1. PALEOLIMNOLOGICAL RESEARCH IN POLAR REGIONS: AN INTRODUCTION

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The world can tell us everything we want to know. The only problem for the world is that it doesn't have a voice. But the world's indicators are there. They are always talking to us.

Quitsak Tarkiasuk, Ivujivik
(1997 Canadian Arctic Resources Committee)

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Introduction

There is growing consensus that we have entered the "Anthropocene" (Crutzen 2002), a time period during which the major changes in the global biosphere are primarily the result of human actions and their impacts on the environment. Anthropogenic activities have a history that, in some areas, stretches back over thousands of years. Yet it is the exceptional warming of the last decade - the warmest decade since instrumental records began - that has provoked widespread concern over human influences on climate. Both indigenous observations of environmental change (e.g., Canadian Arctic Resources Committee (CARC) 1997; Krupnik and Jolly 2002; Fox 2003) and instrumental data (e.g., Magnuson et al. 2000; Houghton et al. 2001; Moritz et al. 2002) provide evidence that the Earth's circumpolar regions are especially sensitive to rapid biophysical and social changes. However, the nature and characteristics of 20th-century climate variability are difficult to define, as the period for which we have instrumental records coincides with the time during which the atmosphere has been increasingly enriched by greenhouse gases, and so we now live in a “no-analogue” biosphere. To put present-day conditions into context and to more clearly understand future global changes, we require an appreciation of long-term climatic and environmental changes.

General circulation model (GCM) simulations of future climatic changes, which may be expected with higher levels of carbon dioxide (CO_2) and other greenhouse gases, show a remarkable consensus that the effects of anthropogenic greenhouse warming will be particularly intense in polar regions (e.g., Nicholls et al. 1996; Kattenberg et al. 1996; ACIA 2001; Houghton et al. 2001). For example, while the most recent report by the Intergovernmental Panel on Climate Change (IPCC; Houghton et al. 2001) predicts an average global temperature rise of between 1.5 and 6°C by the end of the 21st century, increases are expected to be much more significant in the Arctic and Antarctic (Kattenberg et al. 1996; Houghton et al. 2001). GCMs also predict a complete loss of sea ice across the Arctic Ocean basin by the end of this century (Vincent et al. 2001 and references therein). This warming will especially influence the late-autumn and winter temperatures and precipitation, mainly due to the increased sea ice – albedo feedbacks during the winter period, with the thermal inertia of the mixed layer of the open ocean preventing substantial warming during the short summer period (Nicholls et al. 1996). Collectively, the interactions or feedback mechanisms between high latitude oceans (sea-surface temperature), the cryosphere (continental ice masses, sea ice, and snow cover), and the atmosphere amplify the effects of global change (Kattenberg et al. 1996; Nicholls et al. 1996) and are dominant mechanisms controlling circumpolar climate on decadal to centennial timescales (Dickinson et al. 1996). Not surprisingly, the circumpolar regions have been the foci of scientific debates regarding global environmental and climatic change, as changes will likely first be discernible in these regions (Anderson and Willebrand 1996).

The amplification of the global warming signal and increased precipitation in high latitude regions are characteristic features of model predictions, and they are believed to be largely due to feedback mechanisms in which key roles are played by variations in snow and sea ice extent (albedo), the stability of the lower troposphere, and (in the Arctic) thawing of permafrost. However, discrepancies in GCM scenarios arise concerning the magnitude and spatial structure of high latitude warming (reviewed in Serreze et al. 2000). The projections of future changes are complicated, for example, by uncertainties about the effects of changes in cloud cover, albedo, vegetation cover, topography, as well as possible interactions involving stratospheric temperature, stratospheric ozone, and changes in other parts of the system. For these reasons, current estimates of future changes vary significantly. Regardless of the mechanisms, northern populations are already experiencing the consequences of rapid climatic change in the Arctic, such as increased variability and unpredictability of the weather, fewer extended periods of extreme cold, more frequent extreme weather events, such as high wind (summer storm) events and lightning, changes in the seasonal extent and distribution of sea ice cover, different lake ice conditions, the melting of permafrost leading to unstable soils, as well as modified conditions for hunting of wildlife and waterfowl (CARC 1997; Krupnik and Jolly 2002; Fox 2003).

Observational/instrumental evidence for rapid climate change in the circumpolar regions

Although there are pronounced differences between the Arctic and Antarctica (reviewed in Grémillet and Le Maho 2003), both high latitude regions have many similarities arising from a common response to Earth's orbital parameters. For example, the cryosphere is the dominant feature in both regions, and they share common temperature and radiation regimes, ozone characteristics, sea ice ecosystems and polynyas, as well as pronounced aridity. Moreover, atmospheric and oceanographic circulation processes link the polar regions, and also significantly influence world climates. For these reasons, this book describes long-term paleolimnological research from both polar regions, as they are intrinsically connected to the global environment.

Monitoring data from both hemispheres have recorded the warming of surface air temperatures in recent decades, with the largest temperature increases occurring over northern hemisphere land areas from about 40 to 70°N (Serreze et al. 2000). Temperature data from arctic stations over the period 1966-1995 indicate a general warming trend, with the greatest effects in the western Arctic (up to 0.7°C per decade; Weller 1998). In the Antarctic, warming is largely focused in the Peninsula region. The 3.4 ± 1.6°C per century (weighted by length of record) warming of the Antarctic Peninsula over the past 40 to 50 years is amongst the most rapid air temperature increases recorded on Earth (Quayle et al. 2002; Vaughan et al. 2003).

Increased open sea conditions will be accompanied by increased evaporation into the overlying air masses that, at warmer temperatures, can hold more moisture for subsequent cloud formation and precipitation. There is wide regional variability in precipitation trends, from significant increases at certain locations (e.g., from the 1960s to 1990s at Spitsbergen (Svalbard); Hanssenbauer and Forland 1998) to significant decreases at other sites (e.g., Alaska; Curtis et al. 1998).

There is ample evidence that polar regions are already experiencing major ecosystem changes related to recent climate change. Amongst the most striking evidence has been from records of the declining extent and thickness of multi-year sea ice across the Arctic Ocean. Over the period 1978 to 1998, sea ice cover diminished in area by 14% in winter (Johannessen et al. 1999), and by 44% in average thickness during the past three decades (Rothrock et al. 1999). The largest arctic ice shelf, the Ward Hunt Ice Shelf (83°N, 74°W; > 10 m-thick sea ice) along the northern coast of Ellesmere Island, retreated by 79% over the course of the 20th century, with evidence for substantial thinning of the remaining landfast ice in the 1980s and 1990s (Vincent et al. 2001) and break-up and associated loss of an ice-dammed lake in 2002 (Mueller et al. 2003). Likewise, the collapse of extensive ice shelves on both sides of the Antarctic Peninsula during the last two decades has been attributed to rapid regional warming in that region (Vaughan and Doake 1996; Vaughan et al. 2003). In contrast, the ecosystem of the Dry Valleys in eastern Antarctica responded to a recent 14-year cooling with a doubling in lake ice thickness and resulting in 6 to 9% per year decrease in primary productivity in the lakes (Doran et al. 2002).

Arctic and antarctic regions are also experiencing changes in incident ultraviolet (UV) radiation flux as a result of declining concentrations of stratospheric ozone in spring which have been linked to the production of CFCs. Alarms concerning this relatively recent environmental problem were first raised in the Antarctic (Farman et al. 1985), and some of the biological effects were soon realized (e.g., Vincent and Roy 1993). An integrated overview of UV radiation and its effects on terrestrial, freshwater and marine arctic biota is presented in Hessen (2002) and on polar lakes in Helbling and Zagarese (2003). During the last decade, marked stratospheric ozone declines have been observed in the Arctic during winter (Staehelin et al. 2001). During spring, the resulting increases in surface erythemal UV radiation are estimated to be about 22% relative to the values in the 1970s (Madronich et al. 1998). This increase is likely to worsen in duration and severity in the future, in part associated with greenhouse gas effects on stratospheric cooling (Shindell et al. 1998). In the Antarctic, ozone depletion is most significant during spring when total atmospheric concentrations can decline up to 40%. Fluxes of UV-B (280-315 nm) have increased 6 to 14% since 1980 and are expected to persist until at least 2050 (WMO 2002). UV radiation has a broad range of photobiological and photochemical effects on aquatic ecosystems (Moran and Zepp 1997; Miller 1998; Vincent and Neale 2000), emphasizing the need to better understand the implications of changes in snow and ice cover for UV exposure in polar lakes.

Why do we need paleolimnological data from arctic and antarctic regions?

Despite clear signs of marked recent environmental changes in the circumpolar regions, we as yet have only a limited perspective on how arctic and antarctic climates and environmental conditions have varied in the past. To better understand and anticipate the magnitude, nature, and direction of future changes, it is essential to compare current-day conditions to records of past environmental changes. As long-term monitoring programmes in high latitude regions have only been established for the past several decades, indirect proxy methods must be used to infer these past conditions. Several international and national research initiatives have recognized the need for obtaining long-term, high-resolution paleoenvironmental records from which any recent changes can be compared. These include, for example, projects under the auspices of the IGBP-PAGES (International Geosphere-Biosphere Programme - Past Global Changes), CAPE (Circum-Arctic PaleoEnvironments), NSF-PALE (National Science Foundation - Paleoclimates of Arctic Lakes and Estuaries), NSF-PARCS (Paleoenvironmental Arctic Sciences), and SCAR (Scientific Committee on Antarctic Research). The two fundamental goals common to many of these programmes are: (1) to gain a more complete understanding of the role and impact of the polar regions in global change issues; and (2) to provide a longer temporal baseline against which to measure ongoing changes in polar environments.

As summarized by Bradley (1999), a large number of paleoenvironmental approaches are available to reconstruct climatic and other environmental changes from natural archives (e.g., ice cores, dendroecology, corals, pack rat middens). Whilst some of these records, such as ice cores, have provided important paleoenvironmental information from high latitude regions, many of these natural archives are more applicable in temperate and tropical regions. Fortunately, a characteristic feature of most arctic and antarctic landscapes is the large number of lakes and ponds. For example, although 750,000 km^2 of Canada's land mass is covered by freshwater, 18% of these surface waters are north of latitude 60°N (Prowse and Ommanney 1990). Arctic lakes and ponds, and the biota they support, are sentinels of ecosystem change (Douglas and Smol 1994, 1999; Vincent and Pienitz 1996; Rouse et al. 1997). The information contained in the sediments accumulating in each of these lakes and ponds potentially offers a sensitive record of past environmental changes (Smol and Cumming 2000). Similar lakes are present on many antarctic ice-free coastlines.

Paleolimnology, which is the study of the physical, chemical and biological information stored in lake and river sediments (Smol 2002; Cohen 2003), offers considerable potential for reconstructing the long-term trends in environmental and climatic conditions. Paleolimnological records can be determined for periods well before any marked human influences on the global environment, and can thereby provide a unique guide to natural baseline conditions, as well as to the rate of environmental changes up to the modern day. The abundance of lakes and ponds throughout the circumpolar regions makes paleolimnological approaches especially powerful tools to assist in the reconstruction and interpretation of long-term environmental changes. The overall goal of this book is to provide the reader with an appreciation of the broad spectrum of techniques available for generating historical records, their respective potentials and limits, as well as to provide an overview of the geographic extent of paleolimnological work completed thus far in circumpolar regions.

As noted earlier, the Arctic and Antarctica are likely to experience profound changes in the coming decades. However, due to the lack of direct monitoring data some of the most fundamental environmental questions cannot be addressed. For example: (1) Have these ecosystems changed over time, and if so, when and by how much? (2) What is the range of natural variability in these regions? (3) If systems have changed, were these shifts the result of natural phenomena or related to human activities? Although direct monitoring data are not available, paleoenvironmental data can be used in lieu of these missing data sets.

As evidenced by the contents of this volume, the Arctic and Antarctica display a great diversity of paleoenvironmental records. Polar biotic and abiotic processes are strongly governed by climate and the large seasonal differences between the relatively productive summers and non-productive winters. Extreme seasonality is therefore a dominant factor for the geographical distribution and adaptation of polar life (e.g., Billings 1987). This enhances the role of climate forcing over non-climatic processes in these depositional environments and makes the identification of climate forcing in sedimentary records more likely (Smol 1988). There is already widespread and accumulating paleolimnological evidence for dramatic changes in terrestrial and aquatic communities across northern circumpolar regions within the last two centuries (e.g., Douglas et al. 1994; Overpeck et al. 1997; Rouse et al. 1997; Joynt and Wolfe 2001; Wolfe and Perren 2001; Korhola et al. 2002; Sorvari et al. 2002; Perren et al. 2003, Rühland et al. 2003), which has been attributed at least partly to anthropogenically-induced climatic warming. However, as expected, some studies have also shown that the so-called "global climate change" may have regionally varying impacts (e.g., Laing et al. 2002; Ponader et al. 2002; Paterson et al. 2003; Wrona et al. 2004), as has also been shown for Antarctica (Thompson and Solomon 2002; Gillett and Thompson 2003).

Terrestrial records with decadal to centennial resolution exist in the form of lake sediments and peat deposits, whereas annually resolved records can be found in varved lake records (Lamoureux and Gilbert, this volume) and ice cores (e.g., Reeh 1989), which have been a central focus of high latitude paleoenvironmental research over the last few decades (e.g., PARCS 1999; CAPE 2001). Other terrestrial records, such as aeolian deposits (mainly sand sheets and thin loess deposits), which are widespread along proglacial outwash, may provide important complementary information on similar or longer timescales (Eisner et al. 1995; Lamoureux and Gilbert, this volume). Many of the lakes that are located close to present-day ice sheets and glaciers receive considerable amounts of aeolian sediments, and their records may provide a continuous archive of both paleolimnological changes and aeolian activity.

Paleolimnological studies may also help elucidate the origins and pathways of atmospheric pollutants in the polar regions (Muir et al. 2002; Muir and Rose, this volume). Many scientists now characterize the Arctic and Antarctica as "pollution sinks", the final resting places for many contaminants used in industry and agriculture thousands of kilometres away. These contaminants, in particular organochlorines, are persistent, entering the food chain and bioaccumulating at each trophic level. Inuit and other aboriginal peoples may be exposed to health risks as they ingest such contaminants when eating traditional food, including freshwater organisms (e.g., arctic char).

Lake sediments form ideal archives for studying the patterns of paleoenvironmental change and pollution in circumpolar regions (PARCS 1999) for many reasons, including:

(1) Sources of high-resolution paleoenvironmental records, such as ice cores and tree rings, often provide important environmental information at high temporal resolution, though their availability may often be limited spatially (e.g., trees are absent in more extreme regions, ice caps are limited in geographic coverage). Lakes and ponds, on the other hand, have excellent spatial coverage in arctic and coastal antarctic regions.

(2) Many lake basins contain reliable sedimentary records which, given sufficient dating control, allow for continuous reconstructions of environmental change extending back thousands of years.

(3) Paleoecological reconstructions of climate change are likely to be more reliable if derived from areas with little impact from local human activities such as forestry, agriculture and local pollution. Such impacts can impair our ability to estimate the relationship between individual proxies and climate, as the community composition also responds to changes unrelated to climatic conditions (e.g., nutrients, pH and erosion). The circumpolar regions are the least densely

populated areas of the planet and therefore contain some of the most pristine environments, or at least almost always unaffected by local disturbances.

(4) The biological, chemical and physical dynamics of high latitude lakes and ponds are closely linked to climate and meteorological variability at a variety of timescales (e.g., Welch et al. 1987; Hostetler 1995; Doran et al. 1996; Hardy et al. 1996; Schindler et al. 1996).

(5) Polar lake ecosystems have simplified food webs relative to lower latitudes, and so even minor climatic shifts are expected to generate relatively large changes in biota and depositional processes.

Geographic scope of the book

There is considerable debate as to how the polar and subpolar regions should be circumscribed and defined. The terms Arctic, Antarctic, Subarctic and Subantarctic are commonly used, yet ecologists, climatologists, administrators and politicians often use them in different ways (discussed in Osherenko and Young 1989; AMAP 1998; Hansom and Gordon 1998; Hamelin 2000; Nuttall and Callaghan 2000; Przybylak 2003; Sater 2003). Boundaries exist on maps primarily for political convenience, but in reality their positions reflect a continuum or gradients of environmental variables. In addition, these boundaries may also be time-transgressive due to changes, in space or in time, of environmental patterns, such as temperature or sea ice extent. Despite the lack of conformity concerning boundaries and definitions, it seems helpful to sketch the broad limits of the regions covered in this book by referring to the most commonly used delineations and definitions (Figures 1 and 2).

In this volume we refer mainly to ecoclimatic regions and boundaries, which integrate ecological and climatological aspects, such as the position of treeline and the 10°C summer isotherm (corresponding respectively to the July and February isotherms in the northern and southern hemispheres). Some ecologists prefer the summer isotherms to other polar boundaries as they are equally valid over land and ocean, and on land correspond fairly closely with the position of northern or southern treeline (Larsen 1989). Further, the same criteria can be used for both hemispheres and can provide a more solid basis for comparison, although this comprises a much wider area in the south than in the north. In fact, winters are colder over much of the Subarctic in continental northern Canada and Siberia than in the equivalent subantarctic zone, as the latter covers a wide expanse of ocean and scattered small islands where maritime influences stabilize temperatures.

In the Arctic, the position of treeline (Figure 1) is often a more appealing boundary to ecologists, as treeless tundra is an easily recognized biome, characterized by particular kinds of soil, vegetation and fauna. Also, the presence or absence of trees can be plotted accurately over large areas, whereas isotherms are drawn from records of stations that are generally few and far between. Although the position of treeline often matches closely the 10°C July isotherm for much of its length (Bryson 1966), reflecting the strong influence of summer temperatures on tree growth in both hemispheres, departures arise because treeline location is also determined by many other physical, geological, biological, and social factors, including climate (winds), topography, soil characteristics (permafrost presence or absence), biological interactions such as grazing, and human pressure such as farming or logging (e.g., in Norway the treeline-forming species mountain birch shifted northward and upward because of both climate change and grazing by reindeer). Thus, for the terrestrial Arctic, the position of treeline is a useful practical boundary, whilst the 10°C July isotherm is a useful conceptual one. There is no clearly defined southern (biological) boundary for the Subarctic, whereas in the southern hemisphere, treeline is influenced by oceanographic (water mass) boundaries on the southern tip of South America and the subantarctic islands.

Figure 1. The Arctic as defined by different boundaries discussed in the text (after Stonehouse 1989).

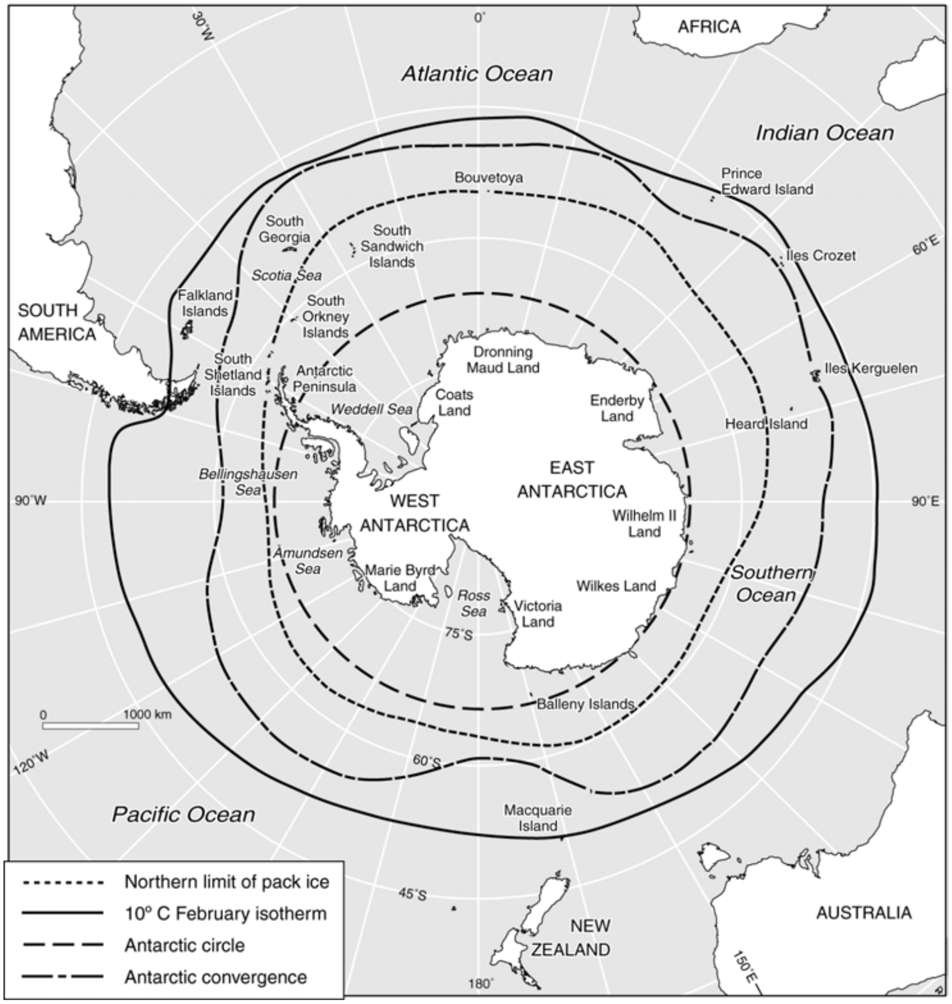

Figure 2. The Antarctic as defined by different boundaries discussed in the text (after Stonehouse 1989).

Antarctica is defined as the Antarctic Continent, whereas the Antarctic has a variety of definitions but is loosely defined as the area south of 60°S. An alternative definition is that the Antarctic lies south of the natural boundary formed by the Polar Frontal Zone or Antarctic Convergence (Figure 2), the region where the cold and dense Antarctic waters meet and sink beneath the warmer and less dense waters of the Pacific, Atlantic and Indian oceans. This oceanographic boundary, which is defined by the convergence of oceanic waters, encircles the continent between latitudes 50°S and 60°S (on average at about 58°S), and roughly corresponds to the 10°C February isotherm (Hansom and Gordon 1998). The subantarctic islands, including Bouvet Island, Îles Crozet, Heard

Island, Îles Kerguelen, Macdonald Islands, Macquarie Island, Marion Island, Prince Edward Island, South Georgia, and South Sandwich Islands, lie close to, but mostly north of, the Polar Frontal Zone. There is also a legal political definition, embodied in the Antarctic Treaty, which defines Antarctica as south of 60°S. Though the terms "Antarctica" and "Antarctic" are often used interchangeably, the former generally refers to the continent itself, whereas the latter denotes the region that includes both ocean and the continent.

Due to the different ways of delineating the boundaries of the Earth's polar regions, we refrained from imposing rigid definitions for the book chapters. Instead, authors defined geographic boundaries in their respective chapters, which in fact were very consistent between contributions.

The focus and the structure of this volume

Aims and scope

As is evident from our title "Long-Term Environmental Change in Arctic and Antarctic Lakes", the over-arching theme of this volume is the paleolimnology of high latitude regions, and not long-term environmental change in general. The time frame covered by the chapters emphasizes late Pleistocene and Holocene events, although other time frames are discussed when appropriate. Each chapter represents a peer-reviewed, up-to-date overview of key aspects of high latitude paleolimnological research by specialists in their fields. Our overall goal is to present an accessible introduction to a non-specialist readership, but also provide a relevant source for paleolimnologists working in high latitude regions.

Despite their importance, the human and social aspects of rapidly changing environments in the circumpolar regions are beyond the scope of this book. Those who are interested in these aspects may refer to other textbooks (e.g., Osherenko and Young 1989; Nuttall and Callaghan 2000). Also, a comprehensive presentation (and overview) of modern arctic and antarctic environments, climate, biota, permafrost and vegetation zonation is beyond the scope of this volume and is not included here. Reviews of these and other diverse themes are provided in Sugden (1982), Stonehouse (1989), Chaturvedi (1996), King and Turner (1997), Hansom and Gordon (1998), Nuttall and Callaghan (2000), Huiskes et al. (2003), Przybylak (2003) and Wonders (2003), to mention just a few sources.

Structure

The general structure of this book is divided into two parts: More specific methodological aspects related to different indicators or approaches are presented in "theme" chapters in Part One, with a focus on their strengths, weaknesses, and challenges. As a series of chapters summarizing paleolimnological techniques has recently been published (Last and Smol 2001a,b; Smol et al. 2001a,b), the focus of the introductory chapters in this volume is on the specialized literature dealing with high latitude regions.

A.P. Wolfe, G.H. Miller, C.A. Olsen, S.L. Forman, P.T. Doran and S.U. Holmgren begin with an introduction to the approaches and problems of dating lake sediment cores in high latitude regions, such as low sedimentation rates, low ^{210}Pb concentrations and the paucity of terrestrial macrofossils (Chapter 2).

In their chapter on the physical and chemical properties and proxies of high latitude lake sediments (Chapter 3), S.F. Lamoureux and R. Gilbert provide an overview of present-day processes that govern sediment formation in glacial and periglacial lake systems, and how these processes might be reflected in sedimentary records. Their chapter also introduces methodologies to investigate sediments from these remote sites, including dating, mineralogy, sediment texture, organic matter and trace element analyses.

K. Gajewski and G.M. MacDonald discuss pollen and charcoal studies of ice cores and lacustrine records in arctic regions, including a synthesis of some of the palynological methods used in polar regions (Chapter 4).

Algal indicators and their potential as proxies of long-term environmental change in high latitude lakes are summarized in Chapter 5 by M.S.V. Douglas, P. Hamilton, R. Pienitz and J.P. Smol. A variety of morphological and biogeochemical indicators and their applications in studies of high latitude environmental and climatic changes (e.g., tracking past changes in the underwater penetration of ultraviolet radiation; the effects of local human and animal populations on water bodies) are discussed.

Chapter 6 by O. Bennike, K.P. Brodersen, E. Jeppesen and I.R. Walker reviews the use of aquatic invertebrates as proxy indicators in high latitude paleolimnological studies. The chapter focuses primarily on the usefulness of the remains of testate amoebae, chironomids and cladocerans as paleoclimate proxies recovered from Holocene lake sediments, with reference mainly to studies from Greenland and northern Europe.

The potential of stable isotopes as tracers of environmental change in polar lakes is explored by T.W.D. Edwards, B.B. Wolfe, J.J. Gibson and D. Hammarlund (Chapter 7). Their chapter reviews major processes controlling isotopic fractionation, as well as other aspects concerning the use of stable water isotope tracers in lake sediment records. This overview is followed by selected case studies of modern isotopic hydrology at regional to watershed scales and paleohydrological applications at sites in northern Canada and Sweden.

In the final chapter of Part One, the pollution of arctic and antarctic lakes, as revealed by their sedimentary archives, is summarized by D.C.G. Muir and N.L. Rose (Chapter 8). The authors critically examine studies on heavy metals, persistent organic pollutants (POPs), and anthropogenic particles in sediment cores, while demonstrating their value and potential for the assessment of large-scale spatial and temporal trends of atmospheric contaminants and the pathways of exposure to wildlife and humans in polar regions.

Part Two of this volume consists of a series of regional syntheses that provide overviews of paleolimnological work completed in high latitude regions from both hemispheres.

In their review of paleolimnological studies from the Canadian Mid- and High Arctic (Chapter 9), A.P. Wolfe and I.R. Smith summarize investigations into late Quaternary and Holocene climatic and environmental changes in regions north of mainland Canada (including the Arctic Archipelago and Boothia and Melville peninsulas), with special emphasis on case studies from Ellesmere and Baffin islands.

B. Finney, K. Rühland, J.P. Smol and M.-A. Fallu provide an overview of paleolimnological work completed in the North American Subarctic (Chapter 10), including studies from Alaska, Yukon, Northwest Territories, southern Nunavut, northern Québec, and Labrador. The importance of the treeline ecotone and permafrost is also emphasized in this chapter.

The Holocene paleolimnology of Greenland and the North Atlantic Islands, including Iceland, Svalbard, Jan Mayen, Bjørnøya, and the Faeroe Islands is surveyed in Chapter 11, authored by N.J. Anderson, D.B. Ryves, M. Grauert and S. McGowan. They elaborate on the potential role of paleolimnological research from the North Atlantic region in studies addressing questions related to climate variability, including the North Atlantic Oscillation (NAO), as well as post-glacial refugia and pathways of species migration.

In their chapter on paleolimnological research from northern Russian Eurasia, G.M. MacDonald, T.W.D. Edwards, B. Gervais, T.E. Laing, M.F.J. Pisaric, D.F. Porinchu, J.A. Snyder, N. Solovieva, P. Tarasov, and B.B. Wolfe present examples of recent biological and stable isotope records from lakes in the far north of European Russia (Kola Peninsula) and Siberia (Chapter 12). They also provide a synthesis of Holocene paleohydrological changes based on Russian lake-level data sets.

A. Korhola and J. Weckström complete the geographical coverage of work done in the northern hemisphere with their review of paleolimnological studies completed in the northwestern European Arctic, including arctic Fennoscandia and the Kola Peninsula (Chapter 13).

Aspects of long-term environmental change in the Earth's southern hemisphere are dealt with by D.A. Hodgson, P.T. Doran, D. Roberts, and A. McMinn (Chapter 14). Their comprehensive review discusses many fundamental and practical aspects of paleolimnological studies in Antarctica and the Subantarctic Islands, links to other paleo-disciplines (e.g., ice core studies), and the relevance of this work to Earth system science and global change research.

In the final chapter of Part Two, P.T. Doran, J.C. Priscu, W.B. Lyons, R.D. Powell, D.T. Andersen, and R.J. Poreda provide insights into the historical records preserved in extreme cold lake habitats, including Lake Vostok and the Dry Valley lakes in Antarctica, and their relevance for a better understanding of the origin and evolution of life on Earth (Chapter 15). They also discuss the connection between these extreme polar environments and water bodies that may exist elsewhere in our solar system, notably on Mars and Jupiter's moon Europa.

Finally, a short epilogue presents a brief synthesis on the strengths and weaknesses of different paleolimnological methods and approaches used in arctic and antarctic regions. It briefly defines some of the most important scientific problems and provides an outlook on future paleolimnological challenges. The volume concludes with a Glossary and Index.

Paleolimnological research in polar regions has seen tremendous advances and progress over the last two decades. We hope this volume will provide a useful synthesis of research completed to date, and serve as a point of departure for the many exciting new projects to be completed in arctic and antarctic regions.

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