CLIMATIC EXTREMES IN SOUTHERN MANITOBA DURING THE PAST MILLENNIUM

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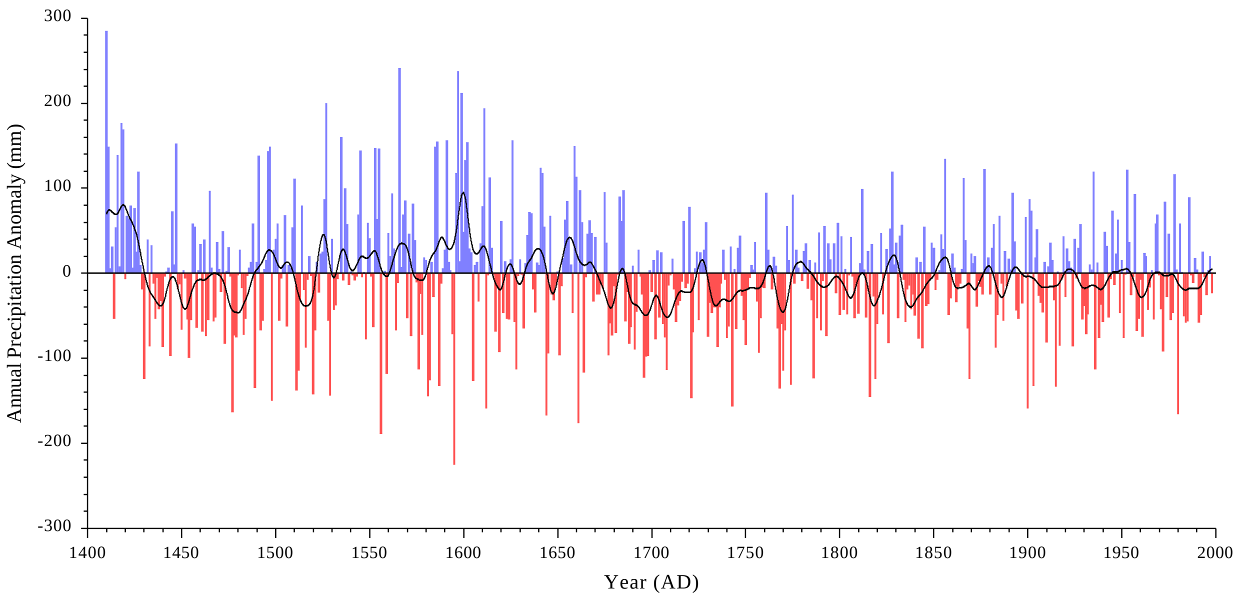

FINAL REPORT

Climate Change Action Fund
Environment Canada
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1. Executive Summary

Our society is adapted to the climate that we have experienced in the past. While we assume that these conditions will continue into the future, unusual climatic conditions, such as the Prairie droughts of the 1930s or the Red River flood of 1997, are tremendously disruptive to our society and economy. While we have instrumental climate records in Manitoba for most of the 20th century, the last 100 years is a tiny fraction of the Earth's history. Therefore, we need to expand our perspective and look at a longer period of time in order to determine how variable our climate can be. The Government of Canada Climate Change Action Fund funded research into past climate change in Manitoba led by Dr. Erik Nielsen of the Manitoba Geological Survey. Dr. Nielsen's team reconstructed the climate history of southern Manitoba over the past thousand years from natural climate records, such as tree rings and layers of sediment on the bottom of Lake Winnipeg.

The growth patterns of old trees provide clues regarding climate changes that occurred hundreds or thousands of years ago. In southern Manitoba, tree-ring research used old living trees, timbers from 19th century buildings and logs preserved in riverbanks to construct an annual record of tree growth that extends back to AD 1286. The changing pattern of wide and narrow tree-rings, representing years of good or poor tree growth, was used to estimate how annual precipitation in the Red River valley has changed over the last 591 years. In the 19th century, tree rings record two roughly 10-year wet 'pulses' around 1830 and the late 1850s, as well as dry episodes in the 1840s and 1870s. The tree-ring record suggests that southern Manitoba experienced an extraordinarily severe and prolonged drought in the late 17th and early 18th centuries. Between 1661 and 1774, annual precipitation was below normal every two years out of three. This dry event is also known from lake records in North Dakota and Minnesota, which suggests that arid conditions may have extended over the entire Red River basin for over a century. In contrast, southern Manitoba experienced a much wetter climate in the late 16th and early 17th centuries, with annual precipitation reaching its peak circa 1600. A parallel investigation into past Red River floods has demonstrated that trees growing along the Red and Assiniboine rivers contain a record of extreme floods spanning the last five and a half centuries. In the future, these records will allow researchers to determine how long-term climatic and environmental change affect flood risks in the Red River basin.

The research also relied on sediment cores from Lake Winnipeg. Side-scan sonar records collected from the Coast Guard Ship *Namao* in 1994 and 1996 were used to select sites offshore from Gimli that had not been disturbed by ice pressure ridges that drag on the lake bottom. The *Namao* was used to collect several sediment cores from these undisturbed sites that were analysed at laboratories across North America. This work showed that the upper 1.5 metres of sediment record significant changes over the past thousand years. Pollen in the sediments shows cycles in willow and alder abundance and abnormal influxes of coarse silt that may reflect past fluctuations in regional hydroclimate and groundwater. Ongoing research will assess the variability of the texture, pollen, and geochemical records from Lake Winnipeg and identify their paleoenvironmental significance.

Our research shows that the climate in southern Manitoba is much more dynamic and variable than previously thought. Over the six hundred years, Manitoba has experienced dry and wet intervals that were more severe and prolonged than those in the 20th century. If such events were to recur in the future, they would have an enormous impact on local agricultural production, flood risks, groundwater supplies and regional hydroelectric potential.

2. Climatic Extremes in Southern Manitoba during the Past Millennium

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Introduction

In order to predict Canada's future climate successfully, it is critical to understand how our climate has behaved in the past. Studying past climatic change puts current trends in perspective, reveals the mechanisms that govern the Earth system, provides data to test predictive models and evaluates the impact of climatic change on biological and geological systems and processes. Although paleoclimatic research has made significant advances toward understanding how the Earth's climate has changed, long, high-resolution (i.e., annual) records of climatic change are still relatively inadequate globally, and large gaps exist in the current Canadian paleoclimatic network. The spatial bias in paleoclimatic proxy records is a significant limitation, as changes in average global conditions are not experienced in all regions uniformly. As global change is the result of changes at the regional or local scale, there is a critical need to understand climate history at the local and regional levels.

The Red River basin has experienced dramatic shifts in regional hydroclimate recently, as indicated by the unrelenting rise of Devils Lake in North Dakota and high-magnitude flooding along the Red River. These extreme events have enormous social, political and economic ramifications and have provided a renewed urgency to better estimate natural climatic variability in Manitoba. This report summarizes research on past hydroclimatic change in southern Manitoba supported by funds received from the Canadian Climate Change Action Fund (CCAF) during the period April 2000 to June 2001. This project involved scientists from Manitoba Industry, Trade and Mines (Manitoba Geological Survey), the Canadian Museum of Nature and Natural Resources Canada (Geological Survey of Canada). The primary goal of this work was to derive a proxy record of annual to century-scale fluctuations in climatic extremes for southern Manitoba over the past millennium, using tree ring, lake sediment, and pollen archives. This project was an outgrowth of investigations into the flood history of the Red River initiated by Natural Resources Canada and the Red River Flood Protection Program in 1999. As climate change is the dominant control of flooding at timescales of less than a millennia, CCAF's support of this project was directly relevant to ongoing research that will identify how flood hazards are affected by climatic change. Additional funding for this programme was provided by the Red River Flood Protection Agreement and the Manitoba Geological Survey.

Significant Outcomes

This report contains three papers describing research supported by CCAF that will improve our understanding of the natural range of climatic variability in Manitoba. The first two papers use paleoclimatic information derived from tree-rings to evaluate climatic change in the Red River valley and southeastern Manitoba.

St. George and Nielsen present a 591-year record of annual precipitation in southern Manitoba derived from a network of bur oak in the Red River valley. This record demonstrates that natural hydroclimatic variability in this region has been much greater in the past than instrumental records would suggest. Tree rings provide evidence of an extreme prolonged dry period in southern Manitoba in the late 17th and early 18th centuries. During this interval, annual precipitation reached its lowest point during the last six centuries, with long-term values below normal for more than a century circa AD 1700. Annual precipitation was below normal every two years out of three between 1661 and 1774. This dry event is also recorded by lake records in North Dakota and Minnesota, which suggests that arid conditions may have extended over the entire Red River basin for over a century. In contrast, southern Manitoba experienced a much wetter climate in the late 16th and early 17th centuries, with annual precipitation reaching its peak circa 1600.

In the second paper, St. George and Nielsen describe the development of new tree-ring network in southeastern Manitoba and northwestern Ontario. In Fall 2000, reconnaissance sampling was conducted to determine the paleoclimatic potential of ringwidth and densitometric records from native conifers. This research has demonstrated that long records spanning the last 300-400 years can be developed from *Thuja occidentalis* (eastern white cedar) growing in eutrophic swamps in southeastern Manitoba. Furthermore, ringwidth records from *T. occidentalis* and *Pinus resinosa* and densitometric records from *P. resinosa* contain strong stand-wide signals that may be related to climatic forcing factors. Future research will identify the external factors that have influenced tree growth during the 20th century and use these relationships to develop additional independent records of past regional climate change.

The third paper by Lewis *et al*. describes limnological work in Lake Winnipeg related to paleoenvironmental research. Several sediment cores were collected from the bottom of the south basin of Lake Winnipeg using the CCGS *Namao*. This material was used to derive a record of sediment properties and compositional variations related to changes in regional environmental conditions during approximately the last millennium. Paleomagnetic and radiometric dating indicated that these lake records spanned the approximate interval AD 900 to 1998. Pollen evidence suggests that southern Manitoba experienced a change to cooler climatic conditions beginning at approximately AD 1100 and terminating at AD 1775. Peaks in *Alnus* pollen could reflect wetter conditions circa AD 1050 and 1620. Further investigations are warranted to determine the extent to which increases in alder and willow pollen are indicators of wet periods and high groundwater tables. Studies of carbon compounds in lake sediments yielded the surprising result that most organic matter in Lake Winnipeg is derived from terrestrial, rather than lacustrine, plant sources. In the future, detailed inorganic chemical analysis of over forty elements will provide a long-term chemical history in the Lake Winnipeg basin. Preliminary analysis of Pb suggests that human activities have increased Lake Winnipeg's lead content since roughly 1920. Work will continue to assess the variability of the texture, pollen, and geochemical records from Lake Winnipeg and identify their paleoenvironmental significance.

Recommendations for Future Research

This project has significantly advanced our understanding of past climatic change in southern Manitoba and demonstrated that high-resolution paleoclimate records that span several centuries can be derived from grassland regions in Canada. However, the excellent preservation of bur oak logs in the geological record suggests that hydroclimatic records for southern Manitoba can be extended back even further. Although absolutely-dated tree-ring records extend presently from AD 2000 to AD 1286, radiocarbon ages for logs recovered from the alluvium of the Assiniboine River range up to 4,400 yrs. BP. Despite their great age, these subfossil logs remain in excellent condition and, with additional collection, could lead to the development of a continuous record of tree growth in southern Manitoba that spans the last several thousand years. Such a record would provide a unique opportunity to study hydroclimatic changes that have occurred in Manitoba over the last several thousand years and would represent an important global resource for the study of climatic change processes.

Secondly, the current paleoclimatic network in southern Manitoba should be expanded to increase spatial coverage in the Red and Assiniboine basins and to include other watersheds across the province. While this project has generated estimates of past hydroclimatic change in the Red River basin, these results are not necessarily representative of conditions elsewhere in Manitoba. As seasonal and annual precipitation can vary substantially within a short distance, it is important that paleoclimatic models be developed at the finest spatial resolution possible. In particular, our success developing long records for the Red River basin suggests that dendroclimatic modeling may be used in the future to develop estimates for past changes in Lake Winnipeg water levels. Based on our results with dendroclimatic estimates in the Red River valley, it may be possible to use tree-rings to better understand hydrological change over several watersheds used for hydroelectric power generation in Manitoba. Such a record would be directly applicable to improved modeling of hydroelectric production.

Summary

Although these projects are described separately in this report, their combined findings represent a comprehensive multi-proxy record of environmental change in southern Manitoba during the late Holocene. Our research provides the first high-resolution record of past climatic change in the eastern Canadian Prairies and fills in a significant gap in the North America paleoclimate network. Our record of annual precipitation derived from tree rings demonstrates that natural variability in southern Manitoba can be much greater than that observed during the 20^{th} century and will allow us to determine how past hydroclimatic changes have affected the risk of flooding in the Red and Assiniboine River valleys. We are also confident that exploratory work with coniferous trees in southeastern Manitoba and northwestern Ontario will lead to a parallel paleoclimatic record that will support our results from the Red River valley. Limnological records from Lake Winnipeg suggest that long-term vegetative changes are driven by shifts in regional moisture supply and represent an invaluable independent record of hydroclimatic variation in southern Manitoba over the last thousand years.

The results presented in this report imply that southern Manitoba’s regional hydroclimate is considerably more variable than previously thought, with unparalleled dry and wet intervals occurring in the recent past. The potential consequences of such natural variability are staggering. If such events reoccurred, it would have an enormous impact on local flood risks, groundwater supplies and regional hydroelectric potential across Manitoba.

3. A 591-yr Record of Annual Precipitation in Winnipeg Derived from Tree Rings

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Introduction

Studies across North America have demonstrated that long records of precipitation may be derived from climatically sensitive trees growing at forest-prairie ecotones (e.g., Case and MacDonald, 1995; Woodhouse and Meko, 1997). Up to this point, however, dendroclimatic reconstructions in Canada have largely been restricted to alpine sites in western Alberta and British Columbia (Case and MacDonald, 1995; Luckman *et al.*, 1997; Watson and Luckman, 2001; St. George and Luckman, 2001). Although this research has provided high-quality high-resolution records of past regional climatic variability, it cannot be considered representative of conditions experienced in the central and eastern prairies. This is particularly true for reconstructions of precipitation, as drought has been regionally asynchronous in North America during the 20th century (Woodhouse and Overpeck, 1998; MacDonald and Case, 2000).

Long paleoclimatic records in the Canadian Prairies are still relatively rare, and only recently has the paucity of high-resolution climate records for Saskatchewan and Manitoba begun to be addressed (e.g., Sauchyn and Beaudoin, 1998; Case, 2000). While the scarcity of long-lived trees within this region has been a significant obstacle to developing local dendroclimatic precipitation records, the recovery of well-preserved subfossil trees from the alluvium of prairie rivers holds great promise for developing long, moisture-sensitive tree-ring chronologies. In this study, we use a ringwidth chronology developed from living, historical and alluvial bur oak (*Quercus macrocarpa* (Michx.)) in the Red River basin to reconstruct annual precipitation in southern Manitoba since AD 1409.

Methods

The Red River Tree-Ring Network

To this point, tree-ring research in southern Manitoba has focussed on dendrohydrological reconstructions of past Red River floods from anatomical anomalies in riparian trees (St. George *et al.*, 1999; St. George and Nielsen, 2000). However, oak ringwidth series from the Red River basin share common variance over several hundred years and nearly a hundred kilometres, which suggests that tree growth in the Red River valley has been strongly influenced by a common set of external factors. This spatial and temporal coherence most likely reflects climatic variability, as no other external factor has been observed to influence tree growth for large areas over long periods of time (Fritts, 1976).

Tree-ring samples were collected from living trees and logs recovered from historical buildings, 19th century archaeological sites and alluvial sediments in the Red River basin (Figure 3.1; Table 3.1). The Red River basin is located at the northern edge of the North American Great Plains and drains territory within Manitoba, North Dakota and Minnesota. Roughly 1.2 million people live in the Red River drainage basin, including 70 and 60 percent of the population of Manitoba and North Dakota, respectively. The Red River valley is also a highly productive agricultural area and is a major livestock, grain and sugar beet producer for local and international markets (International Red River Basin Task Force, 1997).

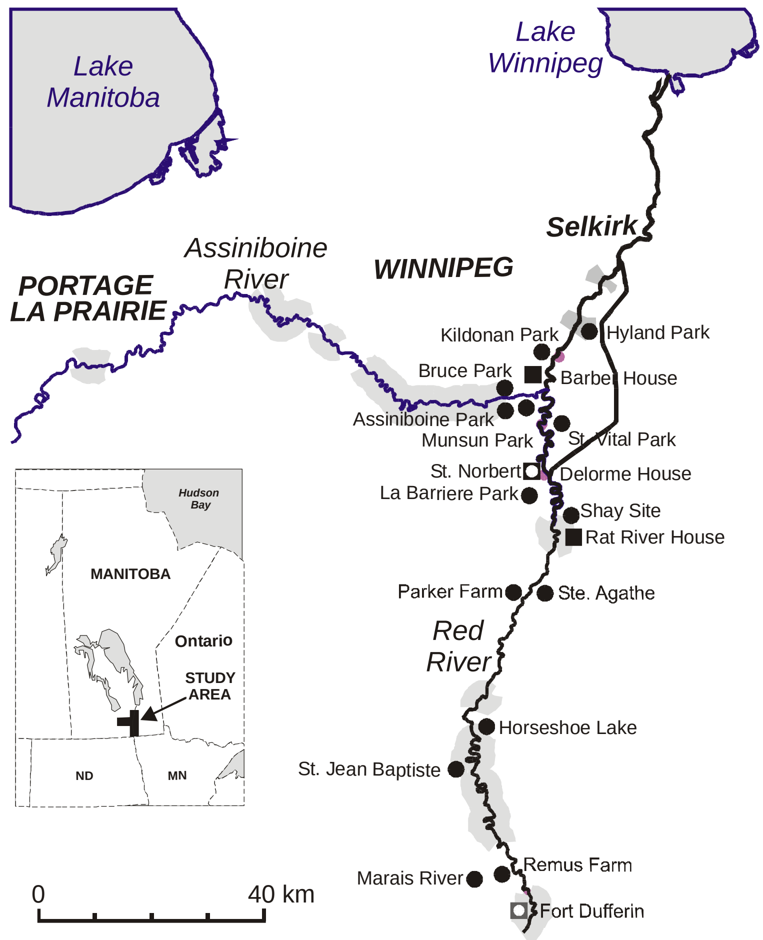

Figure 3.1. The Assiniboine and Red River basins in southern Manitoba and the bur oak sampling network. Circles represent living tree sites. Squares indicate selected historical buildings and archaeological sites. Shaded corridors along the rivers represent reaches where alluvial subfossil logs were collected.

Table 3.1. Bur oak collection sites in the Red River basin.

Site	Lat. (° N)	Long. (° W)	Type	No. of Trees	Span
Hyland Park	49° 59' 05"	97° 02' 55"	Living	17	1823 - 1999
Kildonan Park	49° 56' 30"	97° 06' 00"	Living	38	1720 - 1999
Winnipeg	Various locations		Living	15	1822 - 1994
			Historical	22	1644 - 1865
Barber House	49° 54' 20"	97° 07' 15"	Historical	38	1648 - 1864
Munsen Park	49° 52' 30"	97° 09' 40"	Living	9	1860 - 1999
Bruce Park	49° 52' 30"	97° 13' 30"	Living	15	1855 - 1999
St. Vital Park	49° 49' 45"	97° 08' 05"	Living	17	1830 - 1998
St. Norbert	49° 45' 25"	97° 08' 50"	Living	10	1855 - 1998
LaBarriere Park	49° 43' 10"	97° 10' 30"	Living	11	1892 - 1998
Delorme House	49° 33' 40"	97° 11' 05"	Historical	3	1696 - 1853
Shay	49° 38' 45"	97° 06' 45"	Living	14	1907 - 1999
Rat River House	49° 35' 15"	97° 08' 15"	Historical	6	1659 - 1859
Ste. Agathe	49° 32' 45"	97° 12' 10"	Living	11	1856 - 1998
Parker Farm	49° 31' 50"	97° 13' 00"	Living	24	1877 - 1998
Horseshoe Lake	49° 20' 25"	97° 19' 30"	Living	15	1907 - 1999
St. Jean Baptiste	49° 16' 35"	97° 19' 50"	Living	10	1883 - 1997
Remus Farm	49° 04' 20"	97° 12' 30"	Living	10	1875 - 1998
Marais River	49° 03' 50"	97° 18' 35"	Living	13	1850 - 1998
Fort Dufferin	49° 01' 50"	97° 12' 10"	Living	12	1866 - 1999
			Historical	3	1723 - 1872
Assiniboine alluvium	Various locations		Subfossil	34	1286 - 1968
Red River alluvium	Various locations		Subfossil	43	1448 - 1997

Vegetation in southern Manitoba is dominated by tall- and mixed-grass prairie, with trees largely restricted to narrow (100-200m wide) forest belts along rivers and streams. Native riverbank trees (with increasing distance from river) include plains cottonwoods (*Populus deltoides* Bartr. Ex Marsh. ssp. *monilifera* (Ait.) Eckenw.), willows (*Salix* spp.), basswood (*Tilia americana* L.), green ash (*Fraxinus pennsylvanica* var. *subintegerrima* (Vahl) Fern.), Manitoba maple (*Acer negundo* L.), American elm (*Ulmus americana* L.), and bur oak. We sampled *Q. macrocarpa* due to its abundance in southern Manitoba, long lifespan (up to 300 yr.; Wolfe, 1999, pers. comm.) and excellent preservation. Modern oaks occur most commonly in southern Manitoba along rivers and streams where the elevated local water table protects them from prairie aridity. Samples from living trees were collected at sixteen sites inside an 100-km corridor along the Red River. There are relatively few trees older than 140 years along the Red River due to extensive logging by European and Canadian settlers during the early and mid 19th century[1]. This age limit effectively precludes the development of long tree-ring chronologies using live trees exclusively. The oldest living specimen was located in Kildonan Park and reached an age of 279 yr. before its death of natural causes in 1999.

In order to extend our regional chronology beyond the lifespan of the oldest living trees, we collected tree-ring samples from historical buildings and alluvial logs. Many houses constructed by settlers in the 19th century were built from local oak and a small number of structures survive to the present. Oak timbers were recovered from nearly a dozen historical buildings, the majority of which were built inside present-day Winnipeg between 1852 and 1880. This period is bounded by the Red River flood of 1852 (which destroyed much of the early settlement in the Red River valley; accounts cited in Clark, 1950) and the arrival of out-of-province lumber via the Canadian Pacific Railway (Carter, 1996). Additional oak timbers have also been recovered from archaeological sites near the confluence of the Red and Assiniboine rivers. These logs post-date Euro-Canada settlement in Manitoba and most trees have outer ring dates between 1830 and 1855. Most subfossil oak logs were recovered from riverbank exposures between Emerson and Morris on the Red River and between Portage la Prairie and Winnipeg on the Assiniboine (Figure 3.1). Rivers in southern Manitoba often contain considerable numbers of subfossil oaks, mainly because anoxic conditions in river alluvium protect logs from destructive biological processes. Age-related chemical processes, including infiltration by oils, resins and gums, make the heartwood more durable, less penetrable and less susceptible to decay. Alluvial oaks are commonly lodged in cut banks and become exposed by minor erosion and bank slumping during low water stages in September and October.

Q. macrocarpa Ringwidth Records

Tree-ring samples were prepared, measured and cross-dated following standard techniques (Stokes and Smiley, 1968; Grissino-Mayer *et al.*, 1996). The combined *Q. macrocarpa* record for southern Manitoba includes 398 cross-dated trees and extends continuously for 714 years, from AD 1999 to 1286. However, radiocarbon ages for subfossil logs range up to 4230 ±70 BP (BGS-1851) on the Assiniboine river (Nielsen *et al.*, 1993; Morlan *et al.*, 2000) and future collection of older material could potentially extend the regional oak record to cover the last several thousand years.

Ringwidth measurements are nonstationary time series that generally exhibit declining means and variances with increasing tree age (Fritts, 1976). This age-trend must be removed

[1]Ross (1856) described commercial timber-cutting in the early Red River settlement and stated that "the upper and best wooded part of the settlement has been entirely ruined, and rendered treeless" (page 199).

from the ringwidth series to maximise the desired climate-related signal. Common detrending procedures involve fitting a linear or simple curvilinear function to the ringwidth series for each tree and expressing the original value as anomalies from this fitted line (Fritts, 1976). However, traditional standardisation techniques limit the recoverable frequency of long-term variability in the final composite record to roughly two-thirds the mean segment length of the component tree-ring series (Cook *et al.*, 1995). As the mean tree age for the Red River oak network is approximately 118 years, applying traditional standardisation techniques to these data would result in a composite chronology with a maximum low-frequency variance on the order of only 70 years.

In order to preserve as much low-frequency climate information as possible in the ringwidth series, age-related growth trends were removed using Regional Curve Standardisation (RCS; Briffa *et al.*, 1992; Cook *et al.*, 2000). RCS detrending aligns ringwidth measurements by biological age to estimate a single mean growth curve that reflects the intrinsic trend in radial tree growth as a function of age (Cook *et al*., 2000). Using the RCS method allows the final composite record to retain low-frequency variance greater than the length of its component segments (Briffa *et al*., 1992).

Prior to RCS standardisation, trees were divided into two groups based on their inner ring date. Wood-cutting was a major economic activity for many early Red River settlers and the riparian forests along the Red River were logged extensively during the mid-19th century for use as construction materials and steamboat fuel. Oak trees that survived or were established after local logging were essentially unhindered by competition effects. Since these trees also experienced their juvenile growth increase nearly simultaneously, human influence caused mean oak ringwidth to be dramatically greater in the late 19th and early 20th century than at any time since the early 1400s (Figure 3.2). Mean oak ringwidth increased nearly 200 percent between 1840 and 1900. Living trees that span the interval containing this anthropogenic-induced growth release make up more than sixty percent of the Red River oak database and deriving a mean RCS growth curve by aligning measurements from all oaks would result in a biased composite chronology. As trees that grew prior to the mid-19th century lack the extreme growth release present in later trees, detrending using a biased RCS curve would underestimate regional tree growth prior to 1800.

In an attempt to eliminate the influence of anthropogenic disturbances in the final RCS composite oak chronology, trees were detrended based on their establishment date. Samples were divided into groups for oaks established before and after 1800, effectively separating the oak record into living-tree and historical timber subgroups, with subfossil samples falling into both categories. Figure 3.3 shows the RCS curves used to standardise the Red River bur oak record. Prior to 1800, the mean bur oak ringwidth series is reasonably simple, with ringwidth declining nearly linearly with tree age[2]. In contrast, the post-1800 group exhibits a juvenile increase for the first 30 years of tree growth and has generally higher ringwidth than the pre-1800 group. The post-1800 RCS curve stabilises between 40 and 50 years of age and then declines in a nearly linear fashion afterwards. Both RCS curves contain noise unrelated to age-

[2] Due to the limited number of older oak samples, the variance of the pre-1800 RCS curve increases dramatically after 200 years. Since the present oak dataset cannot provide a good estimate of regional tree growth for this age-class, the ringwidth records for eleven trees in the pre-1800 group were truncated at 196 years before being incorporated into the composite and site chronologies.

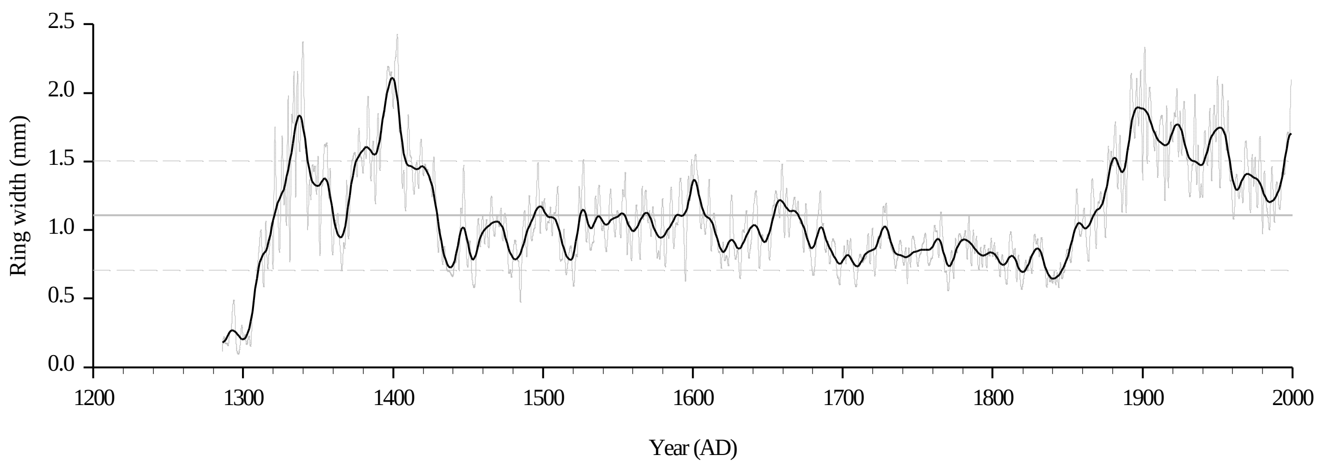

Figure 3.2. Mean (unstandardised) ringwidth, Red River bur oak network. Solid line represents series mean and dashed line indicates one standard deviations.

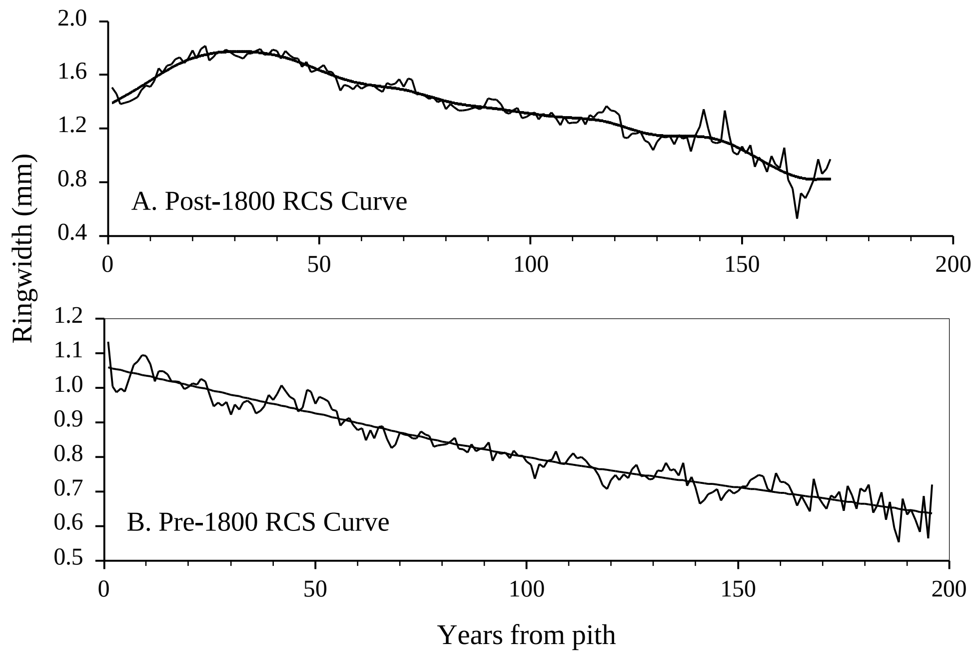

Figure 3.3. RCS curves used in standardisation. Oak ringwidth series are categorised by establishment date.

growth trends and have been smoothed with a theoretical growth curve. These smoothed curves were used to detrend and standardised the individual ringwidth series for each establishment group. The post-1800 chronology was detrended with a 40 percent spline to further remove the late 19th century growth increase caused by logging. The pre- and post-1800 chronologies extend from AD 1286 - 1883 and 1822 – 1998 respectively, with 62 years of overlap.

The two chronologies for the pre- and post-1800 groups were combined (using an average weighted by the number of trees in each chronology) to produce a single composite record that extends from AD 1999 to 1286. Figure 3.4 A plots this composite oak chronology, along with a filtered series used to emphasise longer-term variation. Figures 3.4 B and C show a running series of average correlation (Rbar) and expressed population signal (EPS; Wigley *et al.*, 1984). Both descriptors measure the strength of the common signal in the RCS chronology and were calculated using 50-year windows with 1-year overlaps. The apparent gap in Rbar and EPS values between the two chronologies circa 1840 is an edge effect created by the use of a 50-year window. The Rbar is relatively consistent between 0.2 - 0.4 over most of the last 600 years. Only two trees cover the interval between 1416 and 1463 and therefore standard errors cannot be determined for this period. The running EPS value expresses the degree to which the composite chronology portrays the hypothetically perfect chronology (Briffa and Jones, 1990). The oak chronology maintains an EPS greater than 0.9 back until 1563, where declining sample depth causes it to fall briefly below 0.85. The chronology's EPS value then recovers and stays above 0.85 until the early 15th century. Based on these measures of signal strength, we determined that the oak chronology was suitable for dendroclimatic reconstruction back only as far as AD 1409. Prior to this point, noise associated with decreasing sample depth reduces the reliability of the composite record and precludes paleoclimatic reconstruction for the earliest period in the tree-ring record.

Climate Records in the Red River Valley

Despite sporadic climatic references by early explorers and settlers dating from the late 1700s (Allsopp, 1977; Rannie, 1998), regular daily observations in Manitoba did not begin until the late 19th century. The Meteorological Service of Canada (MSC) has produced a database of Canadian meteorological records that have been corrected for inhomogeneities and missing data (Vincent and Gullett, 1999; Mekis and Hogg, 1999). This dataset includes two stations in the Red River valley, with corrected monthly temperature and precipitation records in Winnipeg running from 1895 to 1999, and a shorter precipitation series at Emerson extending from 1943 to mid-1997. While other long climate records in the Red River valley are available from Morris and Ste. Agathe, these data have not been checked by MSC for inhomogeneities and were not used in this study.

Ringwidth-Climate Relationships

Possible climatic signals in the Red River *Q. macrocarpa* network were identified by correlating the detrended ringwidth indices for each of the 16 living-tree sites that span most of the 20th century against the instrumental climate record at Winnipeg. Several researchers have found that ringwidth correlates most strongly with annualised data that includes contributions from the previous year (e.g., Duvick and Blasing, 1981; Case and MacDonald, 1995; Watson and Luckman, 2001). Therefore, correlations were run between the living tree chronologies and 12 different annual periods from January-December of the growth year to prior February-present January.

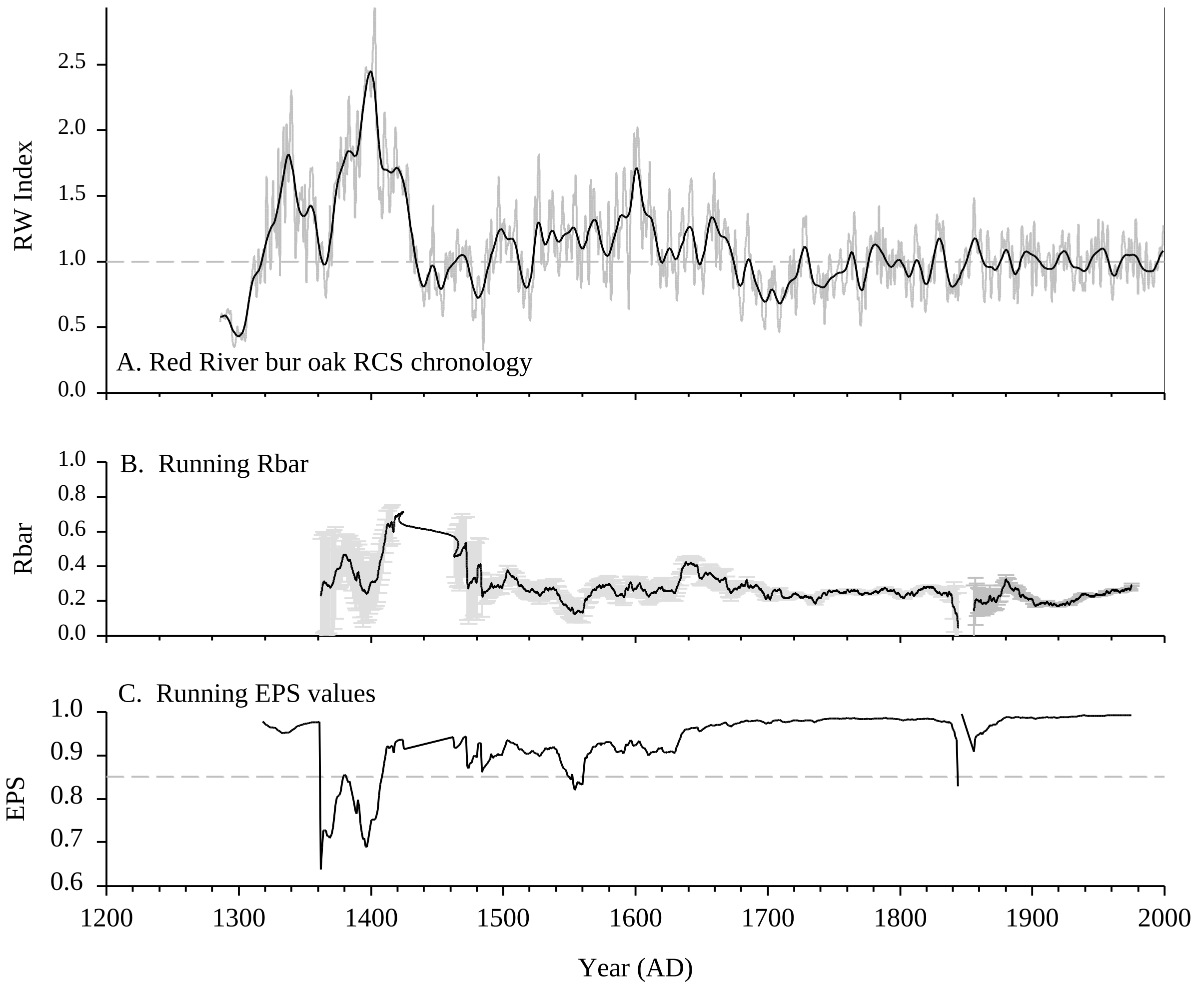

Figure 3.4. The Red River bur oak RCS chronology (**A**) and its running Rbar (**B**) and EPS (**C**) statistics. The moving window used for computing these values is 50 years with 1 year overlaps. The grey bars on the Rbar plot are two standard errors.

Correlations were strongest between ringwidth and precipitation-years that included the spring and summer of the growth year and the fall/winter of the prior year (Table 3.2). The average correlation for all sixteen sites were highest with pAugust-July precipitation; all sites had a significant correlation (p = 0.01) with this variable. Correlations with annual temperature were usually negative but rarely significant. These results suggest that oak ringwidth in the Red River valley is strongly influenced by the amount of precipitation received between July of the growth year and prior August and that this variable is the best candidate for dendroclimatic reconstruction.

Paleoclimatic Reconstruction of Annual Precipitation

Stepwise multiple linear regression was used to obtain a statistical expression relating the composite ringwidth chronology (RW) and August to July precipitation at Winnipeg. To account for lagged and autocorrelated growth effects in the oak chronologies, forward (RW_{+1}, RW_{+2} and RW_{+3}) and backward (RW_{-1}, RW_{-2} and RW_{-3}) lagged ringwidth chronologies were included as potential predictors in the regression analysis. Four variables were significant predictors of August-July precipitation (Table 3.3): RW, RW_{-1}, RW_{-2}, and RW_{+1}. The multiple regression model explains approximately 40% of the variance in the instrumental precipitation record.

The reconstruction of August to July precipitation extends from AD 1409 to 1998 (Figure 3.5) and suggests that southern Manitoba’s hydroclimate has experienced relatively little long term change during the last two hundred years. Mean annual precipitation for the period 1775-1998 (590 mm) is only slightly lower than that recorded during the reference period (1961-1991; 598 mm). Precipitation trends during the 19th century were highlighted by two wet periods centred around 1829 and the late 1850s where annual precipitation was above average for seven and nine consecutive years, respectively. These intervals also coincide with the two largest floods experienced in the lower Red River valley during the last two hundred years (Rannie, 1998). However, the reconstruction suggests that, prior to AD 1790, annual precipitation in the Red River valley was more variable. The most prolonged extreme dry period identified in the reconstruction occurred circa 1670-1775. Although this interval was interrupted briefly by short periods of slightly wetter conditions at approximately 1685, 1730 and 1760, persistent dry conditions dominated southern Manitoba for over a century. Between 1671 and 1774, precipitation was above average for 33 years and below average for 68 years. Annual precipitation was below normal for eight consecutive years between 1730 and 1737. This prolonged dry period corresponds with salinity peaks in lacustrine records from North Dakota and Minnesota at approximately 250 yr BP (Yu and Ito, 1998) and suggests that arid conditions may have extended over the entire Red River basin for nearly a century. This period was preceded by a major wet interval between 1520 to 1670, with running 15-year precipitation reaching its highest value in the record circa 1600. Most extreme annual precipitation values also fall within the earliest half of the reconstruction (Table 3.4). All years with reconstructed annual precipitation values greater than 2 standard deviations above the 1961-1990 mean occur prior to 1800. Extremely dry years are less frequent than wet years but are more evenly distributed throughout the 591-year record. Two years in the 20th century (1980 and 1900) represent the sixth and eighth driest years respectively during the last six centuries.

Table 3.2. Summary of significant correlations between annual climate data and 16 *Q. macrocarpa chronologies.* Annual periods extend from January-December of the growth year to prior February-growth-year January. Highlighted correlations are significant at p > 0.01.

	Winnipeg Precipitation											
Site	Jan-Dec	pDec-Nov	pNov-Oct	pOct-Sep	pSep-Aug	pAug-Jul	pJul-Jun	pJun-May	pMay-Apr	pApr-Mar	pMar-Feb	pFeb-Jan
Hyland Park	0.41	0.44	0.44	0.45	0.46	0.46	0.38	0.19	0.05	-0.03	-0.09	-0.09
Kildonan Park	0.29	0.28	0.29	0.34	0.36	0.40	0.38	0.26	0.11	0.02	-0.05	-0.03
Winnipeg	0.34	0.33	0.31	0.33	0.35	0.34	0.25	0.17	0.00	-0.03	-0.08	-0.09
Munsun Park	0.44	0.48	0.49	0.46	0.46	0.47	0.40	0.19	-0.01	-0.09	-0.15	-0.16
Bruce Park	0.46	0.45	0.45	0.47	0.50	0.48	0.38	0.31	0.14	0.08	0.00	0.01
St. Vital Park	0.43	0.43	0.42	0.45	0.43	0.51	0.46	0.32	0.15	0.05	-0.01	0.01
St. Norbert	0.46	0.44	0.44	0.46	0.41	0.47	0.40	0.32	0.14	0.03	-0.04	0.00
LaBarriere Park	0.40	0.42	0.43	0.45	0.49	0.54	0.39	0.34	0.18	0.11	0.07	0.08
Shay	0.37	0.37	0.37	0.43	0.38	0.44	0.32	0.26	0.08	-0.03	-0.06	-0.01
Ste. Agathe	0.38	0.39	0.43	0.47	0.46	0.49	0.44	0.37	0.25	0.12	0.06	0.07
Parker Farm	0.43	0.44	0.49	0.55	0.55	0.61	0.52	0.43	0.28	0.14	0.10	0.10
Horseshoe Lake	0.39	0.38	0.38	0.42	0.43	0.47	0.27	0.26	0.17	0.07	0.03	0.06
St. Jean Baptiste	0.23	0.24	0.26	0.31	0.35	0.31	0.27	0.18	0.07	0.00	-0.06	-0.02
Remus Farm	0.40	0.40	0.42	0.51	0.54	0.56	0.50	0.43	0.29	0.20	0.15	0.16
Marais River	0.42	0.41	0.46	0.54	0.58	0.57	0.40	0.38	0.26	0.15	0.09	0.11
Fort Dufferin	0.33	0.32	0.36	0.43	0.44	0.45	0.33	0.36	0.22	0.16	0.08	0.11
Mean	*0.39*	*0.39*	*0.40*	*0.44*	*0.45*	*0.47*	*0.38*	*0.30*	*0.15*	*0.06*	*0.00*	*0.02*

	Winnipeg Temperature											
Site	Jan-Dec	pDec-Nov	pNov-Oct	pOct-Sep	pSep-Aug	pAug-Jul	pJul-Jun	pJun-May	pMay-Apr	pApr-Mar	pMar-Feb	pFeb-Jan
Hyland Park	-0.03	-0.07	-0.11	-0.09	-0.09	-0.08	-0.11	-0.09	-0.06	0.00	0.04	0.03
Kildonan Park	0.10	0.06	0.00	0.00	0.00	0.00	-0.02	0.00	0.05	0.16	0.16	0.18
Winnipeg	0.16	0.20	0.19	0.17	0.15	0.14	0.11	0.13	0.14	0.17	0.12	0.10
Munsun Park	0.12	0.08	0.04	0.03	0.01	0.00	-0.04	-0.02	0.01	0.05	0.04	0.03
Bruce Park	-0.07	-0.04	-0.06	-0.07	-0.08	-0.08	-0.12	-0.10	-0.05	0.03	0.07	0.09
St. Vital Park	-0.01	0.01	0.03	0.02	0.00	0.00	-0.03	0.00	0.02	0.09	0.09	0.02
St. Norbert	-0.05	-0.06	-0.04	-0.04	-0.04	-0.04	-0.05	-0.02	0.02	0.08	0.07	0.01
LaBarriere Park	-0.05	-0.09	-0.12	-0.11	-0.14	-0.14	-0.14	-0.13	-0.09	-0.04	-0.01	-0.03
Shay	-0.02	-0.07	-0.06	-0.10	-0.11	-0.11	-0.12	-0.08	-0.05	0.02	0.02	0.02
Ste. Agathe	-0.10	-0.18	-0.20	-0.18	-0.17	-0.17	-0.20	-0.18	-0.13	-0.03	0.01	0.00
Parker Farm	0.00	-0.10	-0.14	-0.14	-0.13	-0.15	-0.18	-0.18	-0.13	-0.06	-0.03	-0.06
Horseshoe Lake	-0.11	-0.15	-0.13	-0.12	-0.12	-0.12	-0.13	-0.10	-0.09	-0.05	0.02	0.01
St. Jean Baptiste	-0.08	-0.14	-0.18	-0.15	-0.13	-0.14	-0.15	-0.11	-0.07	0.00	0.01	-0.05
Remus Farm	-0.22	-0.26	-0.26	-0.22	-0.22	-0.24	-0.25	-0.22	-0.20	-0.14	-0.04	-0.03
Marais River	-0.14	-0.16	-0.16	-0.16	-0.15	-0.16	-0.18	-0.16	-0.12	-0.05	0.00	0.03
Fort Dufferin	-0.09	-0.15	-0.17	-0.12	-0.11	-0.10	-0.13	-0.11	-0.07	0.00	0.07	0.10
Mean	*-0.04*	*-0.07*	*-0.08*	*-0.08*	*-0.08*	*-0.09*	*-0.11*	*-0.09*	*-0.05*	*0.01*	*0.04*	*0.03*

Table 3.3. (A) Results of multiple regression for August-July precipitation (dependent variable) and (B) the regression coefficients of the oak chronology (independent variables).

(A) Regression results					
Calibration Period	*n*	*r*	r^2	[a]Adjusted r^2	[b]SE of Estimate
1896-1996	100	0.653*	0.426*	0.403	75.1

(B) Regression coefficients					
	[c]Beta	St. Error of Beta	[d]B	St. Error of B	[e]*p*-level
Intercept			472.3	92.6	0.000002
PC1	0.612	0.08	399.0	50.6	0.00000000001
$PC3_{t+1}$	-0.196	0.08	-127.9	50.7	0.01
$PC2_{t+1}$	-0.153	0.08	-100.3	51.3	0.05
$PC1_{t+1}$	-0.081	0.08	-53.0	51.6	0.31

[a]Adjusted r^2 is the r^2 adjusted for loss of degrees of freedom.
[b]The standard error of estimated August-July precipitation.
[c]Beta is the standardised regression coefficient.
[d]B is the unstandardised regression coefficient.
[e]*p*-level is the statistical significance of the independent variable's *t*-value.

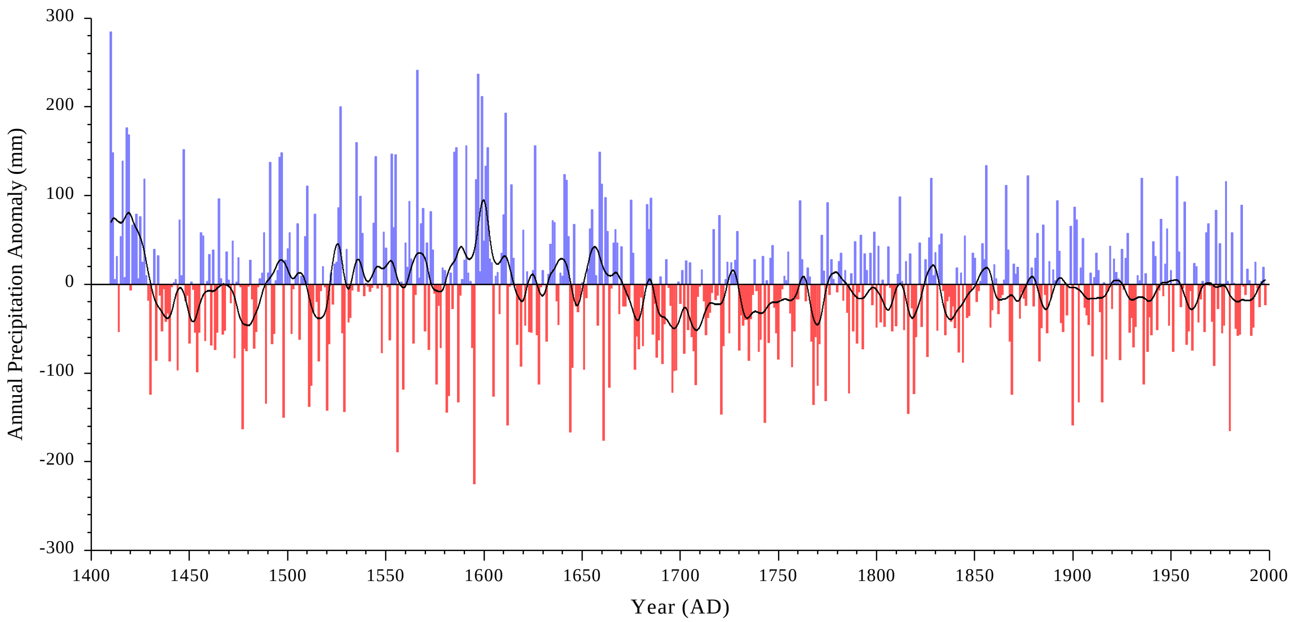

Figure 3.5. Reconstructed annual (August-July) precipitation at Winnipeg from AD 1409-1998. Units are deviations from mean annual precipitation from 1961-1990. Black line represents 15-year Tukey filtered series.

Table 3.4. Extreme reconstructed annual precipitation for Winnipeg.

Wettest years		**Driest years**	
Year	Deviation[a]	Year	Deviation[a]
³ 2 SD above or below the mean			
1410	3.77	1595	-2.91
1566	3.20	1485	-2.60
1597	3.15	1556	-2.44
1599	2.81	1661	-2.27
1524	2.70	1644	-2.15
1527	2.66	1980	-2.13
1611	2.57	1477	-2.10
1418	2.35	1900	-2.04
1419	2.25	1612	-2.04
1535	2.13	1743	-2.01
1591	2.09		
1626	2.07		
1586	2.06		
1602	2.06		
1447	2.03		
1625	2.01		
1580	2.01		
1784	2.01		
1659	2.00		
1.5-2 SD above or below the mean			
1585	1.99	1498	-1.92
1497	1.99	1721	-1.89
1411	1.99	1816	-1.87
1553	1.96	1581	-1.86
1555	1.96	1529	-1.85
1496	1.92	1520	-1.83
1545	1.91	1511	-1.77
1416	1.86	1768	-1.74
1491	1.84	1489	-1.72
1856	1.79	1915	-1.71
1601	1.78	1587	-1.70
1641	1.66	1903	-1.69
1877	1.64	1774	-1.68
1953	1.62	1605	-1.62
1583	1.62	1582	-1.61
1592	1.62	1869	-1.59
1935	1.61	1819	-1.59
1828	1.60	1430	-1.59
1427	1.60	1786	-1.57
1596	1.58	1696	-1.57
1642	1.58	1559	-1.51
1978	1.56		
1660	1.52		
1614	1.51		

[a]Units are deviations from mean annual precipitation between 1409-1998 .

Conclusion

This paper describes a new dendrochronological network in the Red River valley and presents the first high-resolution paleoclimatic record developed in Manitoba. Although most trees in the Red River valley were cut down in the mid-19th century, sample collection from historical buildings, archeological sites and river alluvium have allowed the development of a continuous tree-ring record extending back to AD 1286. Analysis of tree growth during the 20th century demonstrated that ringwidth records from bur oak contain a coherent signal that is related to annual precipitation. Multiple regression of the composite oak ringwidth chronology was used to estimate total August-July precipitation at Winnipeg between AD 1409 and 1998, explaining roughly 40% of the variance. This record indicates that southern Manitoba's climate was more extreme prior to the 20th century, with prolonged intervals both wetter and drier than at any time since permanent European and Canadian settlement. In particular, this record, as well as limnological records from North Dakota and Minnesota, suggests that the Red River valley experienced more than one hundred years of persistent dry conditions circa AD 1700. The extended precipitation series greatly enhances current estimates of natural hydroclimatic variability in the northern Great Plains and suggests that climatic case studies in regional drought and flood planning derived exclusively from experience during the 20th century may underestimate true 'worst-case' scenarios.

Acknowledgements

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4. Paleoclimatic Potential of Ringwidth and Densitometric Records from *Thuja occidentalis, Pinus strobus* and *Pinus resinosa* in Southeast Manitoba and Northwest Ontario

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Introduction

Manitoba's position near the geographic centre of North America causes its climate to exhibit considerable temporal variability, particularly at seasonal and interannual timescales (Blair, 1996). However, instrumental records of temperature and precipitation in Manitoba are sparsely distributed and short, with most records spanning less than 100 years (Vincent and Gullet, 1999; Mekis and Hogg, 1999). To accurately identify climatic change at decadal and century-scales, longer climate records are necessary. Natural archives, such as ocean corals, varves or tree rings can provide 'proxy' records of past climatic change, thereby (i) placing the modern instrumental or observed record into a much longer context of natural variation and (ii) identifying past conditions analogous to those expected in the future. Most high-resolution (i.e., annual to decadal) proxy climate records from the north-eastern Great Plains of North America relate to local or regional hydroclimate variation (e.g., Yu and Ito, 1999; St. George and Nielsen, this volume). While temperature is a major factor controlling evapotranspiration and regional water availability in the region, no equivalent proxy records are available that describe past regional temperature variations.

This paper describes preliminary results from an exploratory study of the paleoclimatic potential of selected conifers in southeastern Manitoba and northwestern Ontario. While several studies in western Canada have used tree-ring records from coniferous trees to estimate past temperature variations (e.g., Luckman et al., 1997; St. George and Luckman, 2001; Wilson and Luckman, submitted), the paleoclimatic potential of trees growing in the boreal forest of southeastern Manitoba and northwestern Ontario is not known. Furthermore, paleoclimate models that include ring width and density parameters are often better predictors of growing-season temperature than ring width alone (Luckman et al., 1997; Wilson and Luckman, submitted). Therefore, the main objectives of this research were: (i) to develop a small dendrochronological network of coniferous trees growing in southeastern Manitoba and northwestern Ontario; and (ii) to evaluate the quality of the between-tree signal at each site for ringwidth and densitometric parameters.

Study area

Southeastern Manitoba and northwestern Ontario are part of the boreal ecotone (Scott, 1996). Dominant tree species include *Pinus strobus* (white pine), *Pinus resinosa* (Red pine), *Pinus banksiana* (jack pine), *Picea glauca* (white spruce), *Picea mariana* (black spruce) and *tamarack* (Larix laricina). Eastern white cedar (*Thuja occidentalis*) usually dominates eutrophic swamps.

We sampled three *T. occidentalis* sites in Manitoba between West Hawk Lake and Moose Lake and a single stand of red pine in northwestern Ontario on the eastern side of Lake of the Woods. *T. occidentalis* collected from the Falcon Lake and East Braintree 3 sites were standing dead trees. Both stands surrounded small "ponds" which formed after road construction altered the local drainage. Samples from East Braintree 2 were separated into two groups. Samples T1-

12 were collected from living trees on the west side of Highway 306. The second group includes samples T13-32 and represents snag trees lying prone on the ground. Several of these logs were covered with a thick layer of moss, suggesting that they had been dead for some time.

Methods

Cross-sections were collected at the lowest part of the stem from living and dead trees. Specimens were air-dried and sent to the Canadian Forest Service in Edmonton, Alberta for densitometric analysis. For each tree, one radius was selected according to wood quality (absence of cracks and rot) and cut into thin laths using a twin-bladed saw. Resins, salts and glues in the wood were extracted using hot water and organic solvents prior to x-raying. Samples containing extensive rot were not x-rayed and provided width parameters only. For additional information regarding the densitometric analytical procedure, see Varem-Sanders and Campbell (1996). Nine parameters were measured for each ring: total ring width, earlywood and latewood width, mean ring density, mean earlywood and latewood density, minimum and maximum density and ring mass. This report presents analytical results for total ringwidth (RW) and maximum density (MXD) records.

Results

Chronology Summary

Table 4.1 presents summary statistics for the *T. occidentalis* and *P. resinosa* sites. *T. occidentalis* were generally between 100 and 200 years old, although some trees were older than 250 years. The oldest tree collected was from East Braintree 3 and reached an age of 334 years. Several samples from the T0013-32 group at East Braintree 3 had outer ring dates falling in the 1930s, indicating that these trees had been dead for nearly 70 years. Both East Braintree sites provide RW and MXD records that extend to the mid 17th century. Mean between-tree correlations (R_{bt}) for *T. occidentalis* are considerably higher for RW than MXD. As MXD is more variable between trees at the same site, we infer that this parameter is sensitive to micro-scale disturbances and may not be related strongly to macro-scale climatic variability. However, between-tree correlations from the *P. resinosa* site at Cameron Lake were equally good for RW and MXD.

Figures 4.1 and 4.2 display signal strength statistics for the RW and MXD parameters at each tree-ring site. We use the expressed population signal (EPS) statistic to measure the between-tree signal that may be related to climate. EPS is the correlation between the composite chronology and the theoretical population chronology based on an infinite number of samples (Cook et al., 2000). EPS statistics are calculated using a shifting 50-year window with one-year lags. The Falcon Lake and East Braintree 3 RW chronologies maintain EPS values greater than 0.85 for most of their span, although both records contain short intervals where increasing between-tree noise cause EPS values to decline briefly. Signal strength results for both groups at East Braintree 2 are generally lower, although the dead trees have acceptable EPS values between 1810 and 1900. The *P. resinosa* RW record from Cameron Lake provides a strong common signal over its entire length.

The quality of the common signal present in the maximum density series is weaker than that recovered from the RW data. EPS values from *T. occidentalis* MXD series are generally poor, often declining below 0.5 for some intervals. These results suggest that cedar MXD is somewhat noisy, with considerable between-tree noise at each site. Conversely, MXD is quite consistent between pines at Cameron Lake and the common signal in these data is relatively strong.

Table 4.1. Summary statistics for tree-ring samples collected in southeast Manitoba and northwest Ontario.

Site	Species	Interval	No. Trees	No. Cores	Mean Age	RW Mean R_{bt}	MXD Mean R_{bt}
Falcon Lake	*Thuja occidentalis*	1833 - 1992	11	12	96	0.452	0.255
East Braintree (3)	*Thuja occidentalis*	1660 - 1995	12	16	168	0.331	0.188
East Braintree (2)							
T1-12	*Thuja occidentalis*	1915 - 2000	12	12	73	0.315	0.213
T13-32	*Thuja occidentalis*	1658 - 2000	19	20	157	0.243	0.175
Cameron Lake	*Pinus resinosa*	1893 - 2000	31	31	89	0.342	0.337

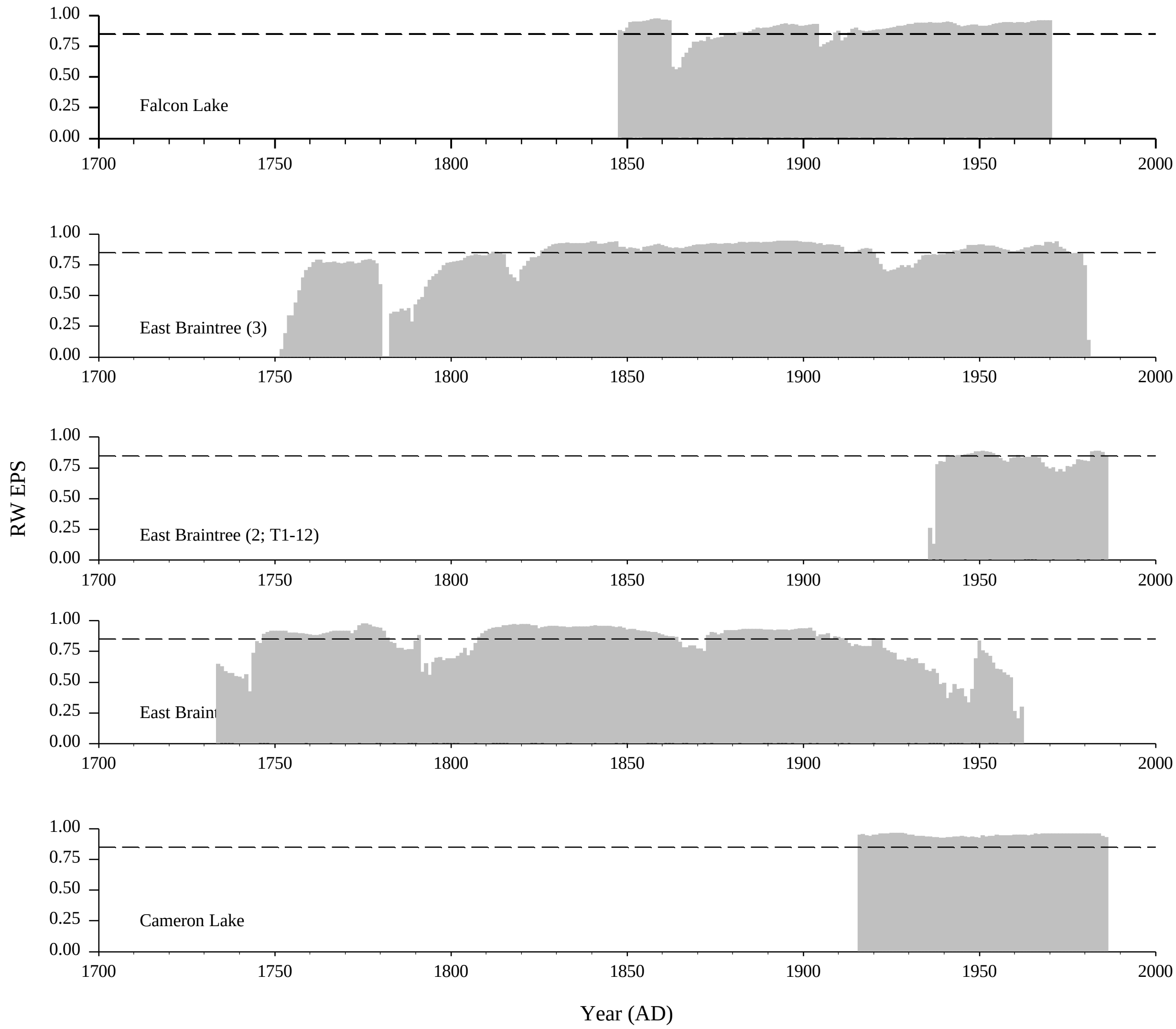

Figure 4.1. Running Expressed Population Signal (Wigley *et al.*, 1984) statistics for total ringwidth. EPS was calculated using a 50-year window with one-year shifts. The dashed line indicates Wigley *et al*.'s EPS threshold of 0.85.

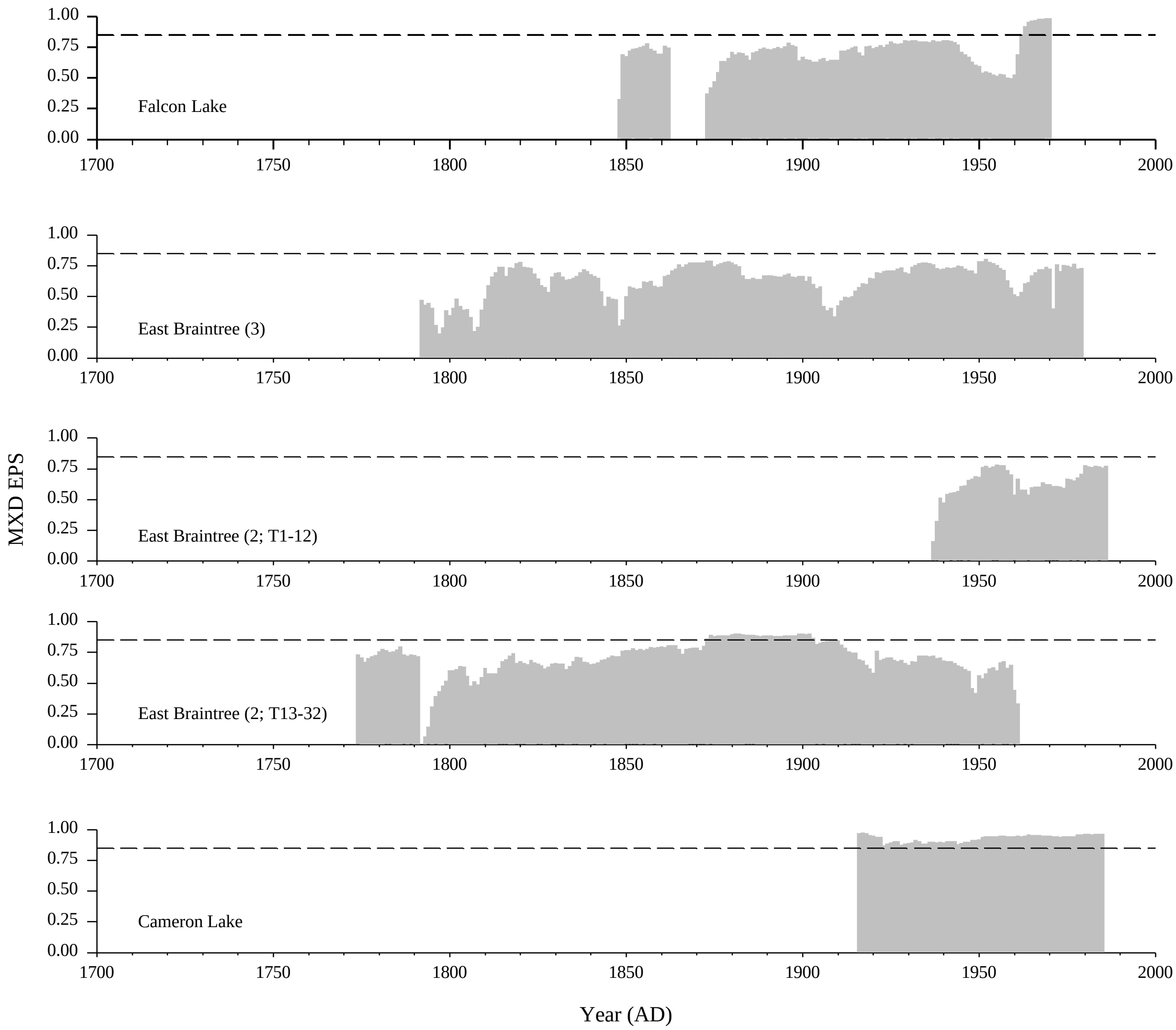

Figure 4.2. EPS results for maximum density.

Therefore, we conclude that: (i) *T. occidentalis* and *P. resinosa* RW and *P. resinosa* MXD data contain a strong stand-wide common signal and (ii) maximum density in *T. occidentalis* is relatively noisy and is likely affected by local exogenous disturbances.

Ringwidth and Maximum Density Chronologies

RW and MXD series were detrended using a straight line or negative exponential function and combined using a robust mean to form composite records for each stand (Figures 4.3 and 4.4). Although composite MXD records are presented for *T. occidentalis*, the above results demonstrated that these records are noisy and must be viewed cautiously.

The RW chronologies contain several examples of short (10-15 year) dramatic increases in mean ringwidth occurring within 3-5 years. Group T32 at East Braintree 3 exhibits the greatest RW peaks circa 1758-67 and 1962-76. However, these RW events are not synchronous across the network. They are also not coincident with noticeable shifts in MXD. Ringwidth and density have been low at most sites since roughly 1975. Mean RW and MXD were both particularly low at Falcon Lake in the 1980s, most likely caused by road construction in 1981/82. The T32 group at East Braintree 3 contains pronounced departures in mean MXD for 1756 and 1887-88, with the latter being accompanied by a decrease in mean RW. These MXD outliers are not present at any other site and may simply represent a localised disturbance event.

Conclusion

This paper is an interim report that describes an ongoing effort to develop a paleoclimatic record for trees in southeastern Manitoba. We have established that *T. occidentalis* ringwidth has sufficient shared variance between trees to allow cross-dating and that records spanning the last three to four centuries may be obtained from this species. However, density records for *T. occidentalis* are relatively noisy with weak between-tree signals and that parameter does not appear to be useful climate proxies. Strong common signals are present in *P. resinosa* for both total ringwidth and maximum density, which suggest that these parameters may reflect the influence of a macro-scale control of tree growth. Additional *P. resinosa* sites should be developed in order to determine if this signal is spatially coherent across the region and whether it represents the influence of one or more climatic factors. Future work will identify common ringwidth and density patterns across southern Manitoba's boreal forest and investigate possible linkages with climatic change during the 20th century. The properties of other ringwidth and density parameters measured but not analysed in this report will also be investigated.

Acknowledgements

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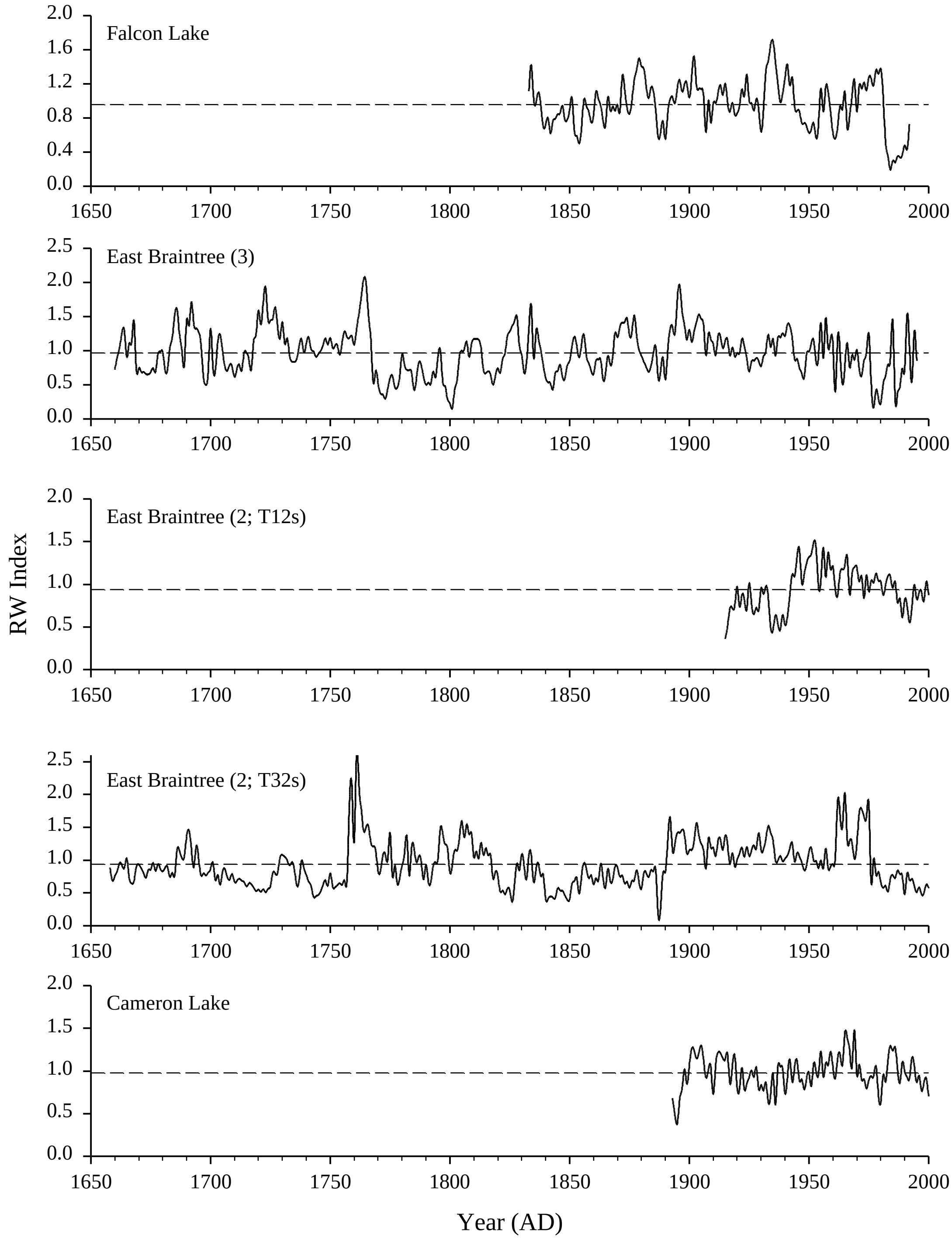

Figure 4.3. Composite ringwidth chronologies for *T. occidentalis* and *P. resinosa*.

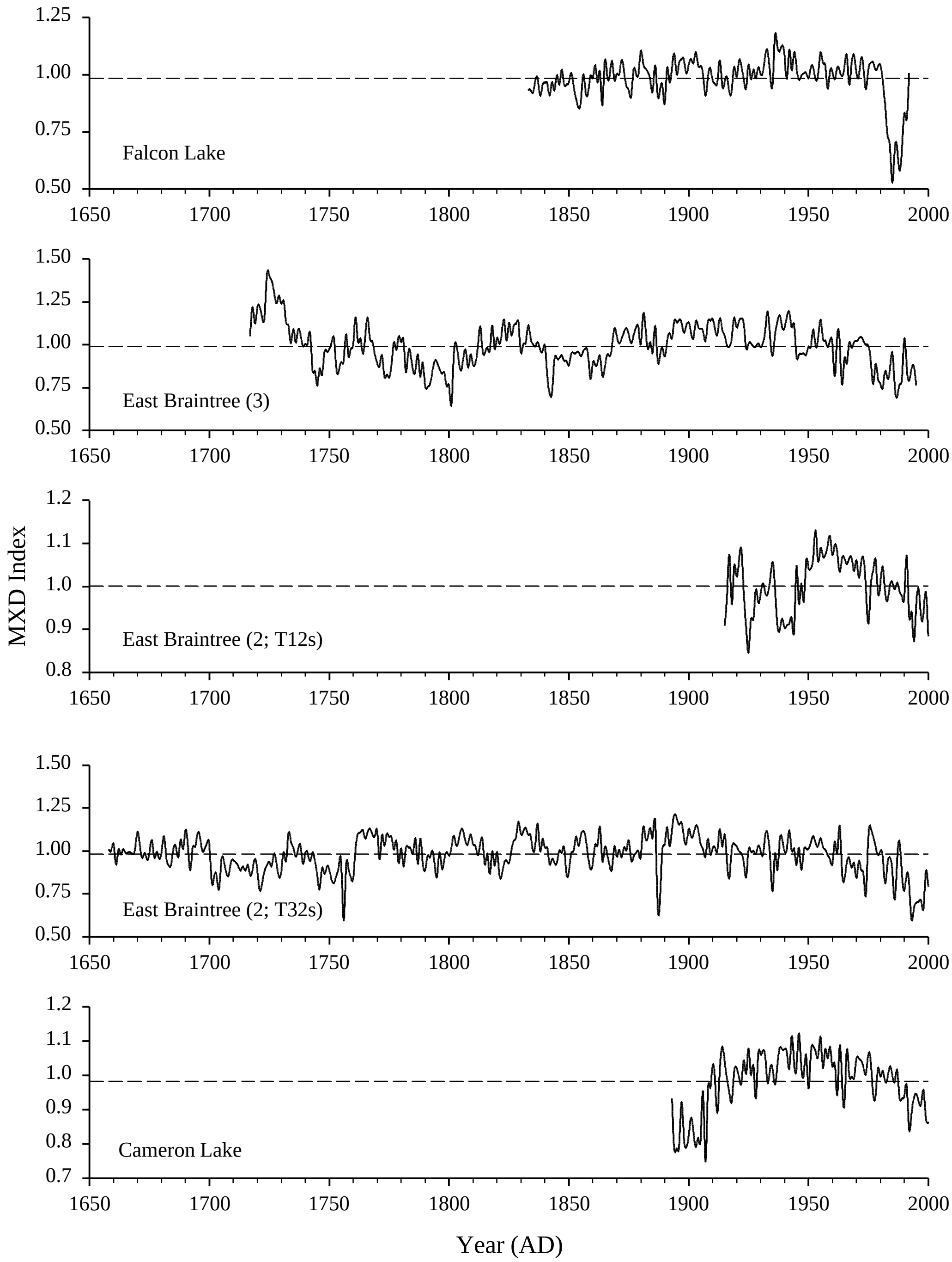

Figure 4.4. Composite maximum density chronologies.

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5. Investigation of Lake Winnipeg sediments: a record of the last millennium

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Introduction

Southern Lake Winnipeg is the receiving basin of the Red River that drains the southernmost part of Manitoba. A study of the upper 1.5-1.7 m of offshore lake sediments was made to derive a record of sediment property and compositional variations for the interpretation of environmental and climate changes in southern Manitoba over approximately the past millennium. The lake sediment changes are complementary to the record of climate variations registered in annual rings of oak trees from the Red River valley (St. George and Nielsen, this volume).

Setting

The southern basin of Lake Winnipeg is approximately rectangular in shape with a north-south length of 80 km and an east-west breadth of 25 km in its southern part (Figure 5.1). It is located with its southern shore about 60 km north of the city of Winnipeg. The lake surface and local surrounding catchment area comprise 10 670 km^2. The northeastern sector of the lake basin receives runoff from the Winnipeg River basin of 135 800 km^2, which drains parts of eastern Manitoba, northwestern Ontario and northern Minnesota. The southern extremity of the basin is the receiving area of Red River inflow, which drains a 105 500 km^2 area in southern Manitoba, western Minnesota, and eastern North Dakota. An additional 182 000 km^2 in southwestern Manitoba, southeastern Saskatchewan, and northwestern North Dakota drains via the Assiniboine River to the Red River at Winnipeg. The southern basin is connected through a narrows area to a large northern basin which drains northward to Hudson Bay via the Nelson River (Lewis *et al. in* Todd *et al.*, 2000)

Seismic reflection transects and sediment cores obtained by the Lake Winnipeg Project (Todd *et al.*, 1996; 2000) show that the lake bottom offshore is relatively shallow in the southern basin (about 9.5-11 m water depth) and consists of a layer of soft, silty clay sediment generally 6-8 m thick which has accumulated over the past 4000 years. Sidescan sonar records revealed that the sediment surface is disturbed in places by shallow irregular furrows (< 1 m deep); these features are thought to result from scouring by keels of ice pressure ridges which have moved under the influence of wind stress and ice pressure during the spring break-up season. The silty clay sediment layer overlies clay deposited in glacial Lake Agassiz, and thins toward shore where the Agassiz clay or other glacial deposits underlie the lake bottom in water depths less than about 4 m. In the northern part of the basin, the shore zone consists of bedrock outcrop. The eastern and western shores are eroded by wind waves during the annual ice-free season. Barrier sand ridges are built by waves along the southern shore between distributary outflow channels of the Red River and local streams. The barrier ridge system is transgressing southward under the influence of waves acting on a long-term rising water surface resulting from glacio-isostatic

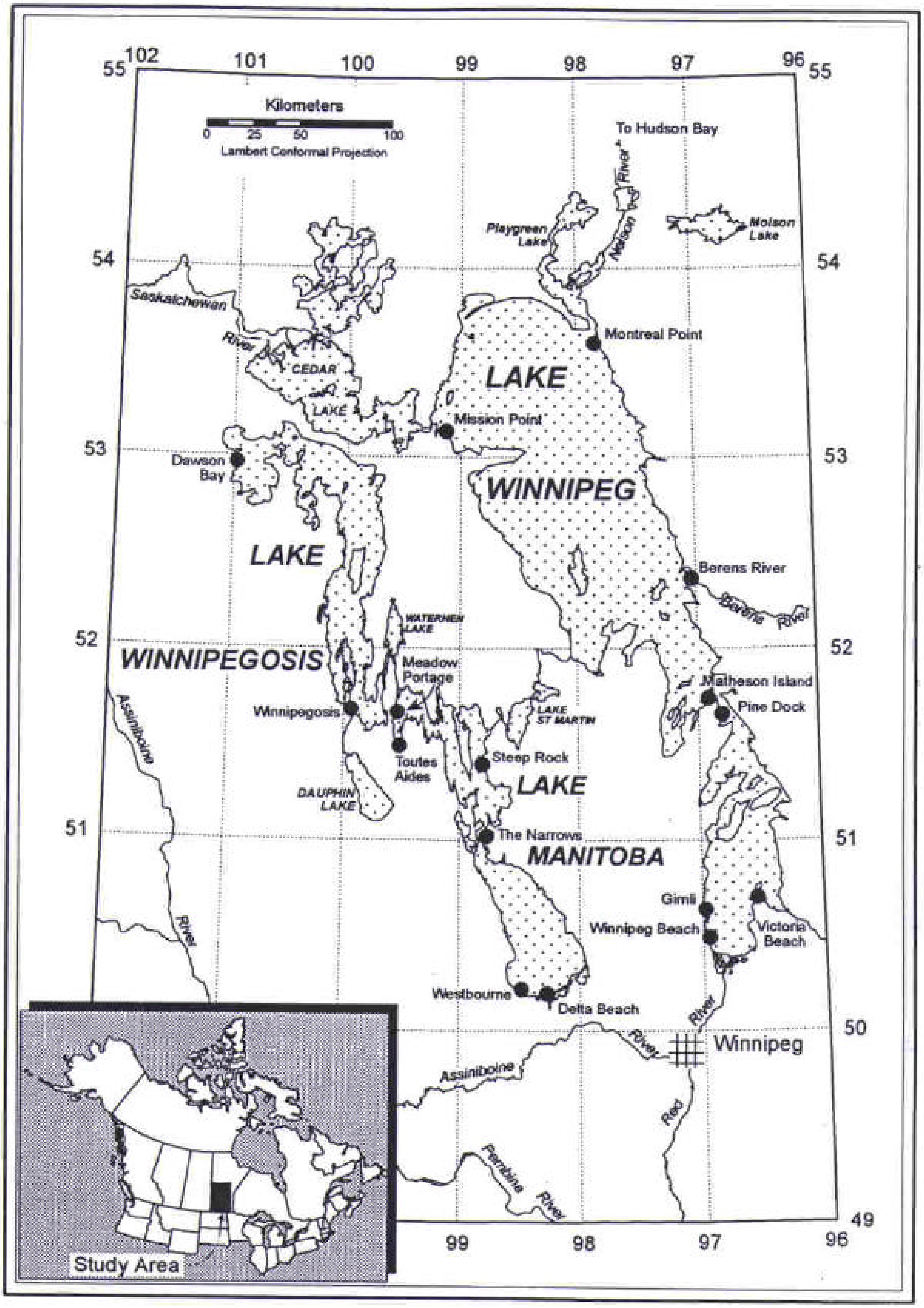

Figure 5.1. Regional map.

tilting (up on the north) of the northward draining Lake Winnipeg basin (Lewis *et al.* and Nielsen *in* Todd *et al.*, 2000).

Sediment cores for this study were collected in the medial part of the southern basin on a transect from just north of Gimli towards the Red River mouth (Figure 5.2). Here, the sediment input is likely dominated by the Red River, the major inflowing stream, with some sediment eroded from the adjacent shore zones.

Methods

Sediment Sampling

The strategy adopted for selection of sampling sites consisted of dual objectives: 1) proximity to the Red River mouth, and 2) acquisition of high quality sediment cores by avoidance of ice-scoured areas. These objectives were achieved by selecting and sampling 5 lake bottom sites showing an absence of ice scour on sidescan sonar records previously obtained on a south-to-north transect in 1994.

Sampling operations were conducted in calm weather on August 24, 1999 (Day 236) from the CCGS *Namao* operating out of Gimli, Manitoba. Before anchoring at each site, two short transects using the ship's echo sounder (Raytheon Survey Fathometer) confirmed the absence of ice scour. At each of the 5 sites (Figure 5.2), the ship was anchored for the collection of three cores (Table 1) using a gravity corer consisting of a 100 kg weightstand over a 2-m steel pipe with 10 cm diameter plastic liner tube, similar to the gravity corer used successfully in 1996 from *Namao* (Todd *et al.*, 2000). A one-way valve at the top of the coring pipe allowed water to exit during sediment penetration but closed and retained the sediment core in the core pipe during its withdrawal from the lakebed and recovery to the ship's deck. A steel plate of about 30cm diameter was fitted to the base of the weightstand above the valve to stop excessive penetration of the core pipe in soft sediment. Ship positions in both 1994 (year of sidescan survey) and 1999 were determined with the differential satellite global positioning system and are expected to be accurate within 10 m or less.

The length of cores varied from 107 cm to 170 cm with an average length of 156 cm. At all sites, the soft muddy sediment allowed the corer to sink further without sampling the deeper sediment, up to 231 cm as measured (apparent penetration) on the weightstand after recovery (Table 1). Most cores were recovered with a slightly tilted upper surface suggesting a small amount (probably < 1 cm) of surface mud had entered the core pipe through the open valve as the corer sank into the mud. The gravity cores were sealed, labelled aboard ship, then transferred to cool storage in Gimli in the evening of August 29, 1999. The cores were transported via commercial refrigerated truck to the Geological Survey of Canada core storage facility in Dartmouth N.S. The cores were maintained upright in their original orientation throughout the trip and during storage until they were sampled. A monitoring device attached to the core bundle during the trip showed that the ambient air temperatures were held between 0.7^{o}C and 10^{o}C August 25-27, and between 13^{o}C and 19^{o}C August 28-30 when they entered the core storage facility held at 4^{o}C to 9^{o}C.

Whole Core Physical Property Analysis and Selection of Cores for Detailed Study

With facilities at the laboratory of J.W. King, University of Rhode Island in Narragansett, RI, the 15 whole cores were analysed for their physical properties by C. Heil. Magnetic susceptibility, compressional sound wave velocity, and gamma ray attenuation for bulk density determination

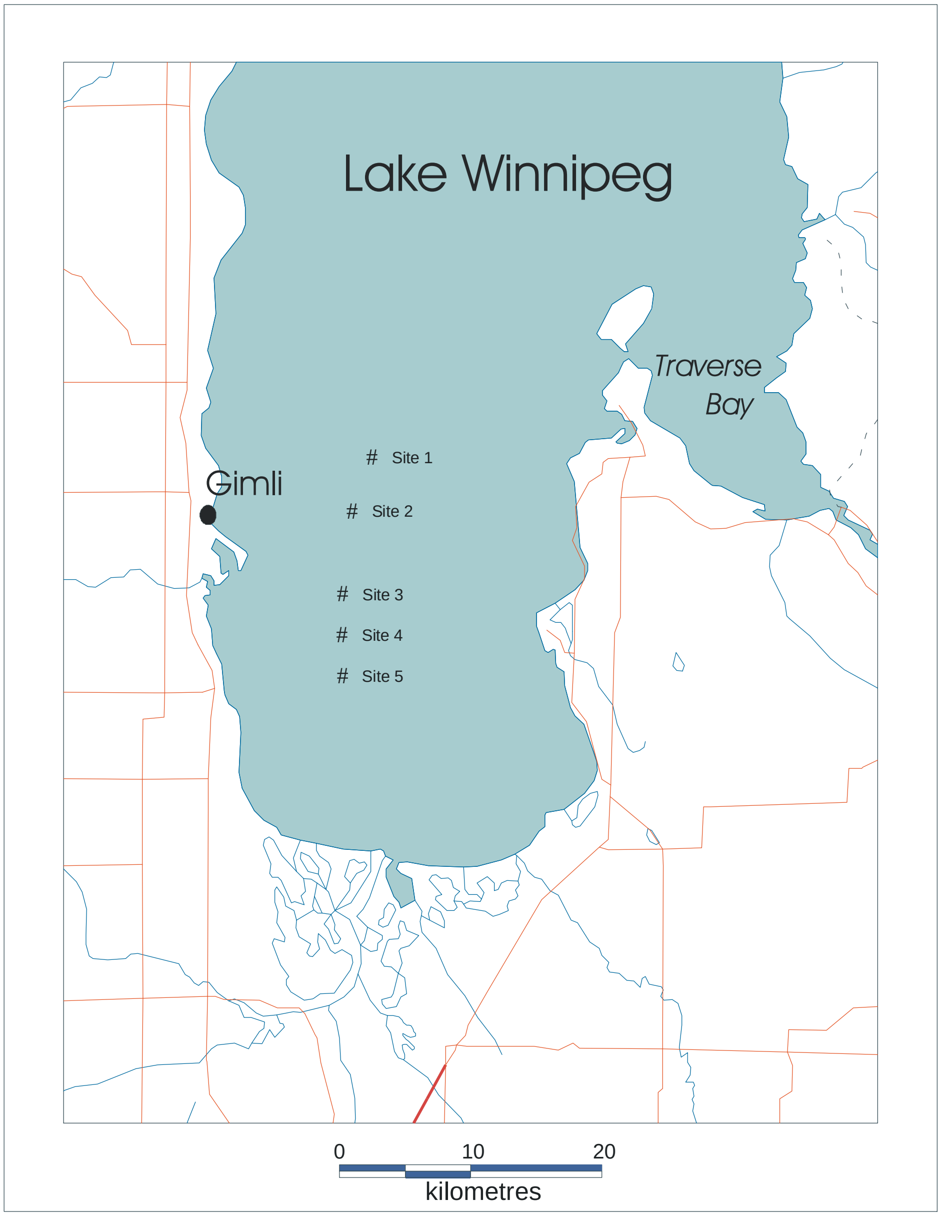

Figure 5.2. Map of southern lake Winnipeg showing site locations.

Table 5.1. Core lengths and locations in southern Lake Winnipeg, August 24, 1999.

Site No.	Core No.	Latitude N	Longitude W	Water depth m	Core length cm	Penetration cm*
1	1	50° 39.834'	96° 48.061'	9.5	156	231
1	2	50° 39.874'	96° 48.115'	9.5	146	231
1	3	50° 39.874'	96° 48.176'	9.5	149	211
2	4	50° 37.713'	96° 49.400'	9.2	166	208
2	5	50° 37.713'	96° 49.393'	9.2	170	214
2	6	50° 37.713'	96° 49.394'	9.2	168	215
3	7	50° 34.341'	96° 50.001'	8.4	168	231
3	8	50° 34.343'	96° 50.004'	8.4	164	231
3	9	50° 34.343'	96° 50.005'	8.4	150	231
4	10	50° 32.676'	96° 50.042'	8	165	231
4	11	50° 32.675'	96° 50.045'	8	150	221
4	12	50° 32.676'	96° 50.044'	8	107	231
5	13	50° 31.009'	96° 50.012'	7.6	160	231
5	14	50° 31.022'	96° 60.016'	7.6	159	231
5	15	50° 31.020'	96° 50.018'	7.6	160	231
* Apparent penetration into lakebed indicated by uppermost sediment adhering to corer						

were obtained at 1-cm intervals using a Geotek Multi Sensor Core Logger, similar to previous physical property measurements of Lake Winnipeg sediment cores (Jarrett *in* Todd et al, 2000). Natural remanent magnetization in the cores, specifically downcore changes in magnetic field inclination, was measured with a 2G Enterprises Model 760 automated cryogenic magnetometer system following procedures adopted previously for Lake Winnipeg sediments (King *et al.*, *in* Todd *et al.*, 2000). With these data in hand, the cores in their plastic liner were cut lengthwise into working and archive halves. The fresh core faces were imaged digitally using the Geotek Multi Sensor Core Logger (Gunn, D.E. and Best, A.I., 1998). Visually, the sediments are consistently soft silty clay, olive gray in colour, and vaguely structured. In places, colour variations show faint laminae and reduced black FeS streaks with many mottled zones. These structures suggest the lake sediments are mixed to some degree by bioturbation.

The core profiles of the physical property and paleomagnetic data were able to be correlated from core-to-core and site-to-site indicating that the cores were of high quality, not disturbed, and that data from one or two cores would be representative of the offshore lake sediment sequence (Figure 5.3). In each core, the magnetic field inclination data showed a distinctive secular variation event, I1, dated at about 870±180 radiocarbon years before present (BP) by comparison with other sites in North America in which similar events have been dated (Lund, 1996). The same event has been assigned a similar age, 915±130 radiocarbon years BP, by King *et al.* (*in* Todd *et al.*, 2000) by correlation with a slightly different reference set of lake sediment inclination profiles. The calibrated age of the I1 inclination feature, using the Lund (1996) determination, the CALIB4.3 program and the 1998 atmospheric data set (Stuiver *et al.*, 1998), is 1190 AD, with a one-sigma uncertainty ranging from 1000 to 1290 AD. The I1 timeline was correlated and traced through the paleomagnetic inclination profiles for a suite of cores at the 5 sampling sites (Figure 5.4). The upward slope to the south of this timeline indicates that fine-grained offshore sediments accumulated more rapidly at the three northern sites than at the two southern sites closer to the Red River mouth. Thus, sites 1 to 3 should contain a higher resolution proxy record of environmental change. Core 8 and its companion cores at Site 3, the southernmost site with higher accumulation rates, were selected as the primary record for more detailed study; core 4 and its companion cores at site 2 were selected as a secondary record for detailed study.

Chronology (Cores 8 and 4)

In addition to the paleomagnetic inclination event, I1, which provided a timeline for the older part of the sediment cores, the chronology of uppermost sediments in cores 8 and 4 were analysed radiometrically using ^{210}Pb and ^{137}Cs activity. Sample material for radiomentric and geochemical analyses was prepared by slicing the working half of cores 8 and 4 into horizontal slices of 1-cm thickness. The slices were freeze-dried and lightly ground at the Freshwater Institute (FWI), Department of Fisheries and Oceans, Winnipeg under the direction of P. Wilkinson.

P. Wilkinson (FWI) estimated the mean ages of the uppermost 35 slices of cores 8 and 4 from the regression of unsupported lead-210 activity against accumulated dry weight as applied previously to lake and ocean sediments in central and northern Canada (Lockhart *et al.*, 1998; and *in* Todd *et al.*, 2000). The “Constant Rate of Supply” method (Oldfield and Appleby. 1984) was used to describe the age structure and compute sedimentation rates. Cesium-137 activity was

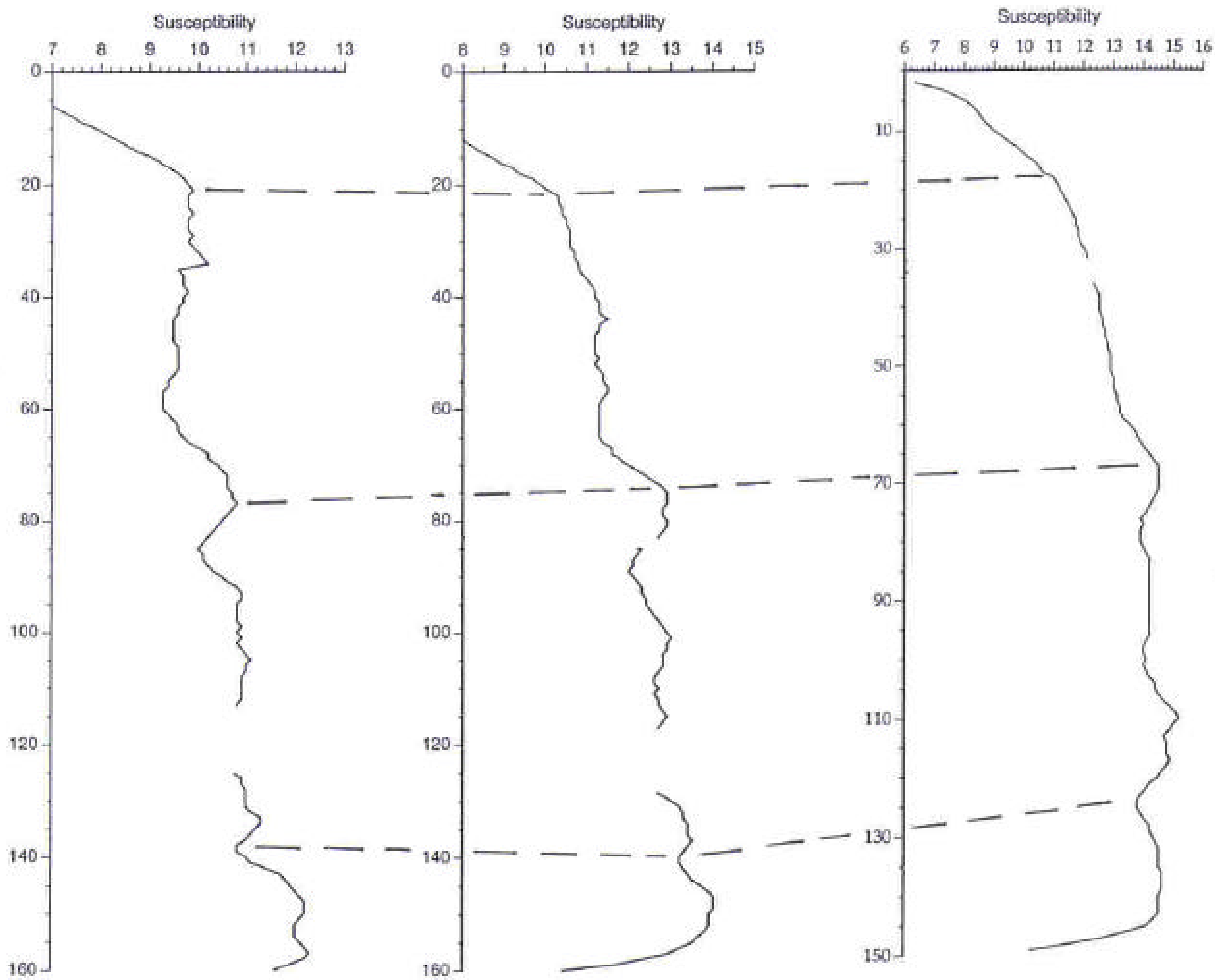

Figure 5.3. Correlation of magnetic susceptibility profiles for three cores at Site 3.

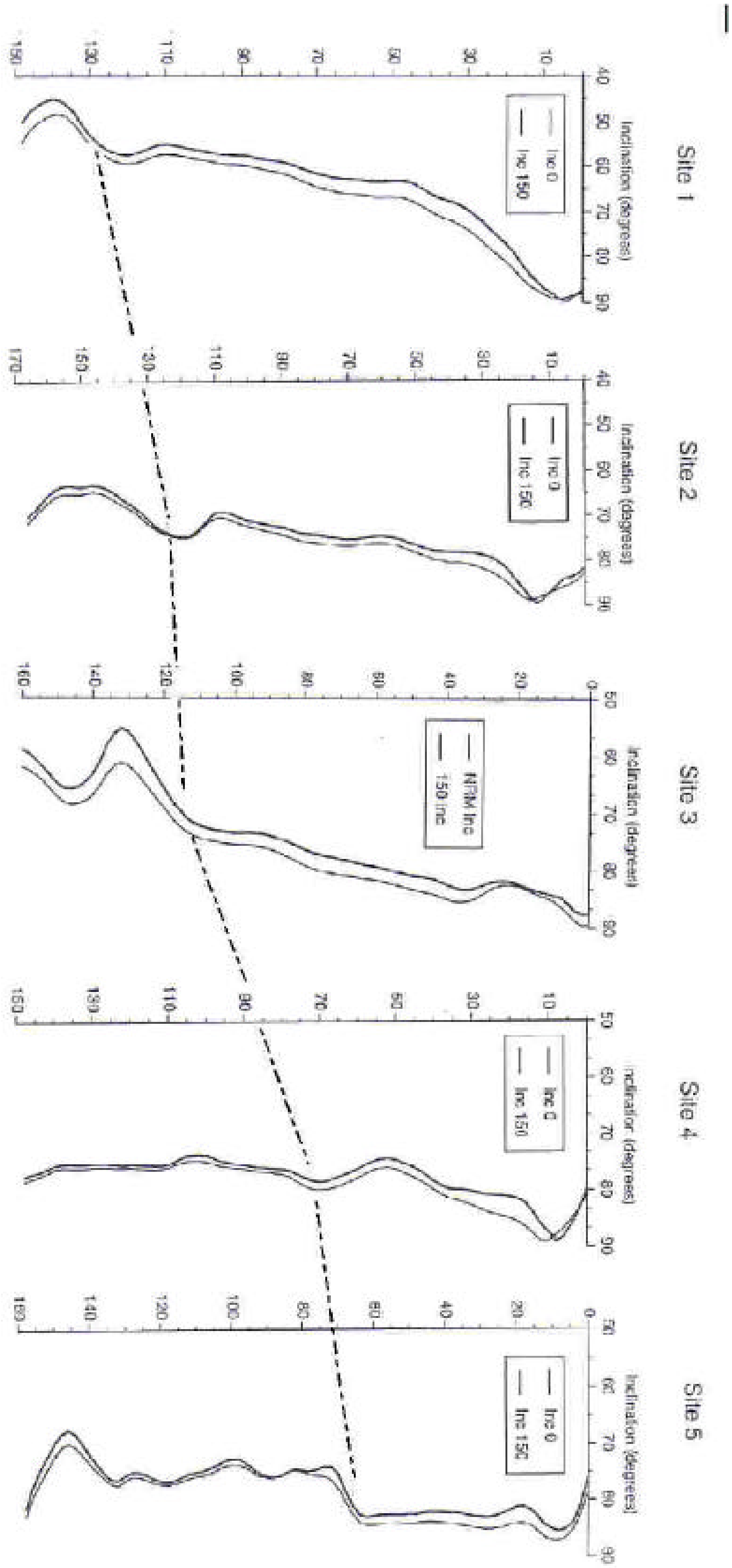

Figure 5.4. Paleomagnetic field inclination for cores at the 5 sites sampled on a N-S transect in southern Lake Winnipeg. The southern site (5) is closest to the mouth of the Red River. The dashed line joins the profiles at the level of the I1 inclination feature (about 1190 AD).

also determined in each slice and the Pb-210 dates were considered reliable if the peak activity for Cs-137 occurred during the mid-1960s.

Palynological Analysis

The aim of this aspect of the study was to prepare pollen stratigraphies and to interpret vegetation history for cores 8 and 4, including possible evidence of the Little Ice Age, records of flooding, onset of agriculture, and other climatic or environmental changes. A list of the samples microscopically examined and comprising the pollen diagrams at the two localities is shown in Table 2. Samples of two-cc volume were collected as wet sediment from the face of the working core half.

Samples 1-cc in volume were extracted from the cores and forwarded to Dr. John King's laboratory at University of Rhode Island where they were processed for pollen content by Carol Gibson. The laboratory procedures involved standard acid digestion with HF and HCl followed by acetolysis. A known concentration of *Lycopodium* was added to each sample during the preparations to compute pollen concentrations (grains/cc). The treated samples were forwarded to T.W. Anderson for pollen identification and tabulation. A minimum of about 220 tree, shrub and herb pollen constitute the pollen sum (excluding *Cyperaceae* and pollen of aquatic plants) which represented the basis for calculating pollen percentages. Pollen diagrams were drafted with the computer programs TILIA and TILIA-GRAPH (Grimm, 1991).

Macrofossil Collection for Paleoecological Analysis and C-14 Dating

Large sediment samples of 150 ml from a companion core (7) to core 8 were examined for terrestrial macrofossil content by A. Telka of Paleotec Services, Ottawa. Samples from 5-cm intervals were gently sieved with the smallest mesh opening of 0.25 mm, and the retained fossil fauna identified (Telka *in* Todd *et al.*, 2000).

Particle Grain Size

Sediment grain size distribution was determined in the Sedimentology Laboratory of Terrain Sciences Division, Geological Survey of Canada (GSC), using a Lecotract LT-100 particle size analyzer. Wet sediment samples from cores 4 and 8 at one-cm interval were soaked in a 50 g/l Na metaphospahte solution and processed in this analyzer using laser diffraction (Percival and Lindsay, 1997). Particle size diameters were determined with a precision of 1 percent (I. Girard, GSC, personal communication, 2001) from the scattering angles of three laser beams of different orientation diffracted from individual particles in a dilute suspension. Results were reported as weight percentages for 6 size classes of silt and clay ranging from 0.064 µm to <0.001 µm.

Organic Geochemistry

Aliquots from the dried one-cm slices from cores 8 and 4 were examined for their bulk organic geochemical properties using Rock-Eval pyrolysis techniques (Espitalie *et al.*, 1977; Peters, 1986; Meyers and Lallier-Verges, 1999). Vinci Technologies Rock-Eval VI instrumentation was used in the Calgary laboratories of the Geological Survey of Canada. A microprocessor-controlled heating program released volatiles from the lake sediment samples in a stream of helium; hydrocarbons were measured in a flame ionization detector, and CO_2 in a thermal conductivity detector. The laboratory also measured the total organic carbon content of each sample.

Table 5.2. Samples (depths in cm) comprising the pollen diagrams.

Site 3/Core 8 (cm)	Site 2/Core 4 (cm)
1, 4, 8, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 42, 48, 52, 56, 60, 64, 68, 76, 80, 84, 88, 92, 96, 100, 104, 112, 120, 124, 128, 136, 140, 144, 152, 156	1, 9, 17, 25, 27, 29, 31, 33, 37, 39, 45

Inorganic Geochemistry

After being freeze-dried and pulverized, one-gram subsamples from the one-cm slices of cores 8 and 4 were subjected to near total digestion using nitric, hydrofluoric and perchloric acids. Standard chemical elemental analysis of the subsamples was completed using inductively coupled plasma (ICP) associated with both optical emission spectrometry amd mass spectrometry (ICP-OES and ICP-MS).

Results

Chronology

The one-cm sediment slices (1-33) have been dated AD from 1998 to 1850 in core 8 and from 1998 to 1842 in core 4, respectively, as shown by the Pb-210 profiles in Figure 5.5 and Table 3. The Cs-137 profiles rise from an early background to reach their peaks in 1965 and 1964 in cores 8 and 4, respectively, according to the Pb-210 profiles. As this corresponds to the mean age for maximum Cs-137 fallout from nuclear bomb testing, the Pb-210 age determinations are deemed to be of high quality.

Quantitative models for the age-depth relationship in each core were obtained by fitting a second-degree polynomial to the Pb-210 AD dates from 0.5 cm to 32.5 cm, and using a linear fit between the 32.5-cm age and the 1190 AD age of the I1 paleomagnetic inclination event at 114 cm and 125 cm in cores 8 and 4, respectively (Figures.5.6a and 5.6b; Tables 4 and 5). The curve-fitting was performed using routines in the GRAPHER program. It should be remembered that the one-sigma uncertainty at the level of the I1 event is +100 years and -190 years. These errors are expected to increase linearly downcore from the I1 level, and decrease linearly upcore to near zero in the range of the oldest Pb-210 dates.

For core 8 between 0 and 32.5 cm depth, Pb-210 data control the depth-age relationship, which is fitted with a polynomial predictor of degree 2:

$$Age = 1999.4 - 1.52606(Depth) - 0.0926649(Depth)^2$$

where $R^2 = 0.963$ (Degree 1) and 0.9959 (Degree 2).

Below 32.5 cm the depth-age relationship is linear, based on the oldest Pb-210 data point and the paleomagnetic inclination feature, I1, at 114 cm with an age of 1190 AD and a one-sigma range from 1000 AD to 1290 AD. For this deeper sector of the core:

$$Age = 2113.19 - 8.09816(Depth).$$

For core 4 between 0 and 32.5 cm depth, Pb-210 data control the depth-age relationship which is fitted with a polynomial predictor of degree 2:

$$Age = 1999.67 - 1.90699(Depth) - 0.0905711(Depth)^2$$

where $R^2 = 0.972$ (Degree 1) and 0.9994 (Degree 2).

Below 32.5 cm, the depth-age relationship is linear based on the oldest Pb-210 data point and the paleomagnetic inclination feature, I1, at 114 cm with an age of 1190 AD and a one-sigma range from 1000 AD to 1290 AD. For this deeper sector of the core:

$$Age = 2071.08 - 7.04865(Depth).$$

Table 5.3. Chronology data for cores 8 and 4.

Core 8			Core 4		
Slice	Depth cm	Years AD	Slice	Depth cm	Years AD
1	0-1	1998	1	0-1	1998
5	4-5	1990	5	4-5	1989
9	8-9	1981	9	8-9	1978
14	13-14	1965	13	12-13	1964
17	16-17	1949	17	16-17	1942
21	20-21	1925	21	20-21	1921
25	24-25	1903	25	24-25	1898
29	28-29	1887	29	28-29	1873
33	32-33	1850	33	32-33	1842
I1 event	114	1190 (1000-1290)	I1 event	125	1190 (1000-1290)

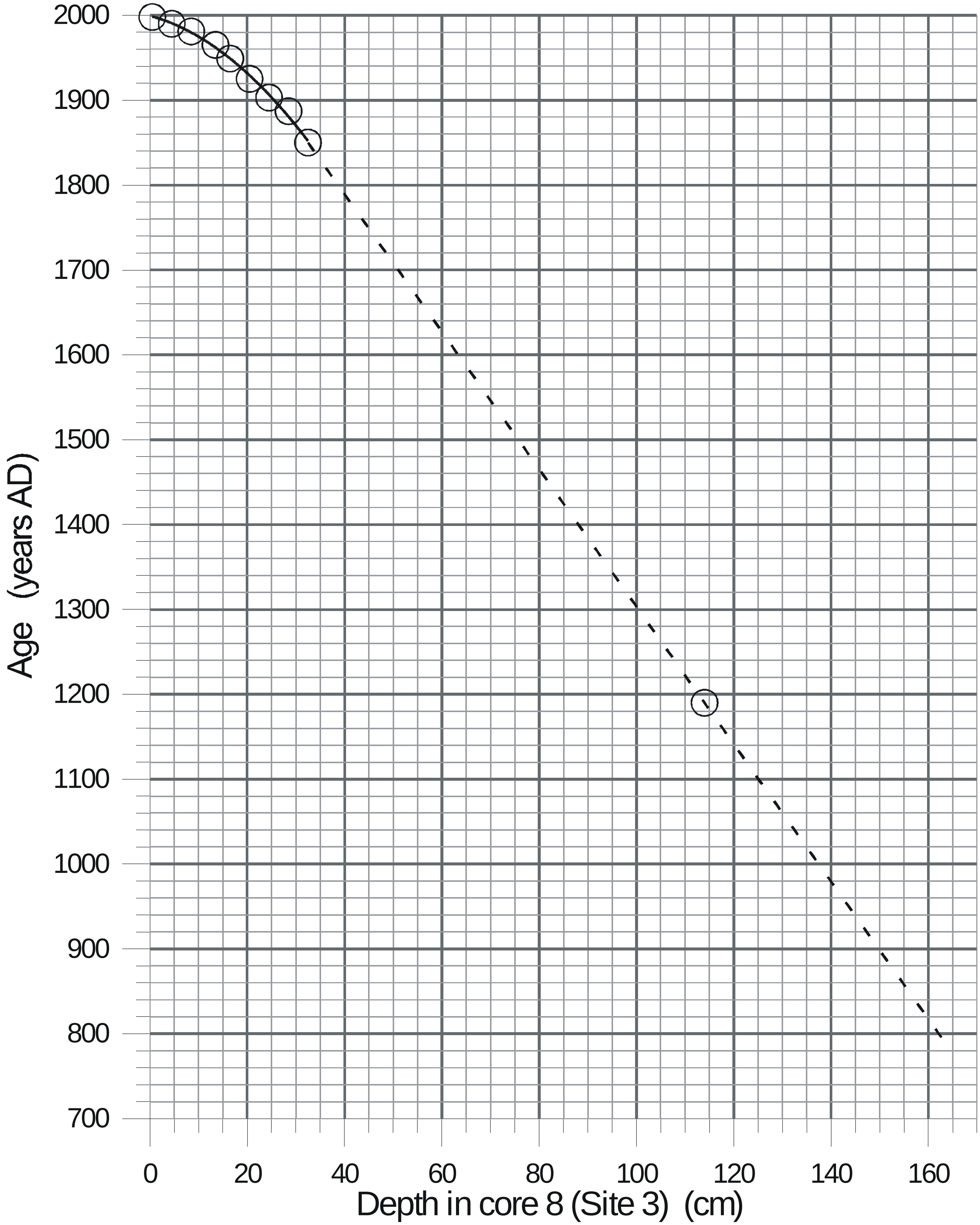

Figure 5.6a. Age model for Core 8 linking core depth (cm) with sediment age in years AD. Chronology control data from Table 3 are shown as circles.

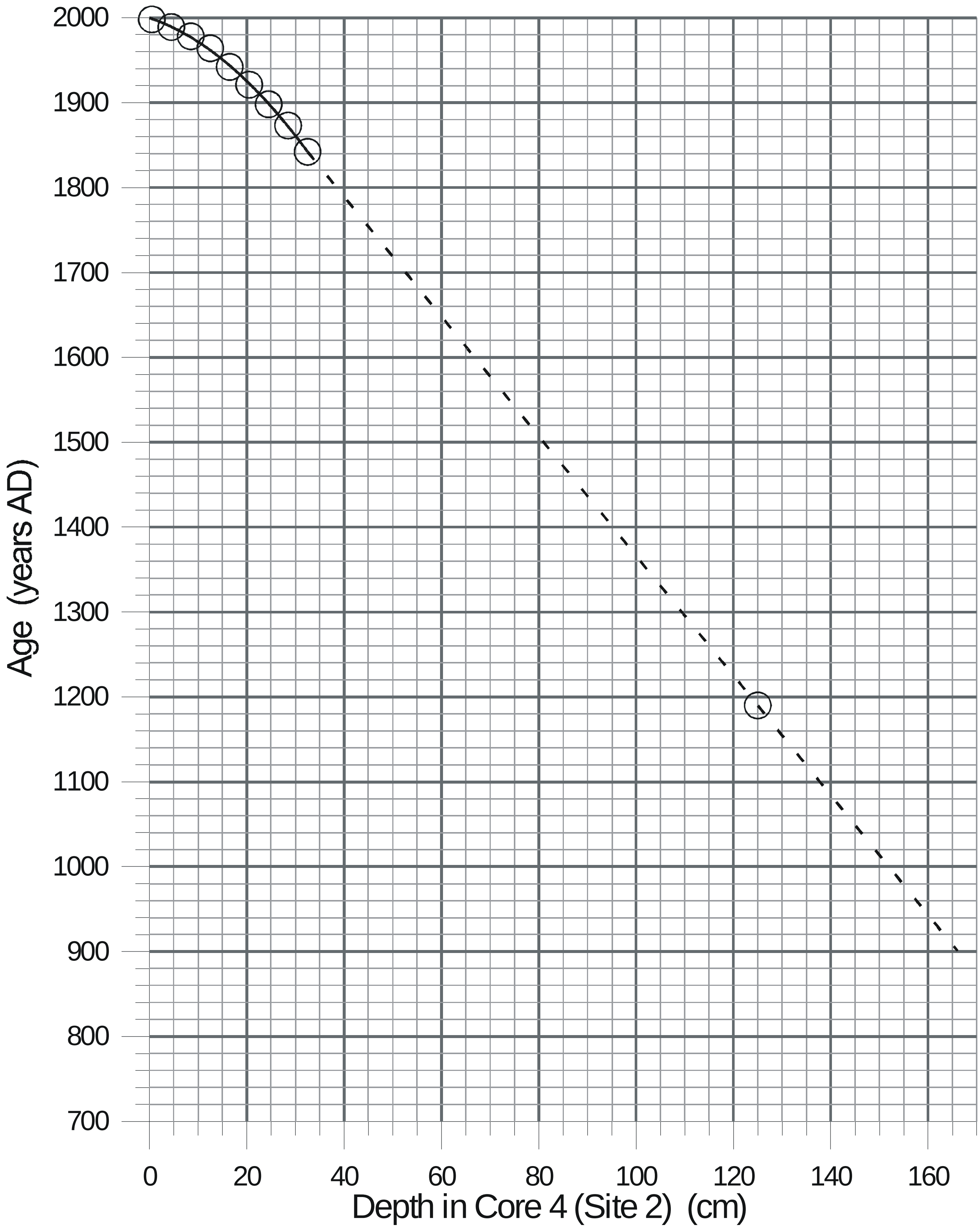

Figure 5.6b. Age model for Core 4 linking core depth (cm) with sediment age in years AD. Chronology control data from Table 3 are shown as circles.

Table 5.4. Age model for core 8.

Depth cm	Years AD	Depth cm	Years AD	Depth cm	Years AD	Depth cm	Years AD
0.5	1998.6	25.5	1900.2	68	1591.8	118	1239.3
1.5	1996.9	26.5	1893.9	70	1577.7	120	1225.2
2.5	1995.0	27.5	1887.4	72	1563.6	122	1211.1
3.5	1992.9	28.5	1880.6	74	1549.5	124	1197.0
4.5	1990.7	29.5	1873.7	76	1535.4	126	1183.0
5.5	1988.2	30.5	1866.7	78	1521.3	128	1168.9
6.5	1985.6	31.5	1859.4	80	1507.2	130	1154.8
7.5	1982.7	32.5	1851.9	82	1493.1	132	1140.7
8.5	1979.7	34	1831.4	84	1479.0	134	1126.6
9.5	1976.5	36	1817.3	86	1464.9	136	1112.5
10.5	1973.2	38	1803.2	88	1450.8	138	1098.4
11.5	1969.6	40	1789.1	90	1436.7	140	1084.3
12.5	1965.8	42	1775.0	92	1422.6	142	1070.2
13.5	1961.9	44	1760.9	94	1408.5	144	1056.1
14.5	1957.8	46	1746.8	96	1394.4	146	1042.0
15.5	1953.5	48	1732.7	98	1380.3	148	1027.9
16.5	1949.0	50	1718.6	100	1366.2	150	1013.8
17.5	1944.3	52	1704.6	102	1352.1	152	999.7
1 8.5	1939.5	54	1690.5	104	1338.0	154	985.6
19.5	1934.4	56	1676.4	106	1323.9	156	971.5
20.5	1929.2	58	1662.3	108	1309.8	158	957.4
21.5	1923.8	60	1648.2	110	1295.7	160	943.3
22.5	1918.2	62	1634.1	112	1281.6	162	929.2
23.5	1912.4	64	1620.0	114	1267.5	164	915.1
24.5	1906.4	66	1605.9	116	1253.4		

Table 5.5. Age model for core 4.

Depth cm	Years AD	Depth cm	Years AD	Depth cm	Years AD	Depth cm	Years AD
0.5	1998.7	25.5	1892.1	68.0	1591.8	118.0	1239.3
1.5	1996.6	26.5	1885.5	70.0	1577.7	120.0	1225.2
2.5	1994.3	27.5	1878.7	72.0	1563.6	122.0	1211.1
3.5	1991.9	28.5	1871.8	74.0	1549.5	124.0	1197.0
4.5	1989.3	29.5	1864.6	76.0	1535.4	126.0	1183.0
5.5	1986.4	30.5	1857.3	78.0	1521.3	128.0	1168.9
6.5	1983.4	31.5	1849.7	80.0	1507.2	130.0	1154.8
7.5	1980.3	32.5	1842.0	82.0	1493.1	132.0	1140.7
8.5	1976.9	34.0	1831.4	84.0	1479.0	134.0	1126.6
9.5	1973.4	36.0	1817.3	86.0	1464.9	136.0	1112.5
10.5	1969.7	38.0	1803.2	88.0	1450.8	138.0	1098.4
11.5	1965.8	40.0	1789.1	90.0	1436.7	140.0	1084.3
12.5	1961.7	42.0	1775.0	92.0	1422.6	142.0	1070.2
13.5	1957.4	44.0	1760.9	94.0	1408.5	144.0	1056.1
14.5	1953.0	46.0	1746.8	96.0	1394.4	146.0	1042.0
15.5	1948.4	48.0	1732.7	98.0	1380.3	148.0	1027.9
16.5	1943.5	50.0	1718.6	100.0	1366.2	150.0	1013.8
17.5	1938.6	52.0	1704.6	102.0	1352.1	152.0	999.7
1 8.5	1933.4	54.0	1690.5	104.0	1338.0	154.0	985.6
19.5	1928.0	56.0	1676.4	106.0	1323.9	156.0	971.5
20.5	1922.5	58.0	1662.3	108.0	1309.8	158.0	957.4
21.5	1916.8	60.0	1648.2	110.0	1295.7	160.0	943.3
22.5	1910.9	62.0	1634.1	112.0	1281.6	162.0	929.2
23.5	1904.8	64.0	1620.0	114.0	1267.5	164.0	915.1
24.5	1898.6	66.0	1605.9	116.0	1253.4	166.0	901.0

Pollen Stratigraphy and Vegetation History

Figure 5.7 is a complete pollen diagram for site 3/station 8 showing all identified pollen taxa. Figure 5.8 is an abbreviated diagram that includes only key taxa. The pollen record is dominated by a mixture of boreal forest taxa (i.e., *Picea*, *Pinus, Betula, Alnus, Salix*) and grassland/parkland taxa (i.e. Gramineae, *Ambrosia*, *Artemisia*, Chenopodiineae) and is divided into three recognizable pollen assemblage zones.

Zone 3 is differentiated on the basis of maximum *Pinus* percentages. *Picea*, deciduous hardwoods and grassland/parkland taxa are minimal. *Alnus* reaches maximum values close to 15%.

Zone 2 is the pre-settlement zone. It is distinguished by lower and upward-decreasing percentages of *Pinus* and higher percentages of *Picea* than in zone 3. *Artemisia* and Gramineae with lesser amounts of *Ambrosia* and Chenopodiineae are the grassland/parkland indicators, but as in the previous zone, the herb percentages are consistently low throughout the zone. *Betula*, *Populus*, *Quercus* and other deciduous taxa are slightly higher than in zone 3. Cyperaceae, like *Picea*, is at its maximum in this zone. *Alnus* is inconsistent as it varies from less than 5% to almost 15%.

Zone 1 is the settlement zone based on significant increases in weed pollen of *Ambrosia* and the chenopods and first appearances of *Salsola*, *Brassica*, *Rumex* and Gramineae (cereal grasses). The weed and grass pollen increases are reflected by a noticeable increase in the total herb profile. *Picea* remains unchanged from the previous zone whereas *Pinus, Alnus* and Cyperaceae decrease slightly towards the top of the zone.

Figures 5.9 and 5.10 are complete and abbreviated pollen records, respectively, for core 4. The pollen record is divided into two pollen assemblage zones, a settlement zone (zone 1) and the pre-settlement zone, zone 2. The settlement horizon (zone 2/1 boundary) is placed at 27 cm depth, and like core 8, is distinguished by abrupt increases in *Salsola* and *Brassica* and enhanced percentages of *Ambrosia* and *Chenopodiineae*. The weed pollen increases parallel the increase in total herbs and the abrupt jump in overall pollen concentration. *Picea, Pinus, Alnus* and *Cyperaceae* show similar trends as in core 8.

The increase in *Picea* and compensating decrease of *Pinus* at the zone 3/2 boundary in the longer of the two records in core 8 (Figures 5.7 and 5.8) is dated by the age model at 1113 AD. The increase in *Picea* is interpreted to indicate a change to cooler climatic conditions, and is possibly related to an early phase of the Little Ice Age whose onset is dated elsewhere about 1430 AD (Gribbin and Lamb, 1978). Temperatures during the height of the Little Ice Age averaged 1-3^{o} C less than today. The cooling trend continued to just prior to settlement based on the persistence of *Picea* to near the top of zone 2. The upper limit of the spruce maximum (at about the 42 cm depth) possibly correlates with the end of the Little Ice Age locally, and is dated about 1775 AD according to the age model. This compares with 1850 AD which is the date generally given for termination of the Little Ice Age (Gribbin and Lamb, 1978).

First appearances of *Salsola*, *Brassica* and other crucifers, *Rumex* and cereal grasses (*Avena*, *Triticum, Secale* type) and increased percentages of the composites (notably *Ambrosia*) and chenopods at 32 cm depth in core 8 and at 27 cm depth in core 4 mark the impact of settlement in the lower Red River valley. These taxa are tolerant of soil disturbances, and being introduced with European settlement, they thrived in new environments created as a result of the increase in cultivated area when the population of southern Manitoba increased four-fold between 1881 and 1900 AD (Statistics Canada, 1986). The year 1881 AD marked the opening of

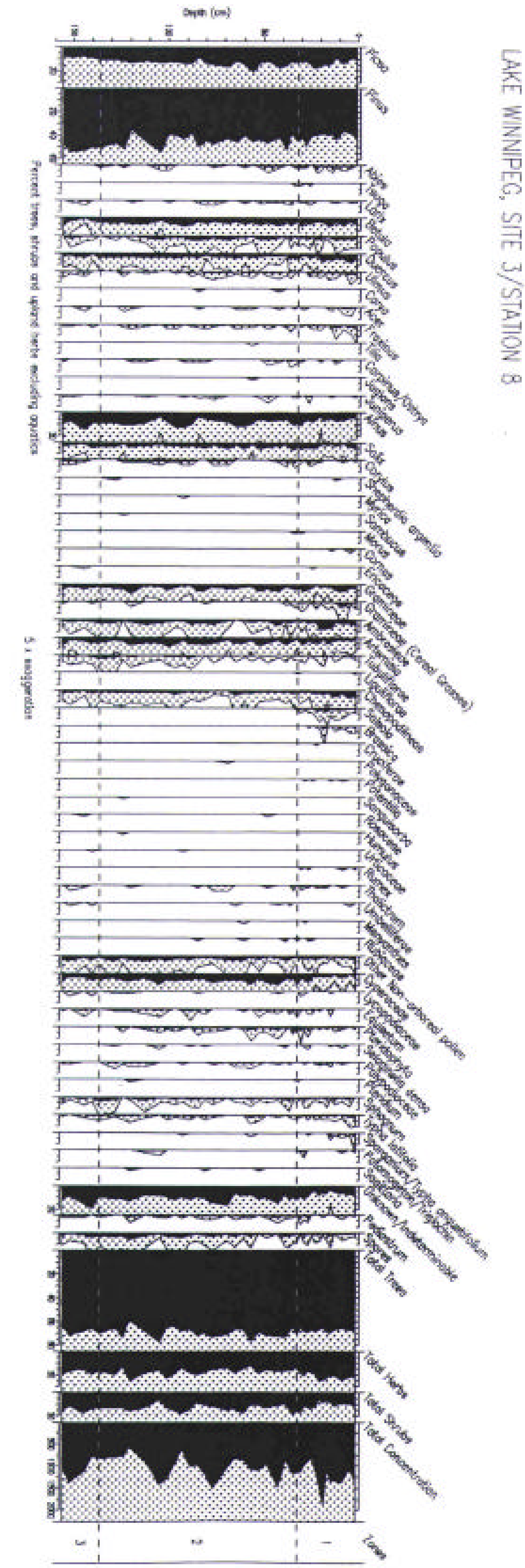

Figure 5.7. Pollen diagram for core 8 showing all identified taxa.

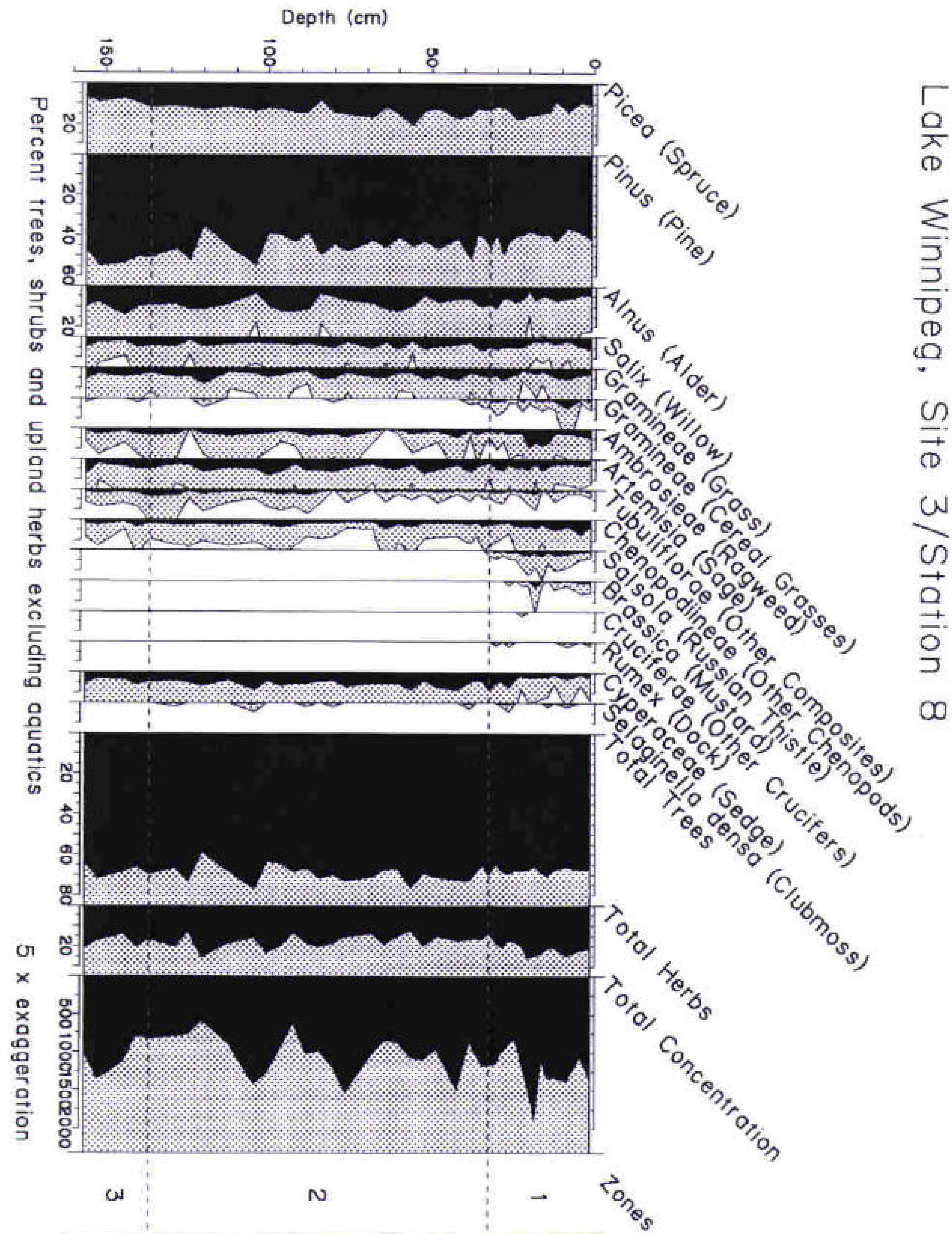

Figure 5.8. Abbreviated pollen diagram for core 8 showing only selected taxa.

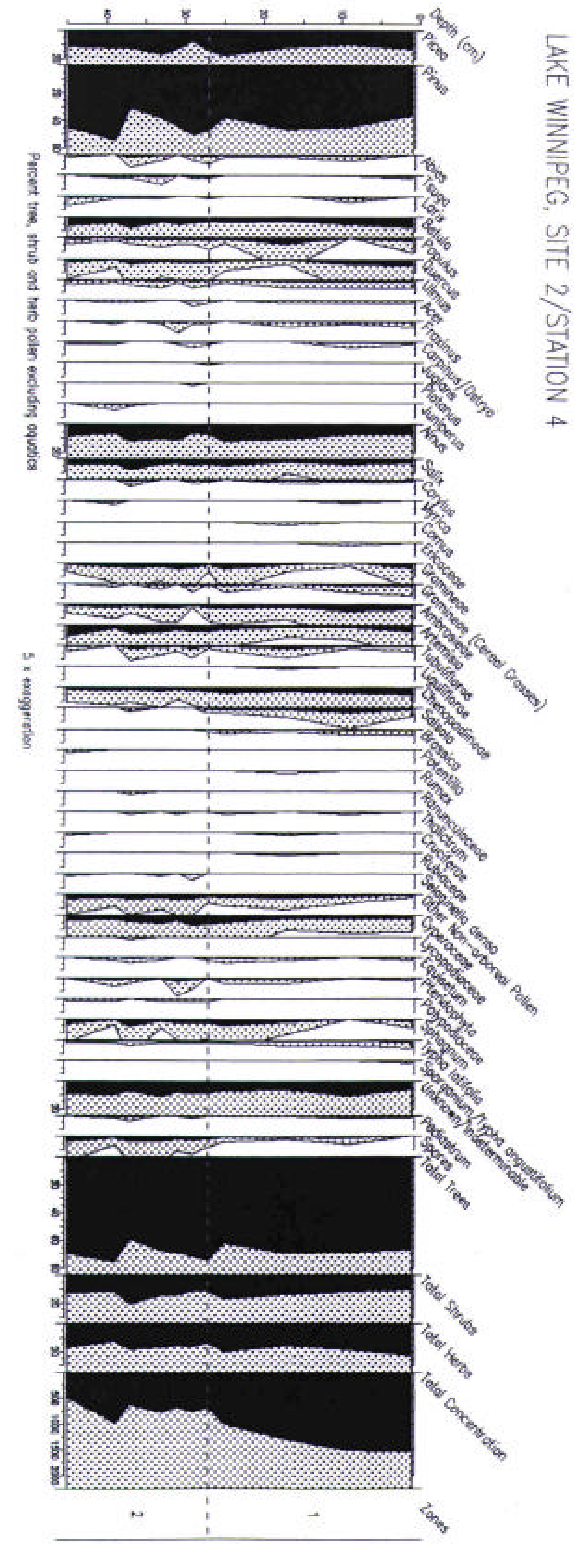

Figure 5.9. Pollen diagram for core 4 showing all identified taxa.

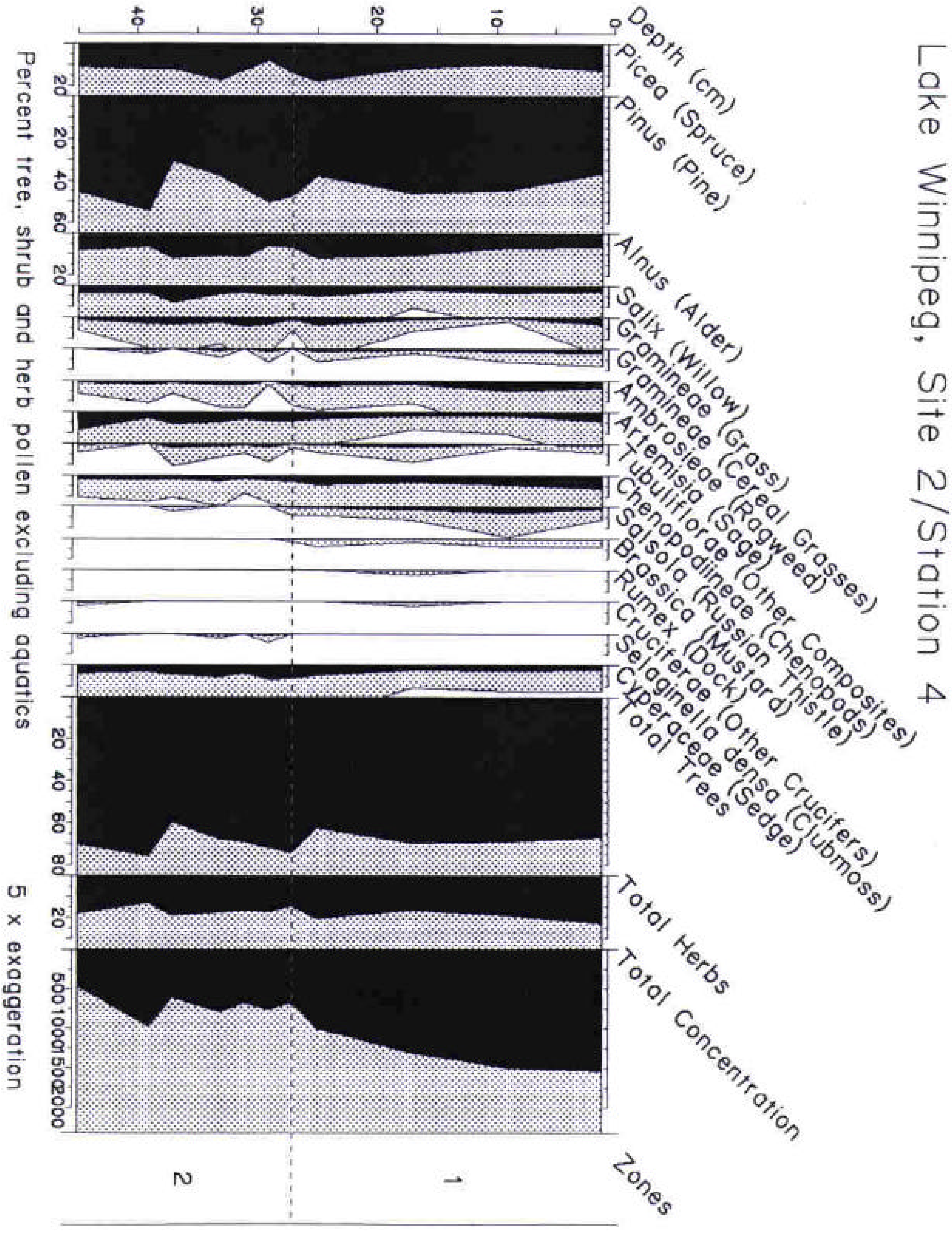

Figure 5.10. Abbreviated pollen diagram for core 4 showing only selected taxa.

the railroad which linked the wheat-growing region around Winnipeg with shipping outlets on the Great Lakes.

The zone 2/1 boundary is marked by an abrupt increase of *Salsola* pollen. The age models suggest dates between 1855 AD (core 8) and 1882 AD (core 4) for this boundary. The pollen evidence could be that of either of two species, *Salsola iberica* or *S. paulsenii* or both. A third species of *Salsola, S. kali,* appears to be synonymous with *S. iberica* according to Beatley (1969). Our ages for the rise of *Salsola* are consistent with the first appearance of *Salsola iberica* in the pollen record at Devils Lake, North Dakota at 1894-1895 AD (Jacobson and Engstrom, 1989). They are also consistent with the earliest observations of plants of *Salsola kali* in southern Manitoba which were reported in 1895 (Dewey 1895).

Increases in pollen concentrations across the zone 2/1 boundary, which are especially apparent in core 4 (Figures 5.9 and 5.10), reflect a real increase in upland weeds and cereal grasses associated with settlement and the beginning of agriculture. The pollen concentrations are highest at the peaks in *Ambrosia, Salsola* and *Brassica* at both core locations. Peak percentages in these taxa probably correspond with the period when the acreage of land under cultivation and disturbance might have been at its maximum. It is interesting to note, particularly in core 8, the maxima in these taxa are sequentially followed by maxima in cereal grasses (8 cm depth) and chenopods (4 cm depth). The peak in cereal grasses suggests that the area of land devoted to wheat growing may have already reached its peak (mid-1970s) and has since been declining.

Figures 5.7 and 5.9 show that *Alnus* fluctuates from less than 5% to almost 15% in both records. *Salix*, likewise, varies between 5 and 10% from top to bottom. Exaggerating the x-axis of the *Alnus* and *Salix* curves (Figures 5.11 and 5.12) accentuates the peaks and valleys of the profiles. For *Alnus*, in particular, a peak-valley pattern becomes apparent. There is no clear correlation of the *Alnus* and *Salix* peaks and valleys except perhaps for the peaks at the zone 2/1 boundary in core 8 and the peaks preceding the zone 2/1 boundary in core 4.

The *Alnus* pollen closely compares with the species *Alnus rugosa* (Speckled alder) which is the common alder of most wetland sites such as stream banks and swamps (Farrar, 1995). Speckled alder is often used as a plant indicator in site identification and it has potential as an indicator of site quality in that it grows vigorously where tree growth is good but is less vigorous and is not as common in areas where tree growth is poor (Vincent, 1964). The alders and willows are known for their tolerance to temporary flooding (Hall and Smith, 1955). Experiments have shown that speckled alder and willow are also tolerant to prolonged periods of flooding as long as the water table is below the root crown, but there is a decrease in growth and increase in mortality with increase in depth of flooding (Knighton, 1981).

Could the *Alnus* and *Salix* peaks and valleys in Figures 5.8 and 5.9 be interpreted in terms of potential indicators of wet-dry cycles, the peaks possibly indicating wet periods, the valleys drier periods? The peaks in *Alnus*, for example at the 90-100 cm and 55-70 cm depths in core 8, could represent periods when conditions favoured *Alnus* growth; the inter-peak valleys, i.e., at 70-90 cm depth, might possibly represent drier intervals with reduced *Alnus* growth. The periods of *Alnus* growth possibly equate with times of high water tables attributed to flooding, whereas the periods of reduced *Alnus* growth perhaps are indicative of lower water tables and non-flooding times.

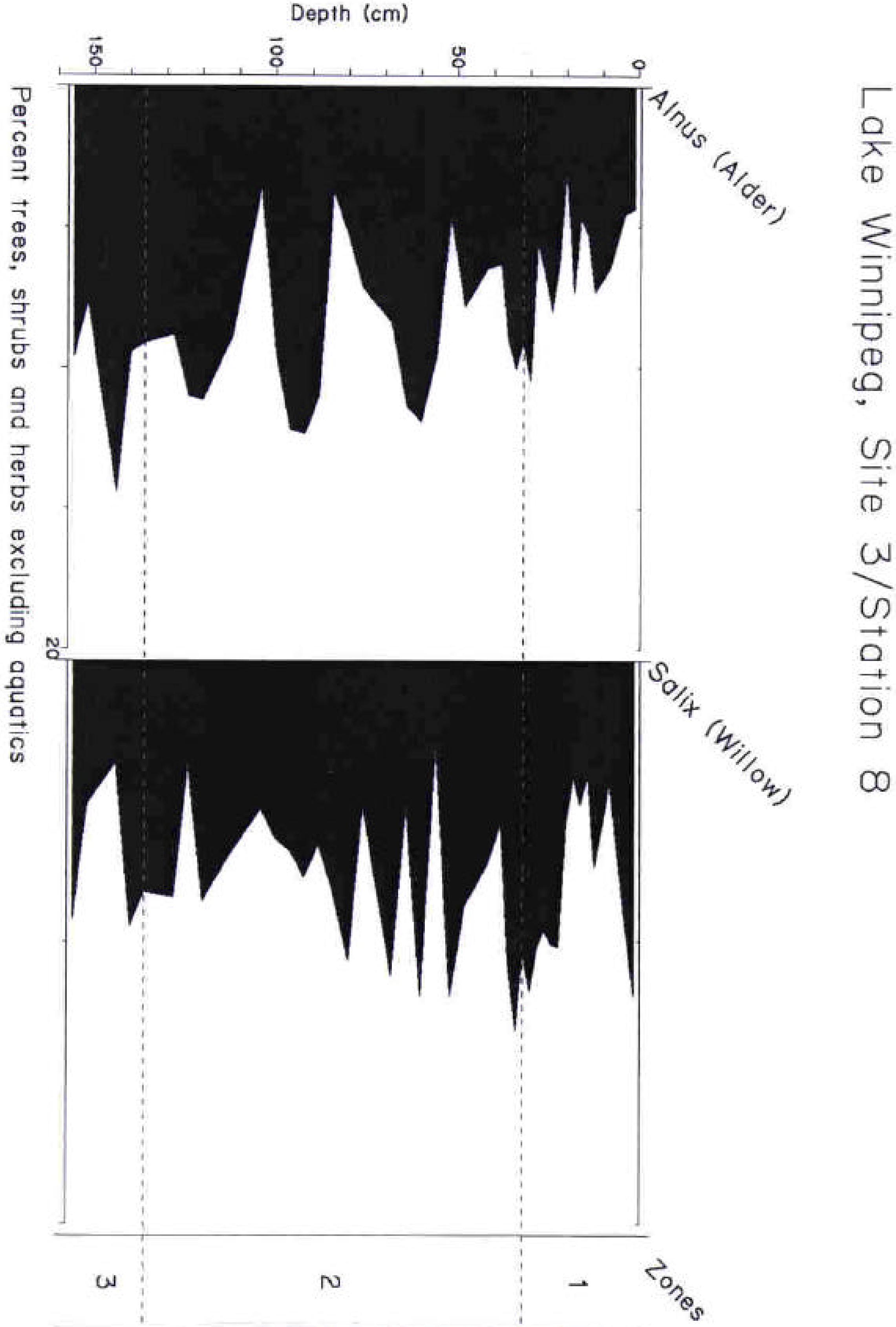

Figure 5.11. Exaggerated *Alnus* and *Salix* profiles at core 8.

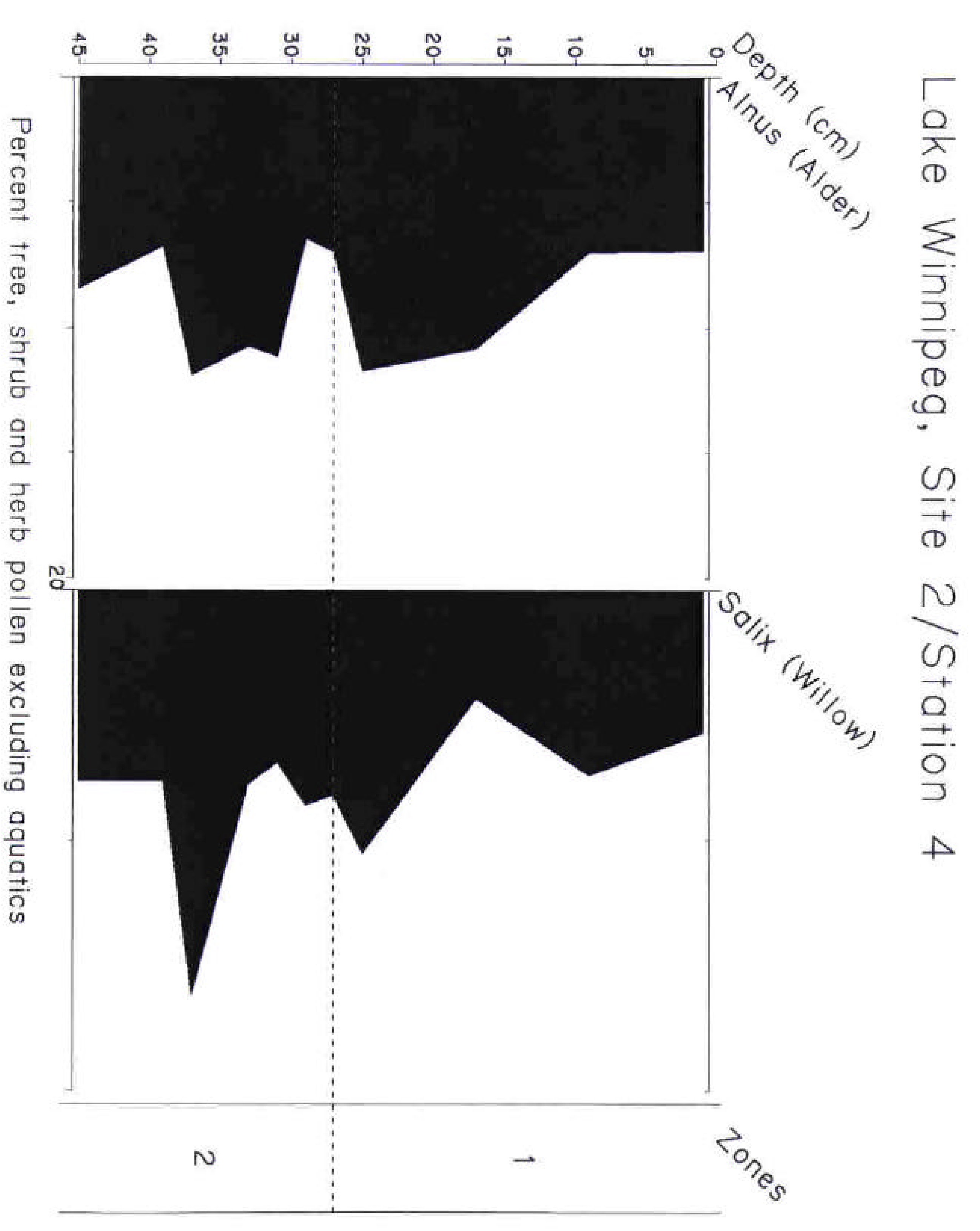

Figure 5.12. Exaggerated *Alnus* and *Salix* profiles at core 4.

Macrofossil Analysis and C-14 Dating

The few macrofossil remains obtained of *Daphnia*, *Chironomidae*, and insect parts, from an apparent depth of 50-65 cm in core 7, were anomalous. A modern age was determined by accelerator mass spectrometry of radiocarbon (CAMS-71707) for the insect fragments from 50 cm to 60 cm. As this is inconsistent with the age of well-dated sediments at similar depths in cores 8 and 4 at sites 3 and 2, we reject the determination.

Particle Size Analysis

Significant occurrences of larger grain sizes in the predominantly fine-grained offshore sediments indicate enhanced sediment transport during periods of energetic conditions, such as enhanced storminess and wave activity, or enhanced land runoff and river inflow. Since the onset of settlement and agriculture, grain size increases might also reflect changes in land use and management in the Red River valley.

The downcore percentages of medium silt in core 4 (Figure 5.13) show distinctive structures, as small-scale variability with a wavelength < 10 cm superimposed on larger-scaled features. The large-scale properties of this profile of 16-32 µm particle size show a modest content of 1-2 % in the lower part. From 100 cm (about 1370 AD) to 70 cm (about 1580 AD), the silt content increases to a peak of 4 % and falls to a minimum of 0 % at 64 cm (about 1620 AD). Above 55 cm (about 1690 AD) the silt rises to a plateau around 2 %, then after 21 cm (about 1920 AD) begins to rise to values exceeding 7 %.

Organic Geochemistry

The Rock-Eval results show that the total organic carbon content of the lake sediment is about 1 % below 30-35 cm (early to mid-1800s) in cores 8 and 4. From this level, the C content increases toward the present reaching values of 1.7-1.8 %. With the Rock-Eval technique, the source of organic matter in the sediments may be evaluated by a cross-plot of the hydrogen and oxygen indices (Meyers and Lallier-Vergès, 1999). The hydrogen index is the ratio of hydrocarbons evolved during heating at 25^{o}/minute between 300^{o}C and 600^{o}C to the total organic carbon content. The oxygen index is the ratio of organic carbon dioxide evolved from 300^{o}C to 390^{o}C to the total organic carbon content. On the cross-plot algal organic matter from lacustrine sources normally plots in the Type II field and terrestrial or vascular plant organic matter plots in the Type III field. Samples from both cores 8 and 4 all plot in the type III region, indicating the Lake Winnipeg sedimentary organic matter is dominated by terrestrial inputs (Figure 5.14). This was an unexpected result. The working hypothesis was that most organic matter would be lacustrine and that runoff and airflow extremes might be detected in the organic matter as zones with increased terrestrial provenance. Dispersion of sample results in the Type III field will be examined further, and additional data in the form of elemental C and N, and isotopic composition of C and O is being obtained by W.M. Buhay, University of Winnipeg to enhance information for the distinction of paleo-environmental variation during the past 1000 years.

Inorganic Geochemistry

The inorganic geochemical results provided a database of 41 elemental contents for one-cm intervals in cores 8 and 4. It is expected that variations with time in climate and other environmental factors may be inferred from measured changes in the sedimentary composition. An example from this database is shown in Figure 5.15 in which the Pb profile is nearly uniform

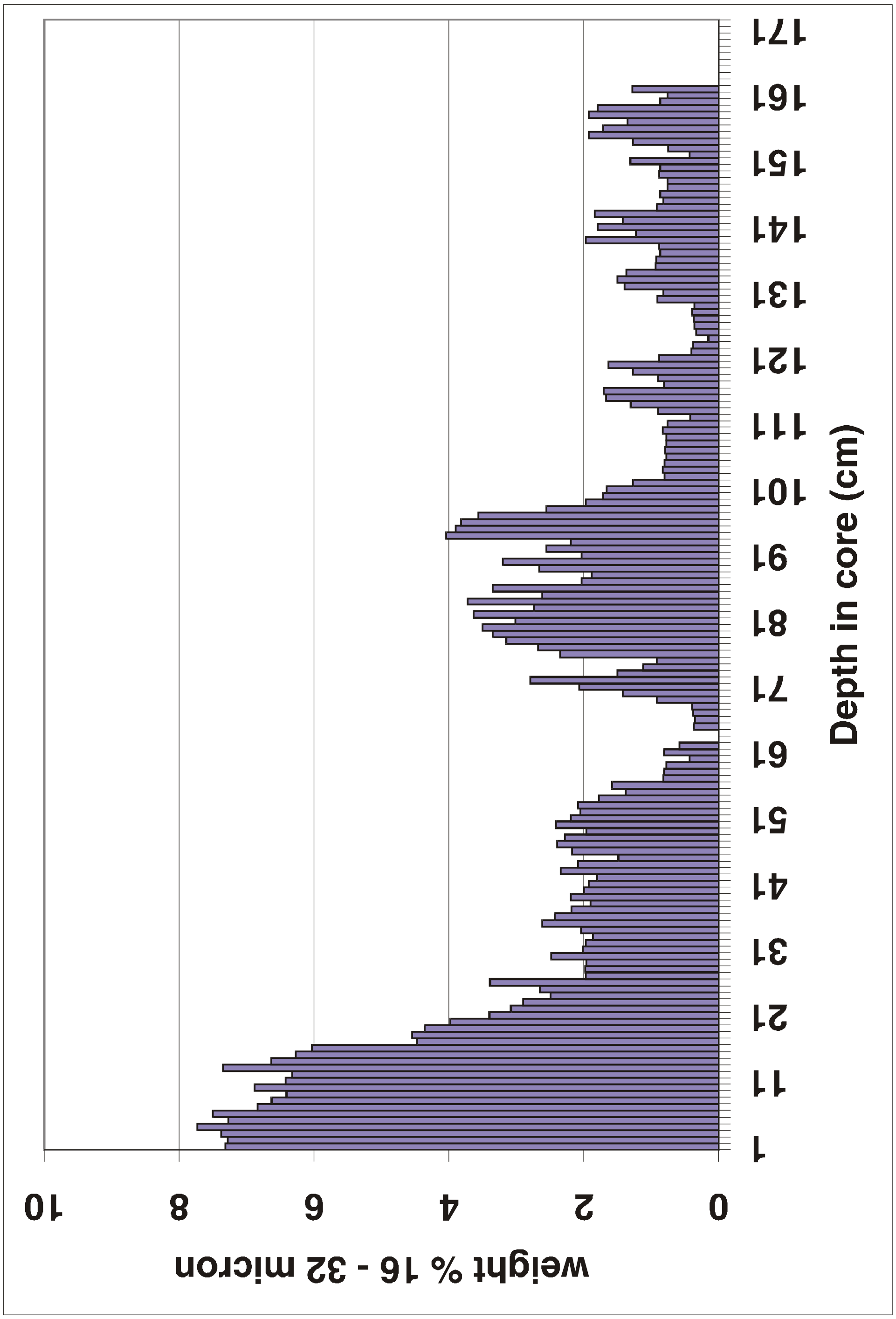

Figure 5.13. Downcore profile of medium silt (16-32 µm) in core 4.

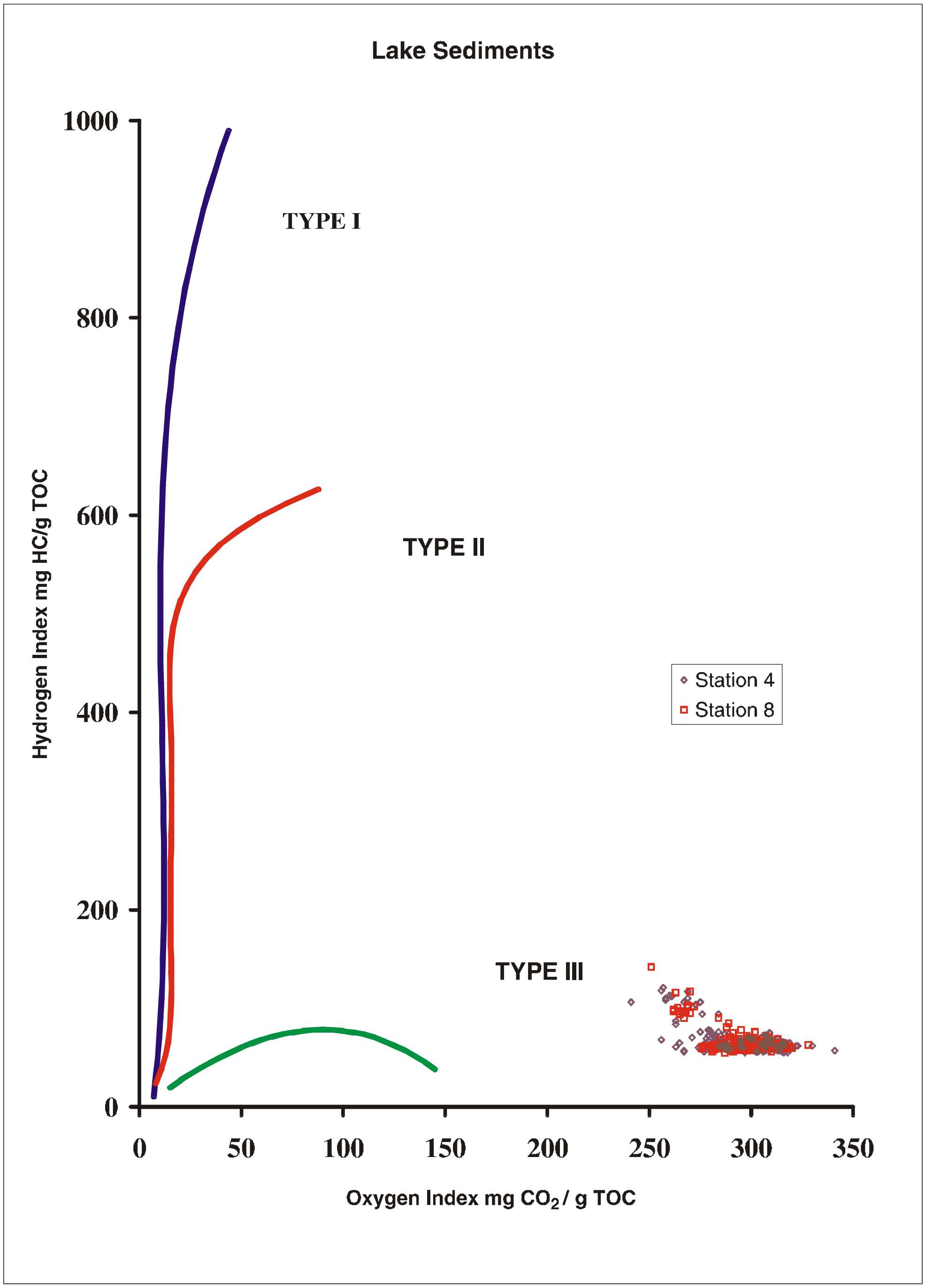

Figure 5.14. Cross-plot of Hydrogen Index and Oxygen Index, a Rock-Eval Van Krevelen-type diagram for sedimentary organic matter.

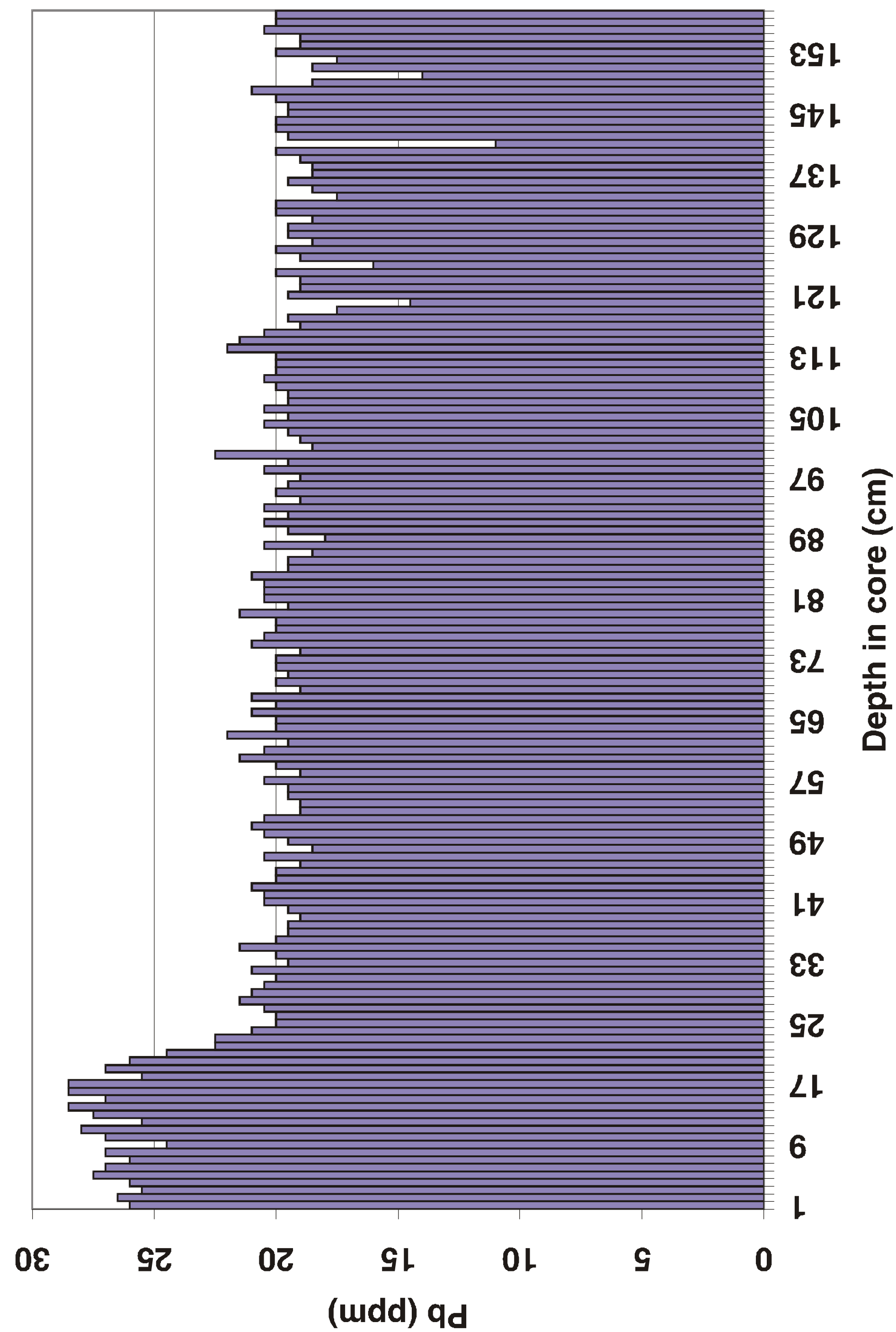

Figure 5.15a. Downcore profile of Pb in core 8.

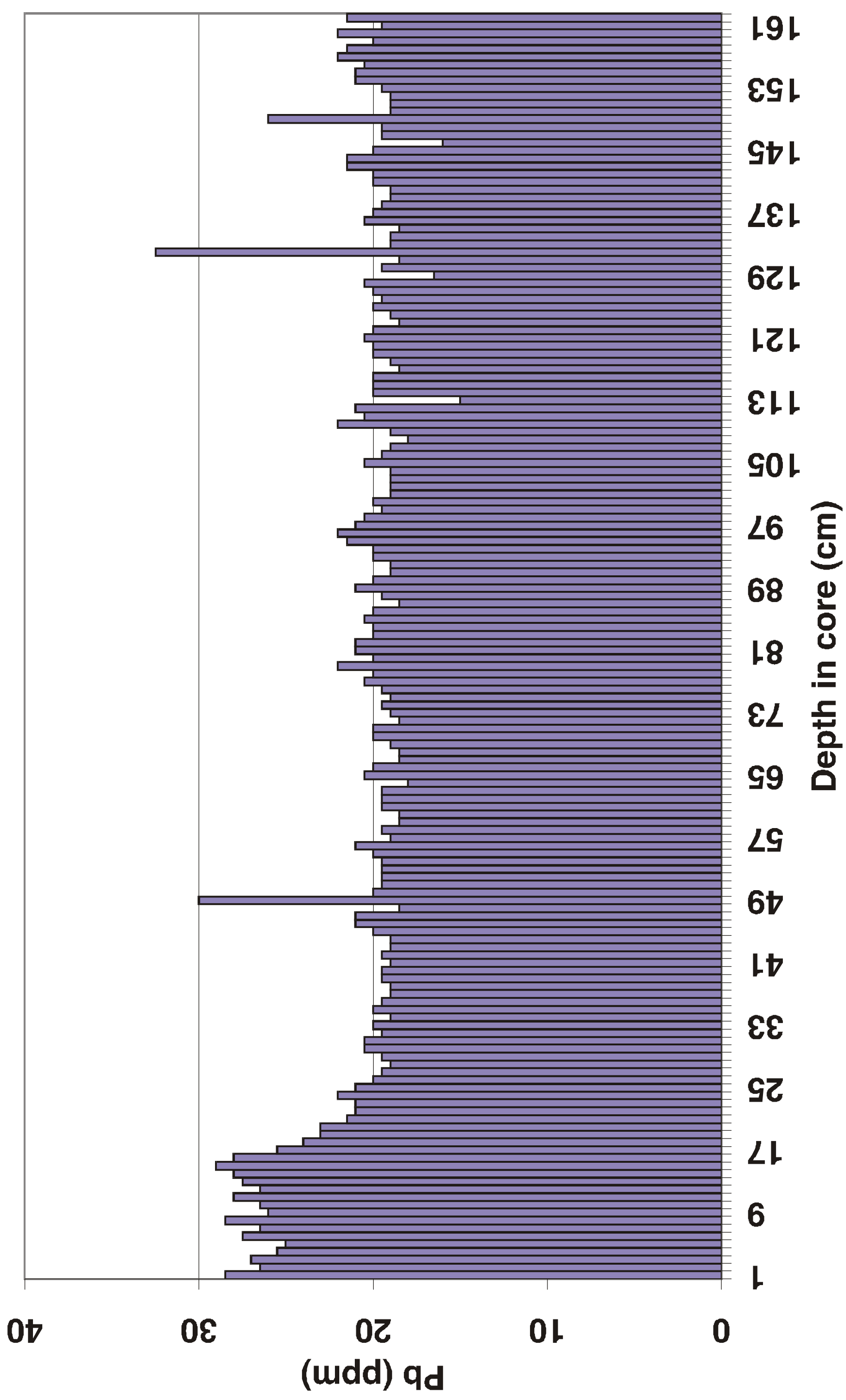

Figure 5.15b. Downcore profile of Pb in core 4

around 20 ppm, then rises above 18-20 cm (after about 1920 AD) to values between 25 and 30 ppm. The similarity of these profiles from independent sites attests to the integrity of the sedimentary record. In this case, the elevation of the lead profile is probably more related to anthropogenic effects than natural environmental or climatic changes.

Summary and Discussion

A suite of silty clay sediment cores ranging in length from 107 to 170 cm has been recovered from southern Lake Winnipeg north of the Red River mouth for investigation of environmental and climatic change in the past 1000 years. Correlation of similar profiles of physical property and chemical compositional changes shows the cores are generally of high quality. Two reference cores, 8 and 4, at different sites, 3 and 2, were selected to represent the environmentally-induced variability of the lake sediment record.

Chronological models have been built which assign age to each cm slice in cores 8 and 4. These depth-age relationships are based on Pb-210 and Cs-137 activity in the upper 33 cm and a radiocarbon-dated paleomagnetic field inclination event, I1, at 870±180 years BP. It is shown that the records in the reference cores begin just after 900 AD.

A palynological study of the core sediment is reasonably complete. Pollen assemblages for the past 1000 years divide into three zones. A basal zone contains maximal pine with minimal spruce, hardwood and grass pollen. After about 1110 AD a zone of higher spruce and other trees is distinguished, and this zone may correlate with occurrences of Little Ice Age evidence elsewhere. After about 1850-1880 AD a settlement zone is characterized by weed and cereal grass pollen. Relatively wide swings in alder and willow pollen contents throughout the 1000-year record were noted. Further investigations are warranted to determine the extent to which increases in alder and willow pollen are indicators of wet periods with higher groundwater tables.

The medium silt component of the sediment grain size distribution varies significantly over the last 1000 years. An early period of moderately low but variable silt content (1-2 %) is succeeded by a period of higher silt content (up to 4 %) between about 1370 AD and 1580 AD Minimal silt (0 %) occurs about 1620 AD, and this condition may correlate with drought conditions registered in the first half of the 17th century in the precipitation record derived from tree ring studies (St. George and Nielsen, this volume). A following period of moderately high silt content (2%) is succeeded in the 20th century by substantial increases of silt content to the 6-8 % range. Short-term cycles are evident throughout the period of record, and further study may reveal their environmental and climatic significance.

Studies of the carbon compounds and components in the cores yielded the surprising result that most organic matter is derived from terrestrial plant vascular sources. However, considerable variability remains in the sedimentary hydrocarbon fraction, and this will be investigated together with additional data on C, N and isotopic composition for information about environmental and climate change.

A large database of sedimentary elemental composition has been obtained, with 41 elements at each centimetre in the two reference cores. Considerable scope for studying the variability of these data remains. Example profiles for Pb are illustrated; they are similar in both reference cores and show a distinct increase from 20 to 25-30 ppm after about 1920 AD.

This study of Lake Winnipeg sediments is a work in progress. Work will continue in the months to come to correlate and assess the variability of the texture, pollen, and geochemical records for their significance with respect to environmental change and information about past climate extremes.

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6. Appendix: Project Contributions

Publications/Abstracts

Buhay, W.M., Mayer, B., St. George, S., Nielsen, E., Harms, P., and Marcino, D. 2001. Tree-ring stable oxygen isotope rations indicating cooler and wetter climate conditions and high flood frequency periods in the Red River Basin, Manitoba, Canada [Abstract]. International Conference on the Study of Environmental Change Using Isotope Techniques, International Atomic Energy Agency, Vienna, Austria, April 23-27, 2001.

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Nielsen, E. and St. George, S. 2001. Paleoflood records and hydrological change in southern Manitoba since AD 1460 [Abstract]. Global Change and its Impact on the North Atlantic Borderlands. Geological Association of Canada - Mineralogical Association of Canada Joint Meeting, St. John's, Newfoundland, May 27-30, 2001.

Nielsen, E., and St. George, S. 2000**.** The paleoenvironmental history of the Red River Valley since AD 1463. *In* Report of Activities, Manitoba Industry, Trade and Mines, Geological Services. p. 220-222.

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St. George, S. and Nielsen, E. 2000. From drought to deluge: four hundred years of environmental change in the Red River valley [Poster]. Annual Meeting, Manitoba Geological Survey, Winnipeg, Manitoba, November 17-18, 2000.

Invited Presentations

Nielsen, E. 2001. Climate change in Manitoba during the Holocene. Presentation to the Manitoba Climate Change Task Force. Brandon, Manitoba, May 17, 2001

Nielsen, E. 2001. Dendrochronology in southern Manitoba. Canadian Water Resources Association, Manitoba Branch. Winnipeg, Manitoba, April 24, 2001.

Nielsen, E. 2001. Perspectives on the past: tree-ring evidence for recent environmental change in Manitoba and the Maritimes. Atlantic Provinces Council of the Sciences - Atlantic Geoscience Society, Earth Science Speaker Lectures; Acadia University, University of New Brunswick, St. Francis Xavier University, St. Mary's University, March 12-16, 2001.

Nielsen, E. 2000. From drought to deluge: environmental changes in southern Manitoba over the last 500 years. Oak Hammock Marsh, Manitoba, September 23, 2000.

Nielsen, E. 2000. Dendrohydrological reconstruction of flooding in the Red River Valley, Canada. GSC–Atlantic. Dartmouth, Nova Scotia, September 8, 2000.

Nielsen, E. 2000. Developing tree-ring records for the Red River valley and southern Manitoba. Department of Earth Sciences, Dalhousie University. Halifax, Nova Scotia, September 7, 2000.

St. George, S. 2001. Flooding and climate change in Manitoba. Presentation to the Manitoba Climate Change Task Force. Brandon, Manitoba, May 17, 2001.

St. George, S. 2000. Climate reconstructions and flood records from tree-rings in southern Manitoba. Climate Research Branch Seminar, Meteorological Service of Canada. Toronto, Ontario, September 18, 2000.

St. George, S. 2000. Trees, time and environmental change in western Canada. Geography Alumni Lecture Series, University of Winnipeg. Winnipeg, Manitoba. November 29, 2000.

Websites

Manitoba Geological Survey webpage titled "*Paleofloods in the Red River Valley*"
(http://www.gov.mb.ca/em/geoscience/pflood/pflood.html)