.

Of course, this is why Birks and Birks (2000) suggest the use of macrofossil analysis to complement pollen analyses, although as Gajewski *et al.* (1993) suggested, macrofossil analysis of lake sediments would not have uncovered the presence of pine, since they are found in dry areas along the river at the northern portion of their range. Charcoal or macrofossils cannot be used to trace this migration, due to low abundance and intermittent deposition, and only serve to support the conclusion arrived at using the spatial analysis of pollen assemblages.

The point here is that if we had confidence in our pollen analyses, the interpretation of an increase in pine locally would have been correct. Because we are assuming pollen analysis is a blunt instrument, we are attributing to random noise what is a real signal. Bennett (1985) has made a similar point about the migration of *Fagus* in southern North America. Using a spatial analysis, range limits in the past may be discerned (Webb *et al.,* 1993). We may arrive at an ambiguous interpretation of any one pollen diagram (Birks and Birks, 2000) if it has been removed from its spatial context; only in the context of the entire region can any paleoecological study be interpreted (Gajewski, 1987, 1993). There are now sufficient data available, as well as several examples such as the author has presented above, that suggest that small variations in pollen values, if identified in a spatial array of sites, are recording real events occurring on the landscape. These need to be identified and studied.

TEMPORAL RESOLUTION

The temporal resolution of a pollen diagram depends on several factors. The first is the sedimentation rate. Bioturbation further mixes the sediment. The “response time of the vegetation to climate variations” is also a factor, although this is the least understood.

Recently, Bourgeois (2000) summarized 20 years of palynological studies on Arctic snow and ice. Ice sheets accumulate pollen from large areas, much as a very large lake would. In one paper, Bourgeois (2001) analyzed the near-surface snow layers, before the ice had been greatly compressed; in this way, she could divide each annual accumulation into four layers. These correspond roughly to (a) late-summer/early-autumn, (b) autumn/early-winter, (c) late-winter/early-spring and (d) late-spring/summer. She analysed the pollen from each of these layers in the snow and firn of several ice caps; the longest series, from Ellesmere Island, contained over 12 years of accumulation.

What is remarkable is how consistently these layers record the seasonal pollen phenology. Largest concentrations of tree pollen are characteristically found in the spring and summer layers. That is, the pollen of trees and shrubs are dispersed into the atmosphere, carried from south of treeline to northern Ellesmere Island and deposited on the ice cap in the season they are released by the plant. Herb pollen, mostly from the tundra, are found in greater concentrations in the summer layer. Variations through time in pollen production and transport were also recorded in the ice layers. The conclusion is that the pollen deposited in sediments faithfully records the pollen being produced and emitted by plants with little or no time lag. Aerobiological studies in Europe confirm these results; both pollen productivity, associated with meteorological conditions, and the composition of the regional vegetation are recorded by pollen assemblages and influx (Hicks, 2001).

The sediment accumulation will ultimately define the resolution of the results obtained from a sediment core. Within these limits the palynologist has control of the sampling interval and averaging distance (thickness of sample). Today, samples used for paleoenvironmental analysis are typically 0.5 cm of vertical sediment length and paleolimnologists sometimes use smaller ones. The sediment core can be sampled continuously, in contrast to the practice of the previous generation of workers (Gajewski, 1993). Webb and Webb (1988) computed a mean sedimentation rate of 0.05 cm/yr in “Arctic” sites (north of 50 °N) suggesting that we are far from exploiting, using present-day methods, the temporal resolution available in Arctic sediments. The major limitation is the time involved in processing and counting the pollen, and recent work on processing methods is already enabling the improvement of the temporal resolution of pollen diagrams (Zabenskie, 2006). The temporal resolution that we can attain in Arctic sediments is an order of magnitude greater than that normally practiced, if we were to, for example, sample continuously at 0.5 cm intervals.

Bioturbation mixes the sediment (Davis, 1974), unless it is laminated or varved. However, recent observations suggest that this may be a lesser problem than thought, especially in the Arctic. Visual inspection and X-rays of Arctic sediment cores commonly show laminations in parts of the core. These structures may provide paleohydrological information, and the detailed study of sediment structures in Arctic cores is only beginning (Gajewski and Frappier, 2001; Lamoureux *et al.,* 2002 and references therein). But if these structures are preserved, this suggests little or no post-depositional mixing and therefore the resolution is dependent only on the sedimentation rate. It remains to be seen if these laminations are equally common in southern regions, or if this is a characteristic of the low aquatic productivity of Arctic regions.

A second piece of evidence suggesting a limited impact of post-depositional processes is the presence in sediments of charcoal from individual fires. The fact that individual fires can presumably be identified in sediment charcoal records (Carcaillet *et al.,* 2001) suggests that the bioturbation is not removing the high frequency variability.

Finally, an obvious fact must be recalled: a pollen diagram records the variations in pollen through time; the vegetation must be inferred. Therefore a change in climate that affects pollen production may be recorded in the sediment immediately, with no time lag (Gajewski, 2000). The time that it may take for the plants on the landscape to be replaced may be longer, and would also be recorded in the pollen diagrams. The point is that the supposed long time lag of vegetation to a climate change is probably exaggerated (Gajewski, 1987).

TAXONOMIC RESOLUTION

In order to increase taxonomic resolution, two resources are needed: detailed pollen floras or keys and an adequate pollen reference collection. The latter requires access to an extensive herbarium and/or years of collection. Developing a collection from herbarium specimens is feasible but time-consuming, as typically there are few flowers or stamens available on herbarium sheets. However a certain percentage of specimens provide the needed material. Collecting in the Arctic requires access during the flowering season followed by long and expensive hours in the lab preparing the reference slides. One obvious solution is to exchange slides among laboratories.

At present, there is no flora of Arctic pollen, and indeed, there is no detailed pollen flora available for North America. Kapp (1969) is dated and contains no photos, McAndrews *et al.* (1973) is limited in extent. Most North American palynologists use European floras such as Faegri and Iversen (1989) or Moore *et al.* (1991).

More importantly, pollen taxonomic work needs to be done. The Greenland and northern European pollen flora are beginning to be well known. Papers by Fredskild (1973) on Greenland pollen types, Funder (1978) on Greenland *Salix*, Comtois and Larouche (1981) and Cwynar (1982) on Ericales, Hebda *et al.* (1988a, 1988b, 1990, 1991) and Hebda and Chinnappa (1990) on the Rosaceae, Parent and Richard (1990) on the Cupressaceae, Parent and Richard (1993) on the Caryophyllaceae of the Arctic, Brubaker *et al.* (1998) on moss spores, among others, indicate that with proper study, the taxonomic resolution of Arctic pollen diagrams can be greatly increased. Ritchie (1995) has suggested that we are approaching the limits of taxonomic resolution possible using light microscopy. This may be, but these limits are not routinely and consistently used in paleoecological work. Although we do not anticipate all pollen will be identifiable to species, a concerted effort to increase the taxonomic resolution is needed. These results need to be transmitted to palynologists working on Quaternary deposits.

Three examples of the importance of taxonomic resolution will be presented; Ritchie (1995) discusses others. The best example of the importance of good taxonomic resolution comes from the analysis of the “Beringia question”. Beringia was used by Birks and Birks (2000) as an example of the where pollen analysis could not resolve the issue, but the author reads this in exactly the opposite sense. The controversy, discussed recently in a series of papers in Quaternary Science Reviews (Brigham-Grette and Elias, 2001), was based around alternative interpretations of paleoenvironmental proxy-data. On the one hand, coarse-resolution pollen analyses could suggest tundra vegetation, but an alternative interpretation, based, for example, on mammal fossils suggested a steppe-type of environment (see Cwynar, 1982). It seems to me that the question was settled by Cwynar (1982) and Ritchie (1982), whose pollen analyses with high taxonomic precision showed tundra, at least in the northwestern portion of the Beringian region where they were working. Other pollen diagrams from around the Beringian region also suggest this interpretation (Anderson *et al.,* 1994; see also Edwards *et al.,* 2000), as do macrofossil studies (Goetcheus and Birks, 2001), although there may not be exact modern analogues to the vegetation. Further analyses can determine the spatial distribution of the different vegetation types that must have existed in the region (Oswald *et al.,* 2003a, 2003b), if the analyses are done with sufficient taxonomic precision and if a spatial analysis is used to account for transport of pollen gains (Brubaker *et al.,* 2005).

Furthermore, much of the currently available taxonomic information is not even routinely being analysed. Many palynologists do not study or even plot some taxa that they have identified, combining lower order taxa into higher-order categories to ensure the published pollen diagram fits on one page. More insight into paleoecological questions has been obtained by the study of databases of pollen diagrams. For example, analysis of *Sphagnum* (Gajewski *et al.,* 2000) and aquatic pollen (Sawada *et al.,* 2003) shows that the Beringian region was a centre from which these taxa migrated to western Canada. The implications of this toward our understanding of the Beringian environment remain to be fully determined, however, the high values of these pollen and spores implies a level of moisture in the region that can aid in understanding the paleoclimates of the region. These studies were performed by mapping and analysis of standard pollen data suggesting that the information available in these pollen diagrams has not even been fully synthesized. Finklestein *et al.* (2005) provides another example of the analysis of understudied taxa from temperate regions. Far from being limited by the relatively coarse taxonomy of standard pollen analysis, there is much detailed information available in currently-available Arctic pollen diagrams and databases.

A second example of pollen analyses performed using high taxonomic resolution is the work of Richard and associates. Examples of this work in Arctic environments include Richard (1981) from northern Québec, where changes through time in the nature of the tundra vegetation could be identified, and several more recent studies from Baffin Island (Wolfe *et al.,* 2000; Fréchette *et al.,* 2006).

Finally, the analysis of the postglacial vegetation development of Greenland, studied over many decades by Fredskild (1973, 1983, 1985) and others, provides another example of careful taxonomic work. These pollen diagrams contain over 208 pollen types, many identified to species, where the Greenland Flora has around 500 species (Böcher *et al.,* 1968). Combined with his extensive knowledge of the Greenland flora, these analyses permitted a detailed reconstruction of the vegetation history of Greenland, and led Fredskild to conclude (1973: p. 223), as we do here, that Arctic palynology is not at all a blunt instrument, a conclusion ignored by subsequent workers.

DISCUSSION AND SUMMARY

The point of this essay is to suggest that the resolution of Arctic palynology is limited more by our attempts to exploit these records than by the nature of palynology or Arctic palynology itself. A number of examples have been given above, and there are certainly more that could be presented, particularly from Europe. To dismiss Arctic palynology as a “blunt instrument”, or to claim pollen analysis is “insensitive” in these regions is premature at best, since so few studies have been accomplished in the Arctic and much of the data already available has not been sufficiently synthesized. Many pollen studies publish only summary diagrams, and the less common taxa are not analyzed. Spatio-temporal analyses of these taxa may well increase the resolution of our interpretations about past environments. Multiple interpretative approaches, combining quantitative and qualitative methods (Anderson *et al.,* 1994), use of pollen concentrations or influx (Gajewski, 1995; Seppä and Hicks, 2006), the study of long-distance transported pollen grains (Bourgeois *et al.,* 2001) and analysis of databases of pollen diagrams (Gajewski *et al.,* 2001; Sawada *et al.,* 2003; Finkelstein *et al.,* 2006) can access untapped or insufficiently synthesized information in pollen data. The author has also tried to suggest that increasing the spatial, temporal and taxonomic resolution in future studies will be profitable. Finally, the author is not arguing against the use of other fossils or approaches, nor counseling that we should not use multiple approaches in analyzing sediment cores. The point is to use pollen data to the maximum extent possible, and to place the confidence in the results that they warrant.

Today, there are hundreds of pollen cores available from North America (http://www.ncdc.noaa.gov/paleo/index.html) and thousands of modern pollen samples for calibration (Whitmore *et al.,* 2004) in public databases. The availability of these data, as well as the well-known properties of pollen discussed above, makes pollen analysis the best, and indeed, the only data source for paleoclimate studies in the Arctic away from ice sheets, as the key to paleoclimate analysis is a spatial analysis of the data (Gajewski, 1987).

Is Arctic palynology a "blunt instrument"? All paleoenvironmental indicators have limits to resolution and problems associated with their application to various questions under study. The point here is that the continual harping on the limits to the interpretation of pollen analyses in Arctic environments is firstly misplaced, as many of these are not truly limits inherent to pollen analysis in the Arctic but rather due to their application by paleoecologists during the past few decades. These limitations can be dealt with using tools presently available. It is time to finally put this expression to rest. Next, any proxy-climate or paleoenvironmental record has comparable limitations, and could therefore be considered blunt, making the expression meaningless. It is necessary to first identify the problems or limitations, describe, study, and if possible quantify their importance and finally deal with them; this was the point of our paper (Gajewski *et al.,* 1995) and subsequent work (Gajewski, 1995, 2002) and that of others such as Anderson *et al.* (1994) or Oswald *et al.* (2003a, 2003b). Finally, the author has argued that available pollen data have not been fully exploited, and that there is considerable information in databases that can be used to better understand paleoenvironments. This would also be true of other paleoenvironmental data, if databases were available. The key to any paleoenvironmental study is a quantitative spatio-temporal analysis providing the necessary context for interpretation (Gajewski, 1993). The study of Arctic palynology has barely begun, but recent work has shown just how sharp the instrument can be.

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REFERENCES

Anderson, P., Bartlein, P. and Brubaker, L., 1994. Late Quaternary history of tundra vegetation in northwestern Alaska. Quaternary Research, 41: 306-315.

Anderson, P., Bartlein, P., Brubaker, L., Gajewski, K., and Ritchie, J., 1991. Vegetation-pollen-climate relationships for the Arcto-Boreal region of North America and Greenland. Journal of Biogeography, 18: 565-582.

Anderson, P. and Brubaker, L. 1986. Modern pollen assemblages from northern Alaska. Review of Palaeobotany and Palynology, 46: 273-291.

Bennett, K., 1985. The spread of *Fagus grandifolia* across eastern North America during the last 18 000 years. Journal of Biogeography, 12: 147-164.

Birks, H.H., 2001. Plant macrofossils, p. 49-74. *In* J.P. Smol, H.J.B. Birks and W.M. Last, eds., Tracking environmental change using lake sediments, Volume 3. Kluwer Academic Publishers, Dordrecht, 371 p.

Birks, H.H. and Birks, H.J.B., 2000. Future uses of pollen analysis must include plant macrofossils. Journal of Biogeography, 27: 31-35.

Birks, H.J.B., 2005. Fifty years of Quaternary pollen analysis in Fennoscandia 1954-2004. Grana, 44: 1-22.

Birks, H.J.B. and Birks, H.H., 1980. Quaternary Palaeoecology. Edward Arnold, London, 289 p.

Böcher, T., Holmen, K. and Jakobsen, K., 1968. The Flora of Greenland. Haase and Sons, Copenhagen, 312 p.

Bourgeois, J., 2000. Modern and Holocene pollen assemblages from Arctic Ice Caps. Ph.D. thesis, University of Ottawa, 117 p.

Bourgeois, J., 2001. Seasonal and annual variation of pollen variability in snow layers of Arctic ice caps. Review of palaeobotany and palynology, 108: 17-36.

Bourgeois, J., Gajewski, K. and Koerner, R., 2001. Spatial patterns of pollen deposition in Arctic snow. Journal of Geophysical Research, 106(D6): 5255-5266.

Brigham-Grette, J. and Elias, S.A., eds., 2001. Beringian Paleoenvironments: Festscrift in honour of D.M. Hopkins. Quaternary Science Reviews, 20: 1-574.

Brubaker, L., Anderson, P., Edwards, M. and Lozhkin, A. 2005. Beringia as a glacial refugium for boreal trees and shrubs: new perspectives from mapped pollen data. Journal of Biogeography, 32: 833-848.

Brubaker, L., Anderson, P., Murray, B. and Koon, D., 1998. A palynological investigation of true-moss (Bryidae) spores: morphology and occurrence in modern and late Quaternary lake sediments. Canadian Journal of Botany, 76: 2145-2157.

Carcaillet, C., Bergeron, Y., Richard, P., Fréchette, B., Gauthier, S. and Prairie, Y., 2001. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? Journal of Ecology, 89: 930-946.

Colinvaux, P.A., 1967. Quaternary vegetational history of Arctic Alaska, p. 207-231. *In* D.M. Hopkins, ed., The Bering Land Bridge. Stanford University Press, Stanford, 495 p.

Comtois, P. and Larouche, A., 1981. Morphologie pollinique des Éricales du Québec. Naturaliste canadien, 108: 245-262.

Cwynar, L., 1982. A late-Quaternary vegetation history from Hanging Lake, northern Yukon. Ecological Monographs, 52: 1-24.

Davis, R.B., 1974. Stratigraphic effects of tubificids in profundal lake sediments. Limnology and Oceanography, 19: 466-488.

Desponts, M., 1990. Dynamisme récent et holocène du pin gris à sa limite septentrionale de distribution au Nouveau-Québec. Ph.D. thesis, Université Laval, 105 p.

Edwards, M.E., Anderson, P., Brubaker, L., Ager, T., Andreev, A., Bigelow, N., Cwynar, L., Eisner, W., Harrison, S., Hu, F.S., Jolly, D., Lozhkin, A., MacDonald, G., Mock, C., Ritchie, J., Sher, A., Spear, R., Williams, J., and Yu, G., 2000. Pollen-based biomes for Beringia 18,000, 6000 and 0 ^{14}C yr BP. Journal of Biogeography, 27: 521-554.

Faegri, K. and Iversen, J., 1989. Textbook of pollen analysis, 4th edition. K. Faegri, P. Kaland and K. Krzywinski, eds. Blackburn Press, Caldwell, 328 p.

Finkelstein, S., Gajewski, K. and Viau, A., 2006. Taxonomic resolution and the postglacial history of the forests of eastern North America: analysis from the NAPD. Journal of Ecology, 94: 415-430.

Fréchette, B., Wolfe, A.P., Miller, G.H., Richard, P.J.H., and de Vernal, A., 2006. Vegetation and climate of the last interglacial on Baffin Island, Arctic Canada. Palaeogeography, Palaeoclimatology and Palaeoecology, 236: 91-106.

Fredskild, B., 1973. Studies in the vegetational history of Greenland. Meddelelser om Grønland, 198: 1-245.

Fredskild, B., 1983. The Holocene vegetational development of the Godthåbsfjord area, west Greenland. Meddelelser om Grønland, Geoscience, 10: 1-28.

Fredskild, B., 1985. The Holocene vegetational development of the Tugtuligssuaq and Qeqertat, northwest Greenland. Meddelelser om Grønland, Geoscience, 14: 1-20.

Funder, S., 1978. Holocene stratigraphy and vegetation history in the Scoresby Sund area, East Greenland. Grønlands Geologiske Undersøgelse, Copenhagen, Bulletin 129, 66 p.

Gajewski, K., 1987. Climatic impacts on the vegetation of eastern North America for the past 2000 years. Vegetatio, 68: 179-190.

Gajewski, K., 1991. Représentation pollinique actuelle à la limite des arbres au Nouveau-Québec. Canadian Journal of Earth Sciences, 28: 643-648.

Gajewski, K., 1993. The role of paleoecology in the study of global climatic change. Review of Palaeobotany and Palynology, 79: 141-151.

Gajewski, K., 1995. Modern and Holocene pollen accumulation in some small Arctic lakes from Somerset Island, N.W.T., Canada. Quaternary Research, 44: 228-236.

Gajewski, K., 2000. Climate of the last millennium in eastern North America and impacts on the vegetation. Prace Geograficzne, 107: 101-105.

Gajewski, K., 2002. Modern pollen deposition in lake sediments from the Canadian Arctic. Arctic, Antarctic and Alpine Research, 34: 26-32.

Gajewski, K. and Frappier, M., 2001. Postglacial environmental history from Prince of Wales Island, Nunavut, Canada. Boreas, 30: 485-489.

Gajewski, K. and Garralla, S., 1992. Holocene vegetation histories from three sites in the tundra of northwestern Québec, Canada. Arctic and Alpine Research, 24: 329-336.

Gajewski, K. and MacDonald, G., 2004. Palynology of Arctic Lakes, p. 89-116. *In* R. Pienitz, M. Douglas and J. Smol, eds., Long-term environmental change in Arctic and Antarctic Lakes. Kluwer Academic Publisher, Dordrecht, 562 p.

Gajewski, K., Garneau, M. and Bourgeois, J.C., 1995. Paleoenvironments of the Canadian High Arctic derived from pollen and plant macrofossils: problems and potentials. Quaternary Science Reviews, 14: 609-629.

Gajewski, K., Garralla, S. and Milot-Roy, V., 1996. Postglacial vegetation at the northern limit of lichen woodland in northwestern Québec. Géographie physique et Quaternaire, 50: 341-350.

Gajewski, K., Payette, S. and Ritchie, J.C., 1993. Holocene vegetation history at the boreal forest-shrub tundra transition in northern Québec. Journal of Ecology, 81: 433-443.

Gajewski, K., Viau, A., Sawada, M., Atkinson, D. and Wilson, S., 2001. *Sphagnum* distribution in North America and Eurasia during the past 21 000 years. Global Biogeochemical Cycles, 15: 297-310.

Goetcheus, V.G. and Birks, H.H., 2001. Full-glacial upland tundra vegetation preserved under tephra in the Beringia National Park, Seward Peninsula, Alaska. Quaternary Science Reviews, 20: 135-147.

Hebda, R. and Chinnappa C., 1990. Studies on pollen morphology of Rosaceae in Canada. Review of Paleobotany and Palynology, 64: 103-108.

Hebda, R., Chinnappa, C. and Smith, B., 1988a. Pollen morphology of the Rosaceae of western Canada. I. *Agrimonia* to *Crataegus*. Grana, 27: 95-113.

Hebda, R., Chinnappa, C. and Smith, B., 1988b. Pollen morphology of the Rosaceae of western Canada. II. *Dryas*, *Fragaria*, *Holodiscus*. Canadian Journal of Botany, 66: 595-612.

Hebda, R., Chinnappa, C. and Smith, B., 1990. Pollen morphology of the Rosaceae of western Canada. III. *Geum*. Canadian Journal of Botany, 68: 1369-1378.

Hebda, R.J., Chinnappa, C. and Smith, B., 1991. Pollen morphology of the Rosaceae of western Canada. IV. *Luetkea, Oemleria, Physocarpus, Prunus*. Canadian Journal of Botany, 69: 2583-2596.

Hicks, S., 2001. The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. Review of Paleobotany and Palynology, 117: 1-29.

Kapp, R., 1969. How to know the Pollen and spores. Brown, Dubuque, 249 p.

Lamoureux, S., Gilbert, R. and Lewis, T., 2002. Lacustrine sedimentary environments in high Arctic proglacial Bear Lake, Devon Island, Nunavut, Canada. Arctic, Antarctic and Alpine Research, 34: 130-141.

Larocque, I., Hall, R. and Grahn, E., 2001. Chironomids as indicators of climate change: a 100 lake training set from a subarctic region of northern Sweden (Lapland). Journal of Paleolimnology, 26: 307-322.

Lichti-Federovich, S. and Ritchie, J.C., 1968. Recent pollen assemblages from the western interior of Canada. Review of Palaeobotany and Palynology, 7: 297-344.

MacDonald, G. and Gajewski, K., 1992. The northern treeline of Canada, p. 34-37. *In* D. Janelle, ed., Geographical snapshots of North America. Guilford Press, New York, 442 p.

McAndrews, J., Berti, A. and Norris, G., 1973. Key to the Quaternary pollen and spores of the Great Lakes Region. Royal Ontario Museum Life Sciences Miscellaneous Publication, Toronto, 61 p.

Moore, P., Webb, J. and Collinson, M., 1991. Pollen Analysis, 2nd edition. Blackwell, Oxford, 216 p.

Nichols, H., Kelly, P. and Andrews, J., 1978. Holocene palaeo-wind evidence from palynology in Baffin Island. Nature, 273: 140-142.

Oswald, W., Brubaker, L., Hu, F. and Gavin, D., 2003. Pollen-vegetation calibration for tundra communities in the Arctic Foothills, northern Alaska. Journal of Ecology, 91: 1022-1033.

Oswald, W., Anderson, P., Brubaker, L., Hu, F. and Engstrom, D.R., 2003. Representation of tundra vegetation by pollen in lake sediments of northern Alaska. Journal of Biogeography, 30: 521-535.

Parent, J. and Richard, P., 1990. Morphologie pollinique des Cupressaceae de l'est du Canada et du nord-est des États-Unis appliquée à l'étude des sédiments quaternaires. Journal canadien de botanique, 68: 79-89.

Parent, J. and Richard, P., 1993. Morphologie pollinique des Caryophyllaceae du Québec nordique, des territoires adjacents et de l'archipel Arctique canadien. Canadian Journal of Botany, 71: 887-905.

Richard, P.J.H., 1981. Paléophytogéographie postglaciaire en Ungava par l'analyse pollinique. Collection Paléo-Québec No. 13, 153 p.

Ritchie J.C., 1974. Modern pollen assemblages near the arctic tree line, Mackenzie Delta region, Northwest Territories. Canadian Journal of Botany, 52: 381-396.

Ritchie, J.C., 1982. The modern and late-Quaternary vegetation of the Doll Creek Area, North Yukon, Canada. New Phytologist, 90: 563-603.

Ritchie, J.C., 1984. Past and Present Vegetation of the Far Northwest of Canada. University of Toronto Press, Toronto, 251 p.

Ritchie, J.C., 1995. Tansley Review No. 83. Current trends in studies of long-term plant community dynamics. New Phytologist, 130: 469-494.

Rousseau, D.D., Duzer, D., Etienne, J.L., Cambon, G., Jolly, D., Ferrier, J. and Schevin, P., 2004. Pollen record of rapidly changing air trajectories to the North Pole. Journal of Geophysical Research, 109: doi: 10.1029/2003JD003985.

Sawada, M., Viau, A. and Gajewski, K., 2003. The biogeography of aquatic macrophytes in North America since the last glacial maximum. Journal of Biogeography, 30: 999-1017.

Seppä, H. and Hicks, S., 2006. Integration of modern and past pollen accumulation rate (PAR) records across the arctic tree-line: a method for more precise vegetation reconstruction. Quaternary Science Reviews, 25: 1501-1516.

Walker, I.R., Levesque, A., Pienitz, R. and Smol, J., 2003. Freshwater midges of the Yukon and adjacent Northwest Territories: a new tool for reconstructing Beringian paleoenvironments? Journal of the North American Benthological Society, 22: 323-337.

Webb, R. and Webb III, T., 1988. Rates of sediment accumulation in pollen cores from small lakes and mires of eastern North America. Quaternary Research, 30: 284-297.

Webb III, T., Bartlein, P., Harrison, S. and Anderson, K., 1993. Vegetation, lake levels and climate in eastern North America for the past 18,000 years, p. 415-467. *In* H. Wright, J. Kutzbach, T. Webb III, W. Ruddiman, F. Street-Perrott and P. Bartlein, eds., Global climates since the last glacial maximum. University of Minnesota Press, Minneapolis, 569 p.

Webb III, T., Laseski, R. and Bernabo, J., 1978. Sensing Vegetational Patterns with Pollen Data: Choosing the Data. Ecology, 59: 1151-1163.

Whitmore, J., Gajewski, K., Sawada, M., Williams, J.W., Minckley, T., Shuman, B., Bartlein, P.J, Webb III, T., Viau, A.E., Shafer, S., Anderson, P. and Brubaker, L., 2005. A North American Modern Pollen Database for Multi-scale Paleoecological and Paleoclimatic Applications. Quaternary Science Reviews, 24: 1828-1848.

Wolfe, A.P., Fréchette, B., Richard, P.J.H., Miller, G.H., and Forman, S.L., 2000. Paleoecology of a >90,000-year lacustrine from Fog Lake, Baffin Island, Arctic Canada. Quaternary Science Reviews, 19: 1677-1700.

Wooller, M.J., Francis, D., Fogel, M.L., Miller, G.H., Walker, I.R. and Wolfe, A.P., 2004. Quantitative paleotemperature estimates from $\delta^{18}O$ of chironomid head capsules preserved in Arctic lake sediments. Journal of Paleolimnology, 31: 267-274.

Zabenskie, S. 2006. Post-glacial Climatic Change on Boothia Peninsula, Nunavut, Canada. M.Sc. thesis, University of Ottawa, 98 p.