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EXECUTIVE SUMMARY

The Red River Flood Project contributes relevant geoscience information on the Red River flood hazard problem. The research provides a century to millennium time-scale context for the modern flood problem. The results enhance understanding of the frequency-magnitude of extreme Red River floods and geological processes that may be affecting the long-term trend of flooding.

The 1826 flood is interpreted to be the largest Red River flood since at least AD 1648, based on tree-ring flood signatures within bur oak trees.

The historical pattern of high magnitude Red River flooding implies that the frequency-magnitude relationship changes over time and that flood flows are not independent and randomly distributed. Better estimates of flood frequency-magnitude could be provided by techniques that account for non-stationarity and non-randomness in the discharge records.

Historical and tree ring evidence indicates that the peak flows of the Red and Assiniboine rivers coincided in 1826 and 1852. Accounting for this synchronism is critical in modeling the 1826 flood accurately.

Peak flow at Winnipeg during the 1826 flood coincided with extremely strong, persistent winds from the south. Wind set-up should be considered by any future hydraulic studies of the 1826 flood.

The rate of valley enlargement through lateral channel migration and incision is not significantly altering the discharge capacity of the shallow valley occupied by the river over time-scales of up to several centuries. The flood hazard on the adjacent clay plain is not being appreciably affected by changes to the valley cross-sectional area.

Differential uplift has caused the Red River to lose gradient gradually over time. Hydraulic modeling for past scenarios of gradient implies that broad, shallow floods are intrinsic to the basic setting of the Red River valley and are not the product of 'recent' landscape changes. The minor rise in mean depth occurring from the continued loss of gradient over the next few centuries will not significantly alter the flood hazard.

Hydroclimatic reconstructions indicate that climate in southern Manitoba has been relatively stable over the last two hundred years, but was more variable prior to 1800. Climatic case studies in regional drought planning that are based exclusively on 20th century instrumental records may under-estimate worst-case scenarios.

Natural fluctuations in hydraulic head from climatic variability within the Upper Carbonate Aquifer near Winnipeg have been much smaller than the effects of groundwater withdrawals during the 20th century. Groundwater usage from this aquifer is the most important consideration for management purposes.

INTRODUCTION

This document is the final report of the Red River Flood Project undertaken by the Geological Survey of Canada (GSC), Natural Resources Canada, and the Manitoba Geological Survey (MGS), Manitoba Industry, Trade and Mines, to contribute relevant geoscience information on the Red River flood hazard problem. The Project, which began in 1999, represents part of the scientific research component of the Canada-Manitoba Agreement on the Red River Valley Flood Protection. The report was submitted to Prairie Farm Rehabilitation Administration (PFRA) on March 31, 2003. The Open File version of the report consists of three main sections:

1. The purpose of the project.

2. An overview of the project results.

3. An appendix that lists all scientific papers and reports completed during the project. (Note, the version of the report submitted to PFRA contains a second appendix that includes copies of the key scientific papers presenting the main project findings. The contents of the PFRA and this open file versions are otherwise identical.)

PROJECT PURPOSE AND BACKGROUND

The Red River Flood Project was conceived to contribute relevant geoscience information on the Red River flood hazard problem. At the start of the project, three questions were posed to focus the research. As originally worded, the questions are:

1. How large can Red River floods get and how often do the large ones occur?
2. Are there geological processes that may be changing the Red River flood hazard?
3. What are the geological controls that govern the character of Red River flooding?

The basic theme of the questions is to provide a longer-term context for the modern flood hazard over a century to millennium time-scale. The answers are intended to enhance understanding of the frequency and magnitude of extreme Red River floods, such as the 1826 flood, as well as the geological processes that may be affecting the longer-term trend of Red River flooding. The answers will also reveal the longer-term temporal pattern of high-magnitude flood events, which could allow climatic controls on flood occurrence to be better recognized and understood. Overall, such information increases knowledge of the Red River flood hazard and thus aids decision-making on enhancing flood protection in the Red River valley.

Question 1 has been addressed in the project by developing a record of Red River floods for the period prior to instrumental and historical records of flooding (i.e., before AD 1800). As summarized below, this paleoflood record is derived from dendrochronological research using bur oak trees of the riparian forest. The record is from one of the four methodologies employed to investigate past Red River floods; the others examined cores from Lake Winnipeg (including Netley Marsh), the deposits in small lakes along the Red River, and alluvial deposits along the river banks. Four methodologies were utilized as it was recognized that the broad, flat topographic setting of the Red River valley is a challenging environment in which to develop a paleoflood record. The results from all four approaches, however, do provide unique insights into environmental changes and geomorphic processes in the Red River valley.

Consideration of Question 2 led to investigation of the evolution of the narrow, shallow river valley occupied by the Red River and the reduction of river gradient from differential uplift of the land surface in southern Manitoba. Both of these processes occur gradually, but their effects on the long-term trend of Red River flooding were not known. With the river valley, geomorphic processes conceivably could be enlarging the cross-sectional area of the shallow valley, thus easing the flood hazard on the adjacent prairie, or they could be aggrading the valley bottom and compounding the hazard. Differential uplift is causing the north-flowing Red River to gradually lose gradient over time. The significance of each process is summarized below.

With regard to Question 3, the influence of geology clearly relates to the topography of the area and its role controlling the development of broad, shallow floods characteristic of the Red River. Although considered during the course of the project, no geological controls on flooding were identified beyond those noted previously recognized (e.g., the presence of bedrock at Lister Rapids which controls the upstream profile of the Red River). The research thus focused exclusively on addressing Questions 1 and 2.

During the course of the project, secondary research questions were raised that required answering in order to address the primary research questions. Such questions produced a number of spin-off results that provide additional insights into understanding the Red River flood problem, environmental changes in the Red River valley as well as other geoscience applications. These include, for example, establishing a record of Assiniboine River floods from historic sources, examining 20th century ground water fluctuations from tree-rings, developing a sedimentological model of the Red River floodplain, and reconstructing hydroclimatic change in south-central Manitoba over the last six centuries. These results are also summarized below.

PROJECT RESULTS

1. Papers and reports

The research results of this project produced 36 scientific papers and reports; all are listed in the appendix. Many of the papers have been (or will be) submitted to scientific journals for publication. Doing this facilitates the dissemination of project results to the broader scientific community and makes the information readily available within the public domain. The peer review process used by the journals also provides a quality assurance for the interpretations in the papers.

The papers that represent the main project results appear in Bold text in the appendix. Although reviewed below, a reader interested in the detailed methods, results and interpretations should consult the individual scientific papers which are the definitive source of information. (The first author can be contacted for information regarding the status of the submitted and unpublished papers.)

The other papers and reports listed in the appendix contain large data sets and/or preliminary results. Most of these results have been condensed and/or the preliminary interpretations superseded by the papers in listed in Bold text within the appendix. However, a reader particularly interested in the raw datasets should consult these reports, which are part of GSC and MGS publication series and can be obtained from the respective agency.

2. Paleoflood research

The main focus of the project was the development of an extended flood history for the Red River derived from geological and biological archives. This approach investigates past floods that were not recorded by gauging stations or by human observation. The long records produced by paleoflood research establish a context for recent instrumental observations and provide better estimates of the frequency and magnitude of extreme floods. Extended flood histories can also help to identify temporal trends in flood frequency and increase understanding of the mechanisms that drive these changes. In this project, paleofloods have been investigated using dendrochronology as well as examining deposits within Lake Winnipeg (including Netley Marsh), small lakes on the Red River floodplain, and the alluvial banks of the Red River.

2.1 Dendrochronology

Dendrochronology uses information stored within the annual growth increment of trees (tree rings) to understand past environmental changes, including climate change and floods. Tree-ring records are particularly advantageous because they can be resolved to individual years, a precision unmatched by most other environmental proxy indicators. From the perspective of flooding, this annual resolution can provide evidence for specific years of flooding, synchronised flooding in separate drainage basins and linkages between flooding and potential forcing mechanisms.

2.1.1 The Red River basin tree-ring network

Dendrochronological research developed a new tree-ring network derived from bur oak (*Quercus macrocarpa* Michx.) growing at sites within the flood zone of the Red River. Samples were collected from living oak trees at sixteen sites along the Red and Assiniboine rivers, oak timbers recovered from local historical buildings and Euro-Canadian archaeological sites, and subfossil logs salvaged from the banks of the two rivers (Fig. 1). Bur oak was targeted due to its relative abundance, widespread usage in 19th century building construction, excellent preservation post mortem, and growth position relative to flood stages. The Red River basin tree-ring network includes data from 403 oak trees and extends from AD 1286 to 1999 (see St. George and Nielsen, 2003; submitted).

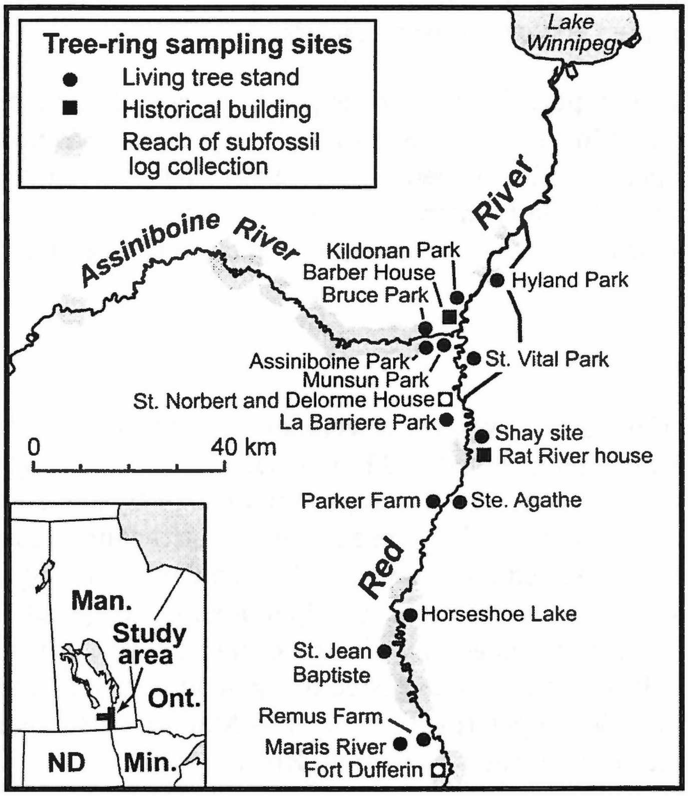

Fig. 1 The bur oak sampling network in the Assiniboine and Red River basins. Circles represent living tree sites; squares indicate selected historical buildings and archaeological sites. Shaded corridors along the rivers represent reaches where alluvial subfossil logs were collected.

2.1.2 *Tree-ring flood signatures ('flood rings')*

As presented by St. George and Nielsen (2000; 2003), it was discovered that high-magnitude Red River spring floods, like the 1950 and 1997 floods, affect the growth of riparian bur oak and can cause anomalous anatomical features to form within annual tree-rings. Compared to normal rings, 'flood rings' contain unusually small conductive vessels (Fig. 2). In cases where the effects on tree growth are more severe, other features may be present, such as amorphous latewood with disrupted flame parenchyma and relatively few fiber cells. The identification of flood rings in bur oak allowed St. George and Nielsen (2003) to develop a proxy record of past high-magnitude floods from the Red River basin tree-ring network.

Bur oak is particularly well suited for paleoflood reconstructions because most oak trees in southern Manitoba grow adjacent to rivers, on or immediately below the level of the prairie. The relative height of these trees prevents them from developing flood rings associated with lesser flows. Key factors controlling the formation of flood rings are: 1) a threshold stage of flooding that inundates the tree trunk, 2) the duration of submergence, and 3) the timing of the flood relative to the growing season (see

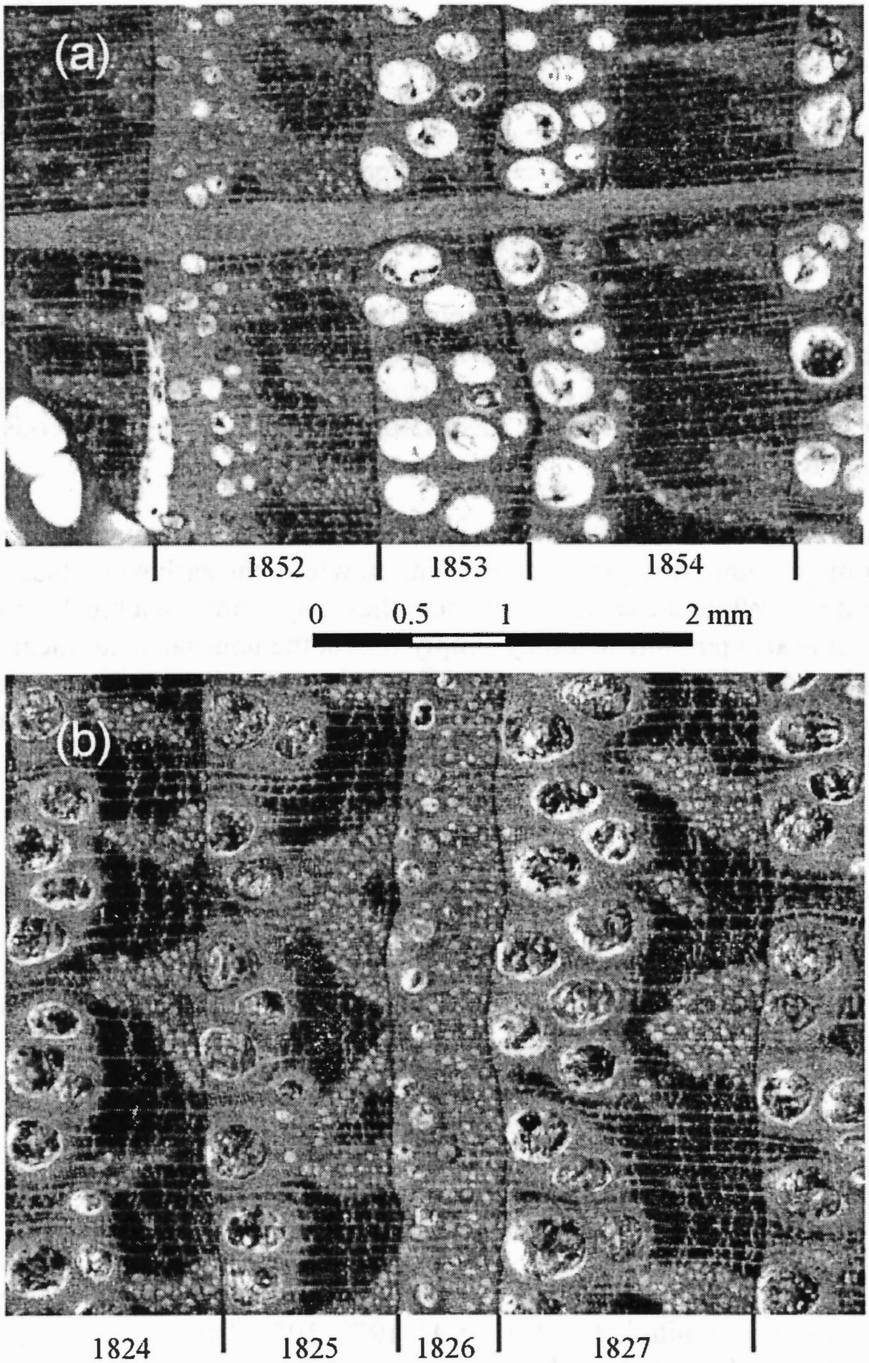

Fig. 2 Photographs showing the unusual anatomy contained within bur oak tree rings caused by high-magnitude flooding. The ring formed in 1852 (a) displays typical shrunken earlywood vessels, while the ring formed in 1826 (b) also shows additional anatomical anomalies, such as disrupted latewood, caused by more severe and/or prolonged flooding. From St. George and Nielsen (2003).

St. George et al., 2002; St. George and Nielsen, 2003). The last factor is particularly important, as flood ring formation depends on the concurrence of the interval of inundation and the growth of the early wood portion of the ring during the spring. Because of this relatively narrow 'window' of sensitivity, the flood-signature approach can only detect the past occurrence of spring floods. However, since the largest historic flows in the Red River have been caused by spring snowmelt, paleoflood records based on flood ring signatures yielded good success in identifying extreme Red River floods that occurred over the last 200 years (see St. George and Nielsen, 2003).

Investigations into the nature of flood ring formation have demonstrated that flood signatures are most strongly developed near the base of the tree and become less visible with distance up the trunk (see St. George et al., 2002). This factor may explain why relatively few flood signatures were identified for the 1979 and 1997 floods (see St. George and Nielsen, 2003).

Additional work also found that highly developed flood rings contain abnormally low values of magnesium, manganese and strontium within the earlywood (see St. George et al., submitted). While these elemental anomalies may represent a biochemical flood signature, it is also possible that they simply reflect the unusual anatomical structure of well-developed flood rings. Biochemical flood signatures have not been used to develop a paleoflood record for the Red River and follow-up research is required to conclusively determine their potential as proxy flood indicators.

2.1.3 Lower Red River paleoflood record

The extended flood history for the lower Red River basin (LRB) developed from flood ring signatures spans AD 1648 to 1999 (see St. George and Nielsen, 2003). The LRB record pertains to the river reach between Emerson and Winnipeg, and is based on 310 trees from the Red River basin tree-ring network. These samples are derived from living trees and historical and archaeological sources. Although the growth locations for live trees are within the area affected by modern Red River floods, the origin of timbers recovered from historical buildings and archaeological sites is difficult to determine. However, these trees were almost certainly harvested from the arboreal fringe surrounding the Red River and, in most cases, were probably cut only a few kilometres from construction sites.

During the period AD 1648 to 1999, the LRB tree-ring record contains flood ring evidence for high-magnitude floods in 1997, 1979, 1950, 1852, 1826, 1762 and 1747 (see St. George and Nielsen, 2003). The five most recent events were recorded by instrumental or historical observations, but the 1747 and 1762 floods predate local written history. Despite comments by an early fur trapper who suggested flooding was unusually extensive in 1776 (Ross, 1856), there is no tree-ring evidence for such an event.

During the period covered by instrumental and historical records, only those floods with peak discharges of ~ 3,000 $m^3 s^{-1}$ or greater at Winnipeg have produced flood-signatures, which suggests that this magnitude represents the approximate threshold discharge for flood ring formation in the LRB. However, there were floods in 1811 (Rannie 1998), 1861 and 1996 with discharges approximately equal to or greater than this apparent threshold, which failed to induce flood ring formation. The absence of these floods in the tree-ring record may be due to a relatively short period of peak flooding or early tree growth (and therefore earlywood formation) prior to flooding, likely due to unusually warm spring temperatures (see St. George and Nielsen, 2003).

Flood signatures formed during 1826 are more frequent and more highly developed than any other signatures in the Red River basin tree-ring record. Therefore, it is inferred that the 1826 flood was the most severe flood in the Red River valley since at least AD 1648 (see St. George and Nielsen, 2003). Using the same logic, it is further inferred that the 1747 flood was equivalent in magnitude to the 1852 flood (~ 4700 m^3 s^{-1}), and that the 1762 and 1950 floods were approximately the same size (~ 3000 m^3 s^{-1}).

The flood signature record for the lower Red River basin (LRB) contains three periods during which the Red River generated multiple high-magnitude floods: the mid 1700s, the mid 1800s and the latter half of the 20th century (see St. George and Nielsen, 2003). Conversely, the record also indicates that the LRB experienced prolonged intervals with little to no extreme flooding, particularly between 1648-1746, 1763-1810 and 1862-1949.

2.1.4 Upper Red River paleoflood record

The tree-ring record for the upper Red River basin (URB) consists of forty-four subfossil logs and thus has a much lower sample depth than the LRB record (see St. George and Nielsen, 2003). These trees were recovered along the banks of the Red River between Emerson and Morris and originated from unknown sources upstream either at the southern end of the LRB corridor or at sites in North Dakota or Minnesota. The URB record spans the interval AD 1448 to 1997, and contains anatomical signatures for nine floods: 1762, 1747, 1741, 1727, 1726, 1682, 1658, 1538 and 1510 (see St. George and Nielsen, 2003). Although interpretations of the URB record must be considered cautiously because it is based on relatively few trees, this flood record appears to differ from conditions in the LRB. In particular, after AD 1648, only the 1747 and 1762 floods are common to both the URB and LRB records. This may indicate that the URB record contains tree-ring signatures formed during localised flooding that was not large enough to produce flows above the threshold magnitude for flood ring formation in the LRB.

2.1.5 Assiniboine River paleoflood record

Like the URB record, the Assiniboine River basin (ARB) chronology was developed exclusively from subfossil logs recovered from river banks (see St. George and Nielsen, submitted). The oldest trees in the Red River basin tree-ring network were obtained from the ARB, which includes data from thirty-seven cross-dated oak trees spanning the period AD 1286 to 1968. A preliminary floating chronology covering an interval of 312 years has been developed from four ARB oak trees, but radiocarbon dating suggests that the chronology terminates at 1120 ± 60 radiocarbon years (GSC-5212; Morlan et al., 2000). It has not yet been possible to cross-date these specimens with the dated oak record.

The ARB record contains anatomical signatures that may reflect Assiniboine River floods in 1925, 1923, 1914, 1882, 1861, 1856, 1826, 1788, 1700, 1675, 1597, 1553, 1538, 1510 and 1496 (St. George and Nielsen, submitted). Several of these signatures coincide with known major Assiniboine River floods (see Rannie, 2001), but the record does not include flood signatures for major floods in 1904, 1922 and 1955, and the 1914 and 1925 signatures do not coincide with significant floods. These discrepancies are likely due to the limited number of ARB samples during the 20th century (less than six trees), and indicate that this flood signature chronology should be interpreted conservatively. Nevertheless, the ARB flood ring chronology does provide some insight into the flood history. Firstly, the signatures of flooding in 1788, 1700, 1597 and 1533 are recorded in multiple trees, which suggest that these represent large, previously unknown, Assiniboine River floods. Also, signatures in the ARB coincide with LRB floods in 1861 and 1826. This evidence suggests that severe floods on the Red and Assiniboine rivers can occur coincidentally. Accounting for this synchronism is particularly critical to model the record Red River flood of 1826 accurately, as previous studies have assumed only minor contributions from the Assiniboine River (see St. George and Rannie, 2003).

2.2 Lake Winnipeg

2.2.1 South basin of Lake Winnipeg

The south basin of Lake Winnipeg is a repository of sediments transported by the Red River. During high flow stages, the river likely carries a greater and coarser sediment load. As the river enters Lake Winnipeg, the silt and clay-sized sediments settle to the lake bottom. These deposits represent a potential record of Red River floods.

To test this, fifteen cores of approximately 1.5 m in length were collected in 1999 from *CCGS Namao* from five sampling sites within the south basin (see Simpson et al., 2003). The coring sites were selected carefully to avoid areas of ice scour on the lake bottom. In the laboratory, paleomagnetic profiles were used to identify cores containing apparently undisturbed, high-sedimentation-rate deposits. Three cores, each from a different sampling site, were chosen for detailed physical (grain size), inorganic chemical (major, minor, trace and rare earth elements), organic chemical (RockEval, $\delta^{13}C$, $\delta^{15}N$) and biological (pollen, diatoms, macrofossils) analyses designed to test for trends that might be associated with Red River floods (see Simpson et al., 2003). Further chronological data were obtained from ^{210}Pb and ^{137}Cs analyses, and two macrofossil samples were submitted for radiocarbon dating.

The paleomagnetic profiles reveal a 1050 to 1100-year record of sedimentation in the three cores. The appearance of *Salsola* pollen (Russian thistle, an exotic weed species) indicates that the upper 27 to 28 cm of the cores are post-AD 1888 to 1893 in age (see Simpson et al., 2003). Beds with enhanced silt content, up to several cm thick and with varying definition, are present in all three cores (Fig. 3). Better-defined examples occur within the post-1888-1893 portion of core 3, at depth intervals of 0 to 2, 4 to 7 and 9 to 11 cm, that might represent the three largest historic floods of the mid to late 20th century (Fig. 3). The dating of the sediments suggests that the upper two silt beds may have formed coincident with the 1997 and 1979 floods, but the age estimate for the third

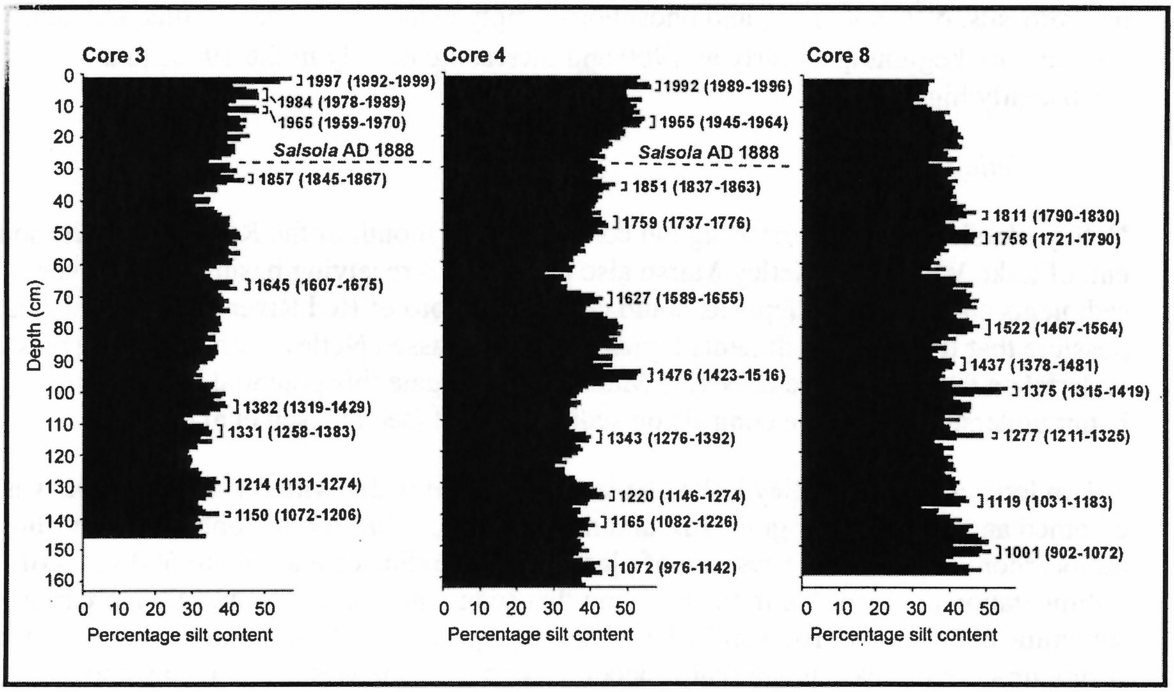

Fig. 3 Down-core variations in percent silt for Lake Winnipeg cores 3, 4 and 8. Beds (cm-scale thickness) with enhanced silt content and varying definition are present in all three cores. The better-defined beds are assigned ages showing a midpoint age and analytical error range (in brackets), based on radiochemistry, pollen, and compositional markers (Ca, Cd, Mg) in the cores. The *Salsola* pollen marker is correlated between the cores and indicates that the uppermost portion of the deposits post-date AD 1888-1893.

feature is too young to support correlation with the 1950 flood. In core 4, two silt beds are present; one possibly correlating to the 1997 flood and the second possibly to the 1950 flood. No equivalent silt strata are present in core 8 (Fig. 3).

Since the Red River is the major source of silt to the south basin of Lake Winnipeg, flooding is a plausible mechanism for the formation of the silt strata. However, despite possible correlations with the 20th century floods mentioned above, there are inconsistencies in the presence of the silts beds between cores and not all known historic floods are associated with silt strata (Fig. 3). This suggests that a relationship between silt strata and flood events is complex and uncertain. As a consequence, silt strata have not been used to develop a flood record for the Red River at this time. (*See addendum.*)

The three south basin cores also provide information on 20th century environmental change (see Simpson et al., 2003). Increased sedimentation rates and sediment coarsening since the late 1800s are attributed to expansion of agriculture and drainage of wetlands. Associated increases in concentrations of the elements Ag, Cd, Cu, Hg, Pb, Sb, U and Zn since the early 1940s are attributed to water and airborne contamination, which has tended to decline in the past two decades. Parallel increases in number of macrofossils, $\delta^{13}C$ and $\delta^{15}N$, and phosphorus imply enhanced nutrient influx and lake productivity beginning as early as 1900 and increasing rapidly in the 1950s to a consistently high level.

2.2.2 Netley Marsh

Netley Marsh is a back-barrier lagoon complex at the mouth of the Red River at the south end of Lake Winnipeg. Netley Marsh also represents a receiving basin of Red River sediments and the marsh deposits could contain a record of Red River floods. It also is possible that Red River sediments typically have bypassed Netley Marsh. Coring was undertaken through the ice in Netley Marsh to investigate this potential and obtain a better understanding of the controls on sediment input (see Nielsen et al., 2003).

A 1-m long core from Netley Lake, the largest body of water within Netley Marsh, was obtained and analyzed for grain size and macrofossils. Chronology, obtained from three radiocarbon dates and the presence of plastic debris, indicates that 400 to 500 years of sedimentation are recorded in the core and that sedimentation rates abruptly increased sometime between AD 1650 and 1950. The most prominent features in the core are an abrupt up-core increase in silt that is accompanied by decreases in sand, clay and dominant macrofossil species (Tubellaria, Spongillidae, *Scirpus* and Chironomidae). These changes indicate a shift from a closed, restricted basin to an open, higher energy environment (see Nielsen et al., 2003).

Several sand-rich layers are present in the core that could correspond to major floods of the past 200 years. However, uncertainties with the sporadic history of openings and closures of levee breaches between Netley Lake and the river, the character of the incoming sediments, the role of sediments from Lake Winnipeg contributed by wind-driven cross-barrier flow, and chronology do not permit an adequate understanding of depositional events in Netley Lake. The chronological data also do not permit the adequate dating of sand layers to make a conclusive correlation to known Red River floods (see Nielsen et al., 2003). Future detailed study may resolve some of these issues, however, other dominant processes in the lake such as periodic openings and closures may overprint any flood record and complicate the chronology with abrupt changes in sedimentation rate.

2.3 Small lakes

Large magnitude Red River floods, such as the 1997 flood, inundate small lakes located on the Red River floodplain depositing sediments and temporarily altering the lake water chemistry. Cores obtained from Lake Louise, near Emerson, and Horseshoe Lake, near Morris, shortly after both the 1997 and 1999 floods confirmed the deposition of flood layers in these lakes (see Medioli, 2003). The deposits in the beds of the floodplain lakes thus potentially contain a stratigraphic record of Red River flooding.

To develop an extended flood record, three lakes on the Red River floodplain were cored: Horseshoe Lake and Lake Louise, Manitoba, and Salt Lake, near Grafton, North Dakota. Subsamples of the cores were analyzed in detail for bulk geochemistry, physical properties (texture, mineralogy), RockEval, isotopic content (^{210}Pb) and micropaleontological composition (pollen, diatoms and thecamoebians; see Medioli, 2001; unpublished). Although sparse in the cores, organic materials were submitted for radiocarbon dating to establish chronology. To aid in recognizing flood deposits in the lake sediments, a micropaleontological signature of flooding was developed based on the diatom and thecamoebian composition of sediment samples collected from the 1997 and 1999 flood zones (see Medioli & Brooks, 2003).

Despite considerable efforts, the stratigraphic work on the Red River floodplain lakes did not yield a flood record (see Medioli 2003; unpublished). Several reasons for this have been identified. The lake deposits are anoxic (chemically reduced) which imparts a uniformly black colour to the sediments that obscures any bedding. Sedimentation in the lakes during floods, while occurring intermittently, aggrades cm-scale beds that account for virtually the entire 19th and 20th century portions of the sediment column. This factor, in combination with limited sedimentation in the lake basins between flood depositional events, hinders distinguishing individual flood beds using the proxy indicators and hence the construction of a stratigraphy of alternating lake and flood deposits.

The cores, however, do provide significant insights into recent environmental changes in the lakes (see Brooks and Grenier, 2001; Medioli, 2003; unpublished). Two distinct zones can be identified in the cores from all three lakes representing pre-settlement (pre-AD 1800) and settlement (post 1800) periods. The pollen stratigraphy reveals a pre-settlement landscape consisting of tall grass prairie and riparian forest. Post-1800, there is a decline of the tall grass prairie and riparian forest pollen marking the initial influx of settlers, while the arrival of pollen from cereal grains and exotic weed species represents the large-scale introduction of European agricultural practices during the 1880s. Diatoms and thecamoebians record the progressive increase in nutrients (from fertilizers) into the lake basins and an increase in water salinity between the two periods. Elevated nutrient levels have caused an increase in aquatic plant growth in the lakes that has led to depletion in the oxygen content of the water column and a completely anoxic (i.e., chemically reducing) sediment column. Of particular note is an increase in the rate of sedimentation (0.7 to 2.7 mm year^{-1}) between the two zones (see Medioli, unpublished). Most of this sediment is carried into the lake basins during flood flows and the increase probably relates to greater erosion on agricultural fields that were previously covered by natural vegetation prior to 19th century settlement.

2.4 Alluvial deposits

The stratigraphic work examining alluvial deposits exposed along the banks of the Red River did not yield a paleoflood record. Twenty-nine bank exposures were logged and 39 organic samples from 12 of these exposures were submitted for radiocarbon dating to establish a chronology for the deposits (see Brooks, submitted). The radiocarbon ages allowed four sites to be identified as containing deposits, 1 to 2 m thick, that accumulated over the past several centuries and which potentially could yield a paleoflood record. Despite careful logging in the field and the x-raying of intact bank samples in the laboratory, the generally weak to indistinct bedding of the bank deposits prevented a flood record being identified from these exposures. At the most promising site, section Au5-1-00 located about 5.5 km upstream of St. Jean Baptiste (see Brooks, submitted), moderately defined bedding is present in the upper 0.94 m of the bank. These beds, however, are 20th century in age, as indicated by the presence of a plastic toy pail at 0.72 m depth. Below 0.92 m, the bedding is weak to indistinct. It was thus not possible to even tentatively identify beds that may have aggraded during the 1826 or 1852 floods at this (or any other) exposure.

In support of the stratigraphic work, optical luminescence dating was utilized at four bank exposures, as reported by Lian and Brooks (submitted). This technique determines when sediment was last exposed to sunlight, an event that should correspond to the time of deposition by the river. Optical dating thus potentially could provide age estimates for beds of flood deposits in the bank exposures.

Optical dating was conducted on six silt-rich alluvium and three hearth (sediments heated in a fire pit) samples. Each of these samples were associated with radiocarbon ages derived from buried charcoal. The alluvial samples yielded optical ages that varied from consistent to substantially older than the related radiocarbon ages. The ages for the hearth samples were all consistent with the radiocarbon ages. Overall, the results demonstrate that optical dating can produce viable results dating silt-rich sediments, but is particularly useful for dating the heat-altered sediments of hearths.

3. Floods during the historical period

3.1 The 1826 Red River flood

St. George and Rannie (2003) conducted a comprehensive review of evidence related to the 1826 Red River flood, using both historical records and paleoenvironmental data. The 1826 flood was preceded by significant spring flooding in spring 1825 and persistently high water levels in early autumn 1825 that filled natural storage in the Red and Assiniboine river basins to capacity. Historical accounts and paleoclimatic data also document a cold, snowy April and an exceptionally late spring throughout much of central North America. The 1826 flood was exacerbated by abundant rainfall during the rising phase (Fig. 4). Historical accounts in western Manitoba and anatomical signatures in alluvial logs suggest that the lower Assiniboine River (downstream of Brandon) produced an exceptional flow in 1826, equivalent to perhaps 20% of the contribution from the Red River. Reports of extremely strong, persistent winds from the south coinciding with the flood peak (Fig. 4) suggest that wind set-up may have been an important factor influencing peak stage and should be considered by any future hydraulic studies of the 1826 flood.

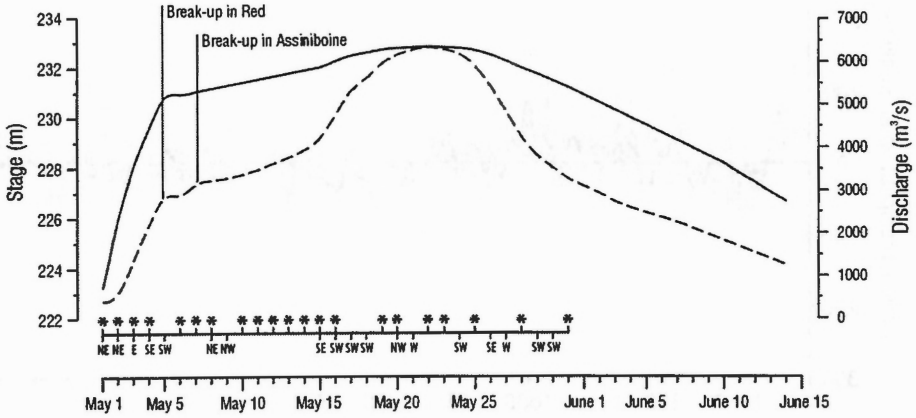

Fig. 4 Reconstructed stage (solid line) and discharge (dashed line) for the 1826 Red River flood at James Avenue, Winnipeg (A.A. Warkentin, unpublished data, 2002; after St. George and Rannie, 2003). Asterisks indicate days with precipitation and directions reflect dominant winds.

3.2 *Historical Assiniboine River floods*

Rannie (2001) reviewed the historical hydrology of the Assiniboine River and watershed between AD 1793 and 1870, using archival and historical materials. This initiative complimented his earlier work describing conditions for the Red River during the same period (Rannie, 1998). Three runoff periods were identified for the Assiniboine River: 1793/94 to 1830/31 (when runoff was highly variable); 1831/32 to 1846/47 (when records are poor, but which seems to be characterized by 'normal' or 'low' runoff with no extremes); and 1847/48 to 1869/1870 (when runoff was classified as 'normal', 'high', or 'very high' during 20 of the 23 years). Archival evidence also suggests that the Assiniboine River experienced high flows in both 1826 and 1852 and that these flows may have accounted for a significant proportion of estimated discharges for the Red River at the Forks. This research compliments the record for the Assiniboine River basin derived from tree rings presented by St. George and Nielsen (submitted).

4. Hydroclimatic change inferred from tree rings

The annual growth of bur oak in the Red River basin is strongly influenced by the amount of precipitation received within the region during the prior hydrological year. St. George and Nielsen (2002) utilized this relationship to develop a record of estimated annual (prior August to current July) precipitation at Winnipeg from AD 1998 to 1409. This record indicates that hydroclimate in southern Manitoba has been relatively stable over the last two hundred years (Fig. 5). Although this stability was interrupted briefly by

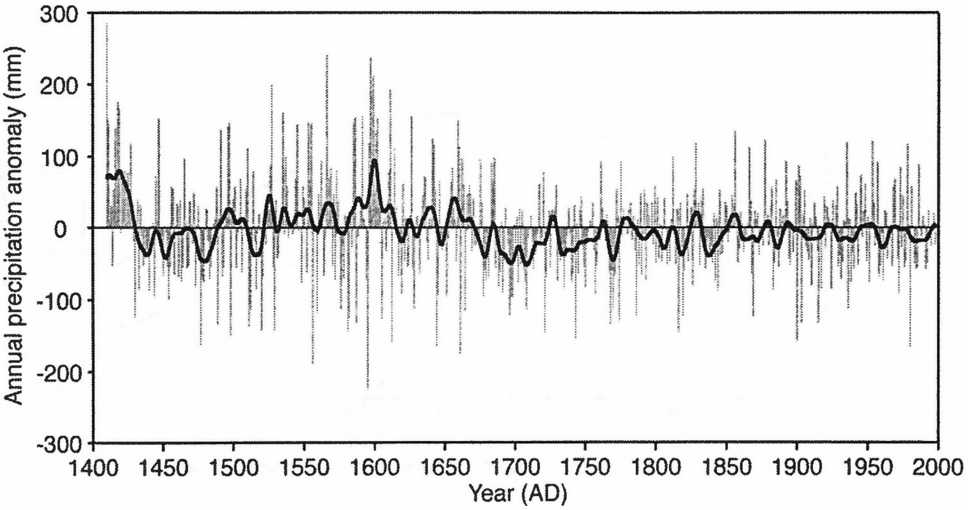

Fig. 5 Reconstructed annual (August-July) precipitation at Winnipeg from AD 1409 to 1998, derived from bur oak ring width data (after St. George and Nielsen, 2002). Units are mean annual precipitation deviations from 1961-1990. Black line represents 15-year weighted running mean.

pronounced wet intervals in the late 1820s and 1850s, hydroclimatic conditions prior to permanent Euro-Canadian settlement were more variable. Tree-ring evidence suggests that the Red River basin experienced dry conditions between AD 1670 and 1775, with below normal precipitation occurring approximately two years out of three (Fig. 5). Annual precipitation is estimated to have been exceptionally low in AD 1477, 1485, 1556, 1595, 1612, 1644, 1661, 1743, 1900 and 1980.

Comparisons with published limnological records from North Dakota and Minnesota suggest that entire northeastern Great Plains was dry for nearly one hundred years around AD 1700 (see St. George and Nielsen, 2002). However, individual dry years in the Red River basin, including 1743, 1900 and 1980, were usually associated with larger-scale drought across much of the North American interior.

Paleoenvironmental records from the Red River valley and surrounding environs indicate that natural climatic variation in this region can generate shifts in precipitation regimes that last for several decades and extend over several thousand square kilometres (see St. George and Nielsen, 2002). The hydroclimatic record further indicates that past long-term changes in regional precipitation near Winnipeg have varied by roughly 10% under 'natural climatic' conditions. This variability represents an obvious forcing factor influencing the occurrence of extreme high and low river discharges at multi-decadal and centennial timescales. It also indicates that climatic case studies in regional drought planning that are based exclusively on 20th century instrumental records may under-estimate worst-case scenarios.

5. Long-term history of the river

5.1 Evolution of the shallow river valley

5.1.1 Floodplain coring

A key geomorphic factor contributing to the Red River flood hazard is that the shallow, narrow, low gradient valley formed by the river has insufficient capacity to contain large flows (see Brooks and Nielsen, 2000). During floods water can thus overtop the valley sides and spread onto and across the flat clay plain of the prairie, forming a broad, shallow flood zone, as occurred in 1997. To assess the relevance of fluvial geomorphic changes (erosion or aggradation) within this valley to the flood hazard on the adjacent clay plain, a borehole investigation of the floodplain was undertaken at two successive river meanders located near St. Jean Baptiste (Fig. 6; see Brooks et al., 2001; Brooks 2003a; 2003b).

The boreholes were cored in two transects (99RR1 and 99RR3) on opposite sides of the valley bottom, with each transect consisting of five boreholes (Fig. 6). The boreholes were sited to follow the path of lateral migration of the channel, as revealed by a ridge and swale pattern on the floodplain (Fig. 6). The floodplain alluvium in the cores ranged in thickness from about 15 to 22 m and consists primarily of silt, as detailed fully by Brooks (2003b).

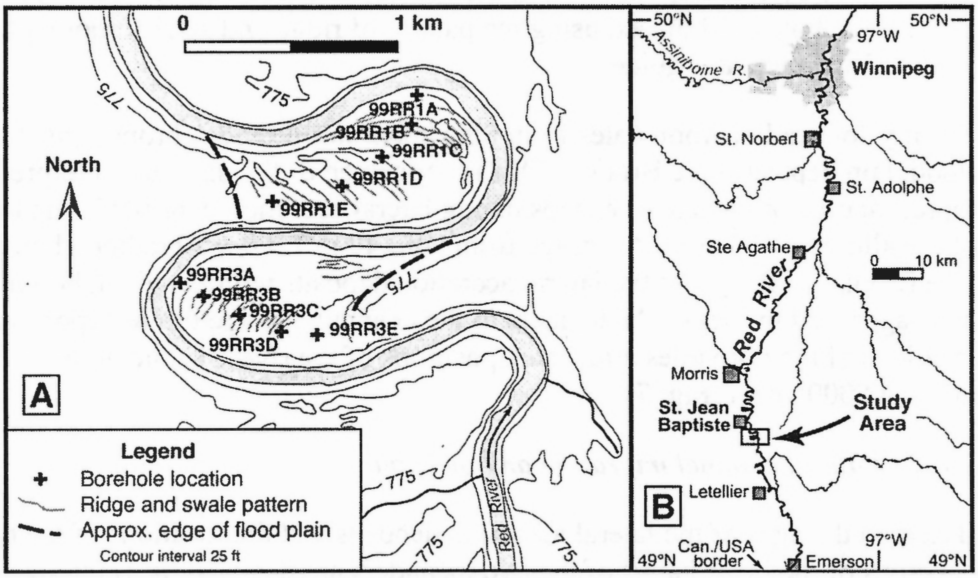

Fig. 6 Map A depicts the locations of boreholes across the floodplain at the St. Jean Baptiste study area (after Brooks, 2003a). Map B shows the location of the study area in southern Manitoba.

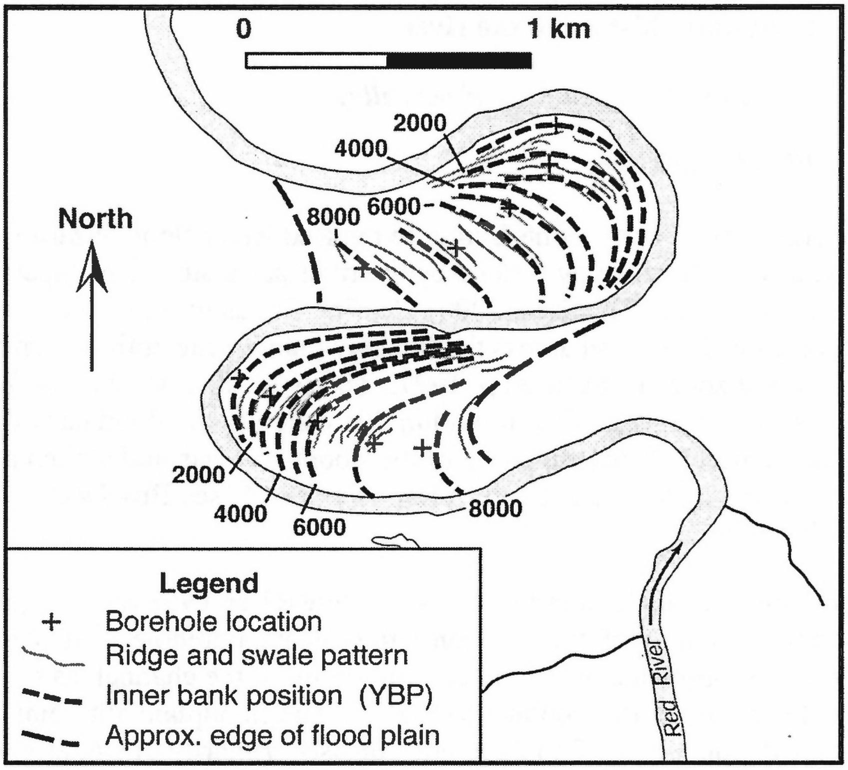

Fig. 7 Map showing meander growth at the St. Jean Baptiste study area over the past 8000 years (after Brooks, 2003a). The positions of the 1000-year isochrones have been extrapolated from the age of the lateral accretion deposits at the boreholes and placed using the pattern of ridge and swale topography on the floodplain as a guide.

Twenty-four radiocarbon dates from nine boreholes provide chronological control on the floodplain deposits (see Brooks, 2003a). Nineteen of the dates are interpreted to be representative of the age of encapsulating lateral accretion deposits in the lower portion of the alluvium. These dates range from 940±40 to 7290 ± 50 radiocarbon years in age (see Brooks, 2003a). As the lateral accretion deposits within a given borehole would have aggraded immediately adjacent to the channel, the age of the deposits and the locations of the boreholes allow past positions of the river channel to be determined over the past 8000 years (Fig. 7).

5.1.2 Lateral channel migration and incision

Based on the ages of the lateral accretion deposits and the locations of the boreholes, past positions of the inner banks of the two meanders are depicted by 1000-year isochrones in Fig. 7. These reveal that the two meanders have extended outwards and rotated downvalley since 8000 years ago in a single sequence of lateral channel migration. The isochrone spacing along both meanders also shows that the rate of lateral channel migration was greater prior to 6000 years ago than afterwards. Significantly, there has been appreciable lateral channel migration over the past 1000 years, when the rate of channel migration averaged up to ~ 0.04 m year^{-1} at both meanders (see Brooks, 2003a). Based on the difference in ages of the lateral accretion deposits, the depths of the base of the alluvium and the slope of the floodplain surface, the average rates of channel incision between 8000 and 1000 years ago at the two meanders are estimated to be between 0.4 to 0.8 mm year^{-1} (see Brooks 2003a). Overall, these results reveal that the Red River channel has experienced low rates of lateral channel migration and incision.

5.1.3 Additional evidence of low rates of lateral channel migration

Other work along the Red River supports the evidence of low rates of lateral channel migration along the river meanders. Brooks and Nielsen (2000) observed that a single pattern of ridge and swale topography is present on the floodplain of most meanders along the river. This simple pattern implies that these meanders have undergone only a single and continuing sequence of lateral migration, as would be consistent with a low rate of channel migration. In contrast, the floodplains of rivers experiencing more rapid rates of lateral migration consist of a complex mosaic of ridge and swale patterns representing multiple sequences of migration and channel abandonment. Calibrated radiocarbon ages of between 3760 to 6710 years old from bank exposures of the floodplain are consistent with a single and continuing sequence of lateral channel migration at seven meanders (see Brooks, submitted). A similar pattern of ridge and swale topography is also present at the two St. Jean Baptiste meanders, for which radiocarbon dating also confirms a single sequence of lateral migration, as mentioned above (Fig. 7; see Brooks, 2003a).

Brooks and Medioli (unpublished) dated the approximate age of formation of cut-off channels that created two ox-bow lakes – Horseshoe Lake, near Morris, and the Marion Lake channel scar, near St. Jean Baptiste (the latter is an ox-bow lake drained in the early 1960s). These data indicate that Horseshoe and Marion ox-bow lakes began forming ~ 1990 and 1520 years ago, respectively. These relatively recent ages, as well as the overall low number (eight) of ox-bow lakes and abandoned channel scars along the Red River, are consistent with a low rate of lateral channel migration along the river meanders.

5.1.4 Relevance to flood hazard

At the St. Jean Baptiste study area, the radiocarbon ages from the floodplain cores demonstrate that outward extension and downvalley rotation of the meanders has gradually widened the valley (Fig. 7). To assess the significance of this widening to the modern flood hazard on the adjacent clay plain, the cross-sectional area of the valley bottom 1000 years ago was estimated and compared to that of the modern valley. Because of the low rate of incision (0.4 to 0.8 mm year^{-1}; see above), deepening of the river valley over this period by incision is not significant.

As summarized from Brooks (2003a), the valley cross section has increased by about 2 and 0.7% at the upstream and downstream meanders, respectively, over the past 1000 years. In absolute terms, this change represents the addition of about 52 and 19 m^2 to the valley cross sections. The limited increase reflects the general low rate of lateral channel migration along both meanders, but more importantly, the very shallow depth of the flood-plain portion of the valley bottom relative to the clay plain. The valley widening produced a decrease in hydraulic radius - the ratio of the cross-sectional area to wetted perimeter of the profiles and a common hydraulic morphological parameter - of 2.64 to 2.56 m and 2.01 to 2.00 m at the upstream and downstream meanders, respectively, between 1000 years ago and the present. These decreases represent a change in hydraulic radius of about 3 and 0.5%.

The section of river valley within the St. Jean Baptiste study area does not control the water surface of valley-full flows. Nevertheless, the low rates of lateral channel migration and incision along the study area meanders are considered to be typical of meanders along the Red River elsewhere in southern Manitoba (see below). Thus over the past 1000 years the river meanders have experienced only a slight change in valley cross-section and hence to the morphological parameter (i.e., hydraulic radius) affecting the discharge capacity of the valley. When considered proportionally over timescales of up to several centuries – timescales that are more relevant to modern flood planning – the amount of widening of the valley cross section is very low to negligible and the resulting change in total valley conveyance would be undoubtedly within the error of discharge measurement. Overall, valley widening is deemed an insignificant factor affecting the modern flood hazard on the clay plain, particularly compared to other variables such as, for example, climatic fluctuations (see St. George and Nielsen, 2002) and changes in roughness due to agricultural land clearance.

5.2 Differential uplift and the long-term variation in flood hazard

5.2.1 Calculating changes in elevation from uplift

An assessment of long-term differential uplift in southern Manitoba and adjacent North Dakota and Minnesota was conducted in relation to the effects of gradient changes on the Red River valley over the past 8000 years (see Lewis and Thorleifson, unpublished). Differential uplift results from recovery of the depression of Earth's crust caused by the load of the last ice sheet which reached its maximum extent 18 000 radiocarbon years ago. In Manitoba, the rates and amplitude of rebound increase in the northeasterly direction towards Hudson Bay, where the thickest ice was located. The accumulated vertical uplift is well demonstrated by the upwarped shorelines of proglacial Lake Agassiz which existed along the ice margin during its retreat across North Dakota, Minnesota and Manitoba between 11 700 and 7700 radiocarbon years ago.

Uplift over time is well described by an exponential decay function (see Lewis and Thorleifson, unpublished). The parameters of this function were evaluated using the values of age and slope for a series of postglacial shorelines around the Lake Winnipegosis basin. The resulting function was used to compute uplift with time at points along the Red River valley with reference to the upwarped Lower Campbell shoreline (see Lewis and Thorleifson, unpublished). The changing slope between Red River localities with time provided measures of valley gradient reduction since about 8000 years ago, and has been applied by Brooks et al. (unpublished) for modeling.

5.2.2 The relevance of loss of gradient to the flood problem

Assessment of differential uplift indicates that the section of the Red River in Manitoba has lost ~ 60% of its valley gradient over the past 8000 years (see Brooks et al., unpublished). To assess the significance of this loss of gradient on the flood hazard in southern Manitoba, a hydraulic model, previously developed by the Canadian Hydraulic Centre to depict modern, major Red River floods between the Canada-USA border and the Red River Floodway control structure, was run using a 1997-magnitude flood for scenarios of gradient at 8000, 6000, 4000 and 2000 years ago as well as for 2000 years in the future (see Brooks et al., unpublished). The modeling indicates that a broad, shallow flood zone was present for all of the gradient scenarios (Fig. 8). Between 8000 years ago

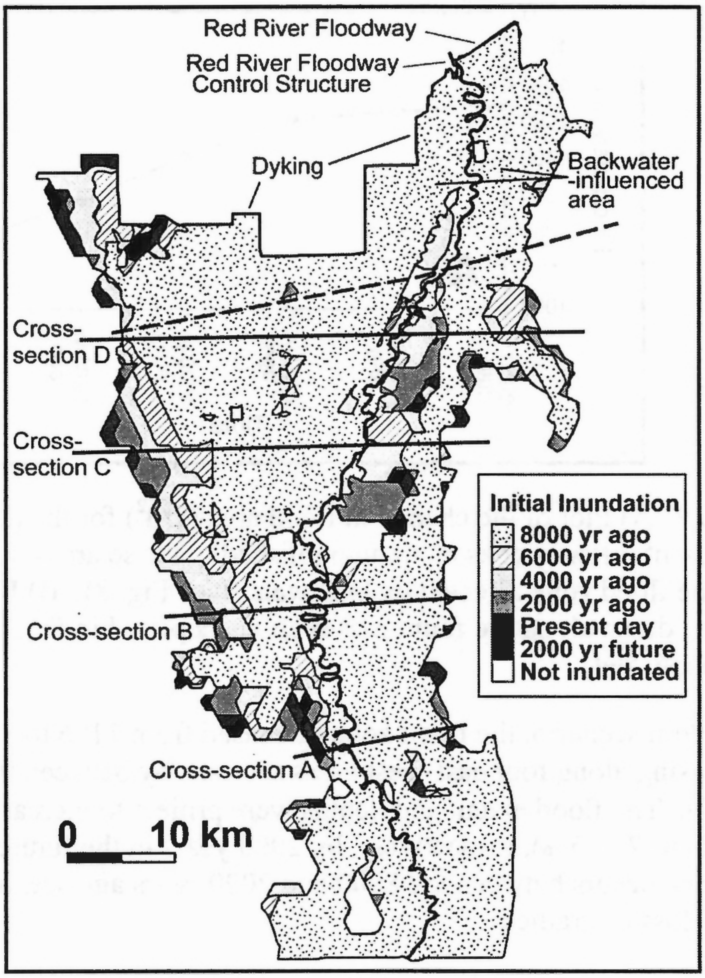

Fig. 8 Composite map showing the extent of flooding in southern Manitoba for the modeled scenarios of gradient using a 1997-magnitude discharge (after Brooks et al., unpublished). The dashed line towards the upper portion of the map delineates the approximate southern limit of the flood zone affected by backwater due to the presence of the East and West dykes adjacent to the Floodway control structure.

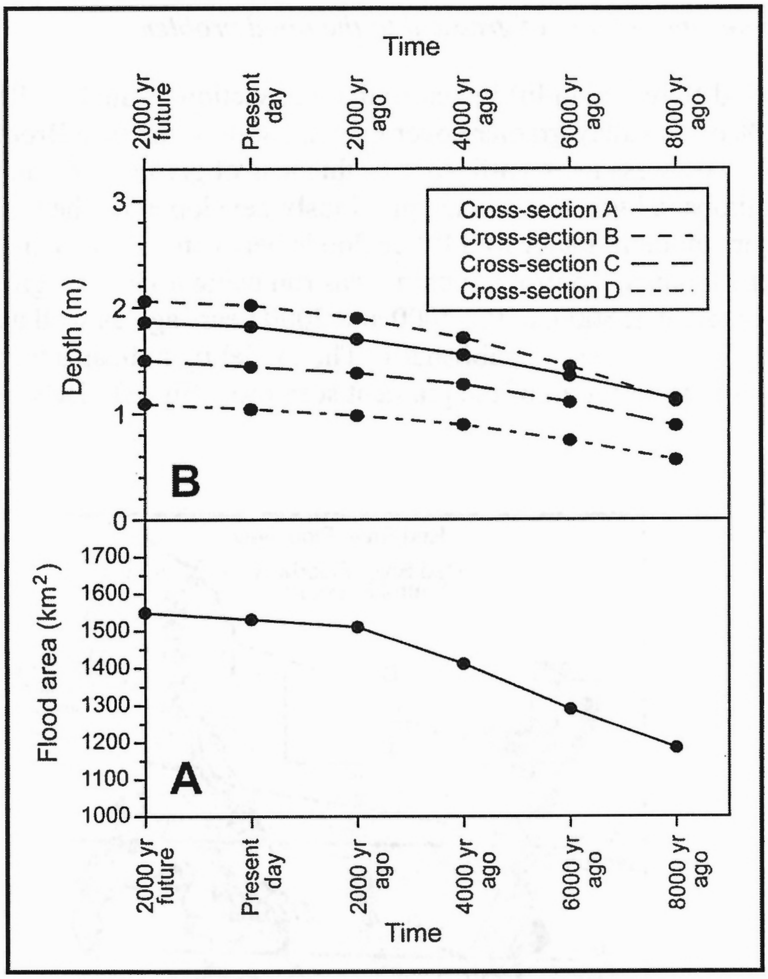

Fig. 9 A) Plot of the change in flood area (km^2) for the modeled scenarios of gradient (after Brooks et al., unpublished). These areas do not include the portion of the flood zone affected by backwater (see Fig. 8). B) Plot of the change in mean depth along the four cross sections depicted in Fig. 8 (after Brooks et al., unpublished).

and the modern scenario, the flood zone increased from 1186 to 1531 km^2 (~ 29%) with depth increasing along four east-west cross sections by between 0.48 and 0.91 m (61 to 86%; Fig. 9). The flood extent and depths were project to increase by 18 km^2 (~ 5%) and 0.04 to 0.06 m (2 to 5%), respectively, by 2000 years in the future. Most of the change to the flood zone occurs between the 8000 and 2000 years ago scenarios, reflecting the exponential loss of gradient.

The presence of a broad, shallow flood zone in all of the modeled scenarios implies that, for a 1997-magnitude flood, this style of flooding is intrinsic to the geomorphic setting of the river and is not strictly the result of the loss of river gradient from differential uplift. In other words, broad, shallow floods have always occurred in the Red River valley and are not a 'recent' phenomenon. Relative to the freeboard height of modern dykes and berms in the Red River valley (0.6 m), the rise in mean flood depth between 8000 years ago and the present day represents a significant, although gradual, increase in the flood hazard along the river. The minor rise in mean depth between the present day and 2000 years in the future scenario is not deemed to significantly alter the flood hazard, and does not necessitate a re-assessment of the design flood level in southern Manitoba.

6. Application of tree-ring data to groundwater fluctuations at Winnipeg

Ferguson and St. George (submitted) used data from the Red River basin tree-ring network to estimate groundwater trends prior to the establishment of observational wells within the Upper Carbonate Aquifer near Winnipeg. Since the beginning of monitoring in the early 1960s, shallow well hydrographs show no obvious long-term trend, but water levels from deeper wells document a gradual increase over the last 36 years. The shallow well hydrographs were strongly correlated with temperature, precipitation and tree-ring data, but the deep wells appear to have been insensitive to past changes in regional hydroclimate. Based on the tree-ring record, hydraulic heads of shallow wells near Winnipeg are estimated to have been more variable prior to instrumental monitoring, most prominently during an interval of lowered groundwater levels between 1930 and 1942 (Fig. 10). However, natural fluctuations in hydraulic head due to climatic variability were much smaller than the effects of groundwater withdrawals, which suggests that the groundwater usage remains the most important consideration for local groundwater management in Winnipeg.

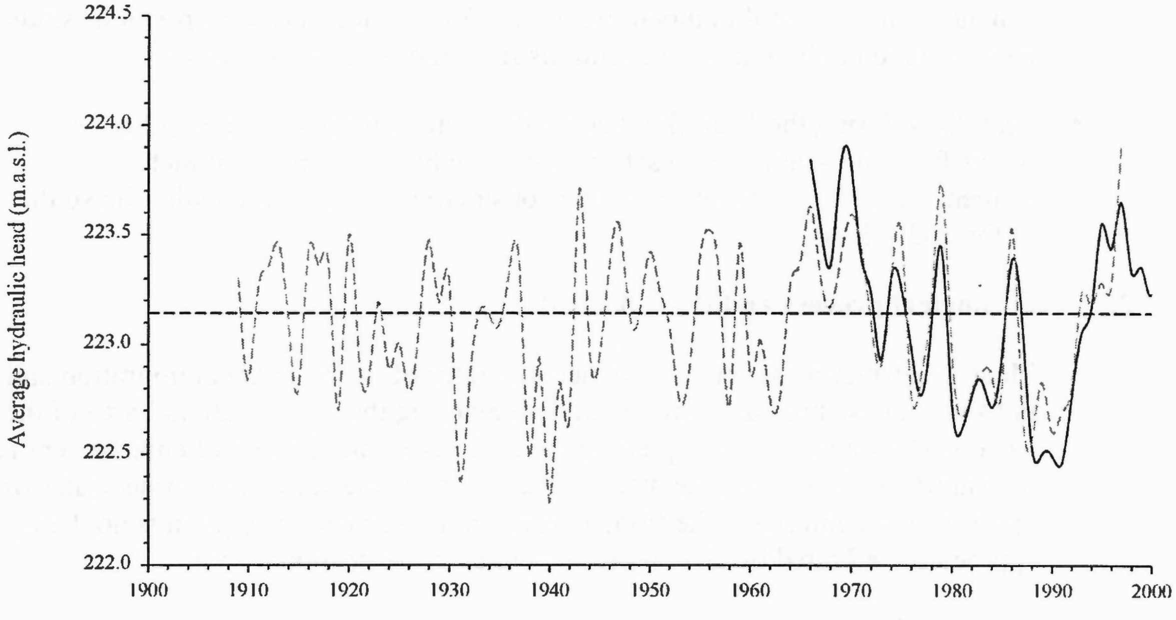

Fig. 10 Observed (solid line) and estimated (dashed line) trends in hydraulic head for shallow wells within the Upper Carbonate Aquifer near Winnipeg (Ferguson and St. George, submitted). The horizontal line represents mean annual hydraulic head between 1965 and 2001.

CONCLUSIONS

1. Frequency, magnitude and character of high magnitude Red River floods

- The 1826 Red River flood was the largest in the lower Red River basin (LRB) since at least AD 1648, based on tree-ring flood signatures. There is no tree-ring evidence in the LRB for a high-magnitude Red River flood in 1776.

- Tree-ring evidence indicates that the Red River in the LRB has experienced three periods of multiple high-magnitude flooding since 1648: the mid 1700s, the early to mid 1800s and the latter half of the 20th century.

- The historical pattern of high-magnitude Red River flooding implies that the frequency-magnitude relationship changes over time and that flood flows are not independent and randomly distributed, as is commonly assumed in flood frequency analysis. Better estimates of flood frequency-magnitude could be provided by techniques that account for non-stationarity and non-randomness in the discharge records.

- Historical and tree-ring evidence indicates that the peak flows of the Red and Assiniboine rivers coincided in 1826 and 1852. The Assiniboine River contribution may have formed a significant portion (up to ~ 20%) of the estimated discharge for the Red River at Winnipeg during these floods. Accounting for this synchronism is critical to modeling the 1826 flood accurately, as previous studies have assumed only minor contributions from the Assiniboine River.

- Peak flow during the 1826 flood coincided with extremely strong, persistent winds from the south. Wind set-up may have been an important factor influencing peak stage and should be considered by any future hydraulic studies of the 1826 flood.

2. Geological process and flood hazards

- Most Red River meanders experience low rates of lateral channel migration and incision. These processes are gradually enlarging the cross-sectional area of the narrow, shallow valley occupied by the Red River, but the rate of enlargement is not significantly altering the discharge capacity of the valley over time-scales of up to several centuries. The flood hazard on the adjacent clay plain is not being appreciably affected by changes to the valley cross-sectional area.

- Uplift modeling indicates that the Red River has lost ~ 60% of its gradient over the past 8000 years. Hydraulic modeling suggests that this has caused increases in flood extent (~ 29%) and depth (~ 61 to 86%) over time, although most of the change occurred prior to 2000 years ago when the rate of uplift was more rapid. Significantly, broad, shallow floods developed in all the modeled scenarios of past gradient implying that such floods are intrinsic to the basic setting of the Red

River valley and are not the product of 'recent' landscape changes. The minor rise in mean depth occurring from the continued loss of gradient over the next few centuries will not significantly alter the flood hazard.

3. Environmental change in the Red River basin

- Hydroclimatic reconstructions based on tree rings indicate that climate in southern Manitoba has been relatively stable over the last two hundred years, but was more variable prior to 1800. In particular, evidence suggests that the Red River basin experienced dry conditions between 1670 and 1775. Climatic case studies in regional drought planning that are based exclusively on 20th century instrumental records under-estimate worst-case scenarios.

- The large-scale introduction of European agricultural practices in the 19th century has caused environmental changes to small lakes along the Red River floodplain. This has caused increased nutrient levels, the development of anoxic conditions in the lake bottom sediments and an increase in the influx of sediment from the river.

- Increased concentrations of the elements Ag, Cd, Cu, Hg, Pb, Sb, U and Zn since the early 1940s were detected in cores from the south basin of Lake Winnipeg and are attributable to water and airborne contamination. Parallel increases in number of macrofossils, $\delta^{13}C$ and $\delta^{15}N$, and phosphorus imply enhanced nutrient influx and lake productivity beginning as early as 1900 and increasing rapidly in the 1950s to a consistently high level.

- Natural fluctuations in hydraulic head within the Upper Carbonate Aquifer near Winnipeg from climatic variability have been much smaller than the effects of groundwater withdrawals during the 20th century. Groundwater usage from this aquifer thus remains the most important management consideration.

ACKNOWLEDGEMENTS

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ADDENDUM

As an update to section *2.2.1 South basin of Lake Winnipeg*, information which was unavailable when this report was completed, further supports the notion that floods represent the most plausible mechanism for the formation of the silt strata in the three cores from the south basin of Lake Winnipeg (Fig. 3). Based on a composite record from the three cores, silt beds are interpreted to correlate with ten flood events of magnitude greater than ~ 2500 m^3s^{-1} that occurred over the past millennium (up to ~ AD 1800; see Simpson et al., unpublished). This, however, is considered to be only a partial record due to inadequate silt bed formation and/or preservation at the coring sites.

APPENDIX

1. Complete Listing of Project Research Papers

*(Papers highlighted in **Bold** summarize the 'main' results of the project.)*

1. **Brooks, G.R., 2003a, Holocene lateral channel migration and incision of the Red River, Manitoba, Canada. *Geomorphology*, (*in press*).**

2. **Brooks, G.R., 2003b. Alluvial deposits of a mud-dominated stream; the Red River, Manitoba, Canada. *Sedimentology*, (*in press*).**

3. **Brooks, G.R., (submitted). Floodplain chronology and vertical sedimentation rates along the Red River, southern Manitoba. *Géographie Physique et Quaternaire.***

4. **Brooks, G.R. and Grenier, A. 2001, Late Holocene pollen stratigraphy of Lake Louise, Manitoba. In *Current Research 2001-B1, Geological Survey of Canada*, 7 p.**

5. **Brooks, G.R. and Medioli, B. E. (*unpublished*). Age of formation of the Horseshoe and Marion ox-bow lakes, Red River, Manitoba.**

6. **Brooks G.R. and Nielsen, E. 2000. Red River, Red River Valley, Manitoba. *Canadian Geographer*, v. 44, p. 304-309.**

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Manitoba Industry, Mines and Trade website, *Paleofloods of the Red River basin*
http://www.gov.mb.ca/itm/mrd/geo/pflood/index.html

Paleoclimatic and tree-ring data from St. George and Nielsen (2002) are available from the World Data Center for Paleoclimatology
(http://www.ngdc.noaa.gov/paleo/paleo.html)