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**A 1300 year reconstruction of paleofloods using oxbow lake
sediments in temperate southwestern Québec, Canada**

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Draft

Abstract

The study of paleofloods provides important information on past flood frequency and intensity for regions where there is a paucity of records, it therefore extends our knowledge of flood occurrence beyond the historical record. Many paleoflood reconstructions come from the arid dry climate of southwestern USA and from Europe with few studies being conducted in temperate climates of North America. This study uses sediment cores from oxbow lakes to reconstruct past flood events in a temperate region. Cores extracted from two oxbow lakes along the Désert River in southwestern Québec, Canada were analyzed for magnetic susceptibility, loss-on-ignition, grain-size and were radiocarbon dated (^{14}C). Using a combination of magnetic susceptibility variations, along with changes in grain-size and organic material content, 5 floods were identified within the 220 cm core (1300 years) from the North oxbow lake, and six floods in the 118 cm core (600 years) from the South oxbow lake. This study provides evidence to support the use of oxbow lakes in temperate regions as a proxy of past floods, thus helping us understand hydroclimatic changes at regional scales. Data that spans a longer period of time and in different environments is key to increase flood modelling accuracy to improve mitigation strategies under a changing climate.

Keywords: Paleoflood, hydroclimatology, hydrology, oxbow lake

Introduction

Floods “are low-probability, high-impact” (Confalonieri et al. 2007) events and are amongst the most destructive hydrological hazards. A poor understanding of floods and the forces that drive them has led people and businesses to still build in flood-prone areas (Woodward et al. 2010) and thereby caused unnecessary casualties, damage, famine and epidemics (Jarrett and Tomlinson 2000; Knox and Kundzewicz 1997). Knowing the conditions that have led to past flood events, as well as how and when they have occurred is key to mitigating future impacts of floods. In some regions the historical record of flood occurrence is short. Paleoflood reconstruction based on the sedimentary record provides a solid approach to adding knowledge to the short historical climate record of these regions (Knox and Kundzewicz 1997; Benito and Thorndycraft 2000).

Paleoflood hydrology is “the study of past or ancient flow events using physical or botanical information” (Baker 1987a) and is gaining importance in the field of climate change research (Baker 2008). Paleoflood records provide additional data for model validation which improve our understanding and predictive ability for future hydrometeorological extreme events (Baker 2006; Saint-Laurent 2004). Paleoflood signatures can be preserved in the sedimentary record for millennia (Baker 1994). Slackwater flood deposits are coarser grained sediments that are deposited during waning flows. These coarser sediments that have higher magnetic susceptibility values create stratigraphic markers within the sedimentary records in environments usually shielded from high energy flows (Baker, 2008; Baker, 2006; Baker, 1987b; Benito and Thorndycraft, 2000; Saint-Laurent, 2004; Saint-Laurent and Lavoie, 2004; Wolfe et al. 2006). These signatures can bring insightful information on floods in changing climatic conditions (Baker 2008). Studies have shown more frequent and intense floods occur during periods of colder and wetter climates (Benito and Thorndycraft 2000; Fuller et al. 1998; Smith 1992). Since

the majority of paleoflood studies in North America have been undertaken in the arid landscapes of southwestern USA (e.g. Baker 1987a), an increase in research in temperate regions would fill knowledge gaps in paleoflood hydrology.

Oxbow lakes as paleoflood archives

Other than physical characteristics of the watershed, floods result mainly from local or regional changes in precipitation and spring temperatures (Confalonieri et al. 2007; Kundzewicz et al. 2007; O'Connor et al. 2002). Therefore, a change in climate, whether leading to an increase or a decrease in temperature, or precipitations can greatly affect the frequency of floods (Woodward et al. 2010). Global scale seasonal climatic variations and oscillations such as El Niño or La Niña also have a direct impact on the location and frequency of floods (Alila and Mtiraoui 2002). Oxbow lakes are dynamic and complex depositional environments due to the bimodal nature of their infilling. They are a lacustrine depositional environment which can reattach to rivers during spring floods or extreme hydrometeorological events. The reattachment leaves a distinct sedimentary signature of coarser sediments that are low in organic matter and high in magnetisable minerals (Byrne and Sullivan 1996) in the oxbow lakes which makes them suitable sites for paleoflood reconstructions (Toonen et al. 2011). This study provides evidence to support the use of oxbow lakes in temperate regions as a proxy of past floods.

Study sites

Two oxbow lakes in the Désert River watershed were sampled. The watershed covers an area of 3113 km² with a Gravelius index of 2.19. It is part of the Maniwaki sub-catchment, which is one of 6 sub-catchments of the broader Gatineau River watershed (Boucher et al. 2012). The Désert River runs 96 km mostly north to south from its head waters at the Lac Désert at 228 m of altitude to reach the Gatineau River at Maniwaki at 167 m of altitude. The Désert River flows on

the Canadian Shield and is underlain by marble with the exception of a few sections that cross through Precambrian biotite gneiss and migmatite bedrock (Douglas 1977). The surficial deposits which the river runs through are mostly composed of loam with varying concentration of fine sand and silt (Fulton 1995). The hydrological station near the study sites (~3 km downriver of the North oxbow lake and ~1.5 km upriver of the South oxbow lake) reports an average discharge of $25 \text{ m}^3\text{s}^{-1}$, with an average annual peak discharge of $115 \text{ m}^3\text{s}^{-1}$ and a peak discharge of $188 \text{ m}^3\text{s}^{-1}$ (values calculated on 50 years of discontinuous data distributed between 1927 and 2014) (Centre d'expertise hydrique, 2014).

The climate of the region is a moderate to mild subpolar climate, associated with hot and humid summers and cold, humid and snowy winters (Drolet et al. 2007). Station data from Maniwaki show a mean annual temperature of 3.9°C , a mean July temperature of 18.5°C and a mean January mean temperature of -13.3°C (Weather Office 2012). The average total annual precipitation is 910 mm with 690 mm of rainfall and 240 cm of snow (Weather Office 2012).

The North oxbow lake is located at $46^\circ36'57.4'' \text{ N } 076^\circ02'50.9'' \text{ W}$ and the South oxbow lake is located at $46^\circ34'52.4'' \text{ N } 076^\circ02'11.9'' \text{ W}$ in southwestern Québec approximately 35 km north of the city of Maniwaki (Figure 1). The North oxbow lake is located behind a semi-abandoned meander which is seasonally detached from the river (Figure 2). The North oxbow lake has a maximum depth of 5.0 m and an average depth of 2.2 m. The South oxbow lake has a maximum depth of 4.1m and an average depth of 1.8 m. (Figure 3).

Methods

Site Selection

The study sites were chosen using several criteria: meander abundance along a river; oxbow

lakes with low sensitivity to spring flooding; accessibility and logistics. Landsat images were examined to exclude oxbow lakes along the Désert River that are prone to annual spring floods (Arnaud-Fassetta et al. 2010; Byrne and Sullivan 1996). Annual spring flooding would disturb the thin layers of lacustrine accumulation and would make dating organic material very unreliable. A low-altitude flyby and ground reconnaissance helped identify the best potential oxbow lakes based on accessibility and logistics.

Field Work

The field work consisted of coring the North oxbow lake in two locations (sites North A and North B), and the South oxbow lake in one location (Figure 1). Cores were taken to refusal using a Livingston piston corer from a platform built over two canoes. At each location two cores were taken at approximately a meter apart in order to not collect disturbed sediments and with 30 cm of overlap vertically to ensure continuity (Wolfe et al. 2006). Drive 0 was taken to include the water-sediment interface. Drive 1 the next drive down was taken to overlap with drive 0, and so on. Site North A was located near the bank of the most probable sediment entry point (Babek et al. 2011; Wolfe et al. 2006; Figure 3A; sites North A1 and North A2). Site North B was located further into the oxbow lake at the lake's deepest location (Figure 3A; sites North B1 and North B2). The South oxbow lake was cored in one location following the same method used at the North oxbow lake. All cores were wrapped in plastic and aluminum foil and placed in split 2" ABS tube and refrigerated at 4°C for preservation.

Topographic profiles were measured using a Nikon NE-10 digital theodolite and a Cansel stadia pole for measurements on dry-land and along a graduated rope using a Speedtech Depthmate Portable Depth Sounder for the river profile (Figure 3B-D). The bathymetries of the oxbow lakes were measured with a Garmin GPSMap 520S sonar chartplotter using a grid pattern (Figure 3A-C).

143 *Magnetic susceptibility*

144 Magnetic susceptibility measurements were taken at every centimeter using a Bartington MS2
145 meter equipped with a Bartington MS2C 60mm diameter loop sensor which generates a low
146 frequency and intensity alternating magnetic field current. Magnetic permeability varies with
147 mineralogy. The difference in permeability is converted into a magnetic susceptibility value
148 (Bartington Instruments 2012). After calibrating the meter with a magnetic standard (serial no:
149 211; $\chi = 2046 \times 10^{-6}$) the entire core was fed through the sensing area. The entire process was
150 repeated three times to ensure reproducibility of measurements (average standard deviation $\leq 3 \times$
151 10^{-5}) and to validate the studied peaks. All measurements were recorded as volume ($\kappa = \chi \times 10^{-5}$)
152 in the International System of Units (SI) and the drift warning set to 5 was never issued.

153 *Sedimentology*

154 The cores were halved in the laboratory and visually analyzed and described; color was defined
155 using a Munsell soil color chart. One cubic centimeter (cc) of material was subsampled at every
156 centimeter of each core to perform loss-on-ignition (LOI) according to Heiri et al. (2001) to
157 quantify the organic matter and total carbonates by weight loss. For grain-size analysis, the
158 remaining section of the half-core was oxidized (H_2O_2 30%) to remove the organics then
159 dispersed with $(\text{NaPO}_3)_6$ prior to laser particle size analysis (e.g. Babek et al. 2011; England et
160 al. 2010; Saint-Laurent 2004) using a Microtrac s3500. Sediments were examined under low
161 power stereomicroscope for qualitative description of mineral composition, angularity and
162 sphericity.

163 *Radiocarbon dating and age depth modelling*

164 Accelerated mass spectrometer (AMS) radiocarbon (^{14}C) dating was chosen to build a
165 chronology (England et al. 2010; Kochel and Baker 1988; Macklin and Lewin 2003; Partridge
166 and Baker 1985; Saint-Laurent 2004; Saint-Laurent et al. 2010; Saint-Laurent and Lavoie 2004;

Wolfe et al. 2006). Organic material was picked from the cores (Table 1) in sections of finer, lacustrine sediments (Wolfe et al. 2006). Radiocarbon dating (AMS) was performed at Beta Analytic Inc. Miami, Florida (no. 349813, 342428, 340298, 342429 and 340299) and the University of Ottawa's A.E. Lalonde AMS Laboratory (no. UOC-0436 and UOC-0437). The Bacon program (Blaauw and Christen 2011) was used to generate a Bayesian model of the age-depth relationship.

Results

North oxbow lake

General stratigraphy and core description

The magnetic susceptibility at site North A ranges from 0 to 250. At site North A1 the magnetic susceptibility peaks at 10 cm, 35 cm, 98 cm and at 140 cm. At site North A2 there are visible peaks from 15cm to 35 cm, at 102 cm and between 120 and 170 cm of depth (Figure 4).

The cores at sites North A1 and North A2 (Figure 3A) were composed of several stratigraphic beds (Figure 4) that ranged from massive structure to fine laminations. Individual beds vary from dark grey (2.5Y 4/1) to very dark grey (2.5Y 3/1) with the exception of one bed varying from grey (2.5Y 5/1) to dark grey (2.5Y 4/1) (Munsell 1994). All beds are composed of a majority of quartz grains with varying concentrations of magnetite, feldspars and micas. The organic matter content varies from 0 to 30 % in most of the cores with a maximum of 60 % at 61 cm depth at site North A1. Carbonate content range from 0 to 7 % at site North A1 and 0 to 2 % at site North A2. The mean grain-size ranges from 20 μm to 109 μm with an average of 58 μm at site North A1 and ranges from 22 μm to 447 μm with an average of 107 μm at site North A2 (Figure 4). The standard deviation (sorting) ranges from 19 μm to 60 μm at site North A1 and ranges from

189 22 μm to 249 μm at site North A2. Variability in sorting is consistent with the mean grain-size
190 by varying more when the grain-size is larger.

191 Magnetic susceptibility at site North B1 ranges from -4.0 to 871.6 and ranges from 1.03 to 992.9
192 at site B2. The magnetic susceptibility is consistently higher past a depth of 70 cm at site North
193 B1 and past 50 cm at site North B2 with major peaks all the way down.

194 The cores at sites North B1 and North B2 (Figure 3A) were composed of several beds (Figure 4).

195 Individual beds vary on the Munsell soil color chart (Munsell 1994) from very dark grey (2.5Y
196 3/1) to black (2.5Y 2.5/1) at the top of the cores. The top beds of the deeper drives (drives 1 and
197 2) are composed of solely very dark grey (2.5Y 3/1) sediments. The bottom beds are light
198 yellowish brown (2.5Y 6/3) and very dark greyish brown (2.5Y 3/2) with some dusky red (10R
199 3/4) sediment (Munsell 1994). All beds are composed of a majority of quartz with varying
200 concentrations of magnetite, feldspars, micas and clays. The organic matter content varies from 0
201 to 32 %. There is an almost complete absence (< 1 %) of organic matter between 75 and 237 cm
202 with very few exceptions not exceeding 4 %. The carbonates in the core range from 0 to 3.6 %.

203 The mean grain-size ranges from 32 μm to 674 μm with an average of 281 μm at site North B1
204 and an average of 349 μm at site North B2 (Figure 4). The standard deviation (sorting) ranges
205 from 25 μm to 460 μm .

206 **South oxbow lake**

207 *General stratigraphy and core description*

208 The magnetic susceptibility of the sedimentary sequence ranges from 18.2 to 191.6. It rises from 18.2
209 to 115.2 from 1cm to 36 cm before decreasing between 50 and 60 from cm 44 to 55. Magnetic
210 susceptibility rises back up to 144 at 79 cm and plunges to 111 at 85 cm. Finally, it varies between
211 150 and 190 from 90 cm to 110 cm and then drops below 50. Standard deviations of the three runs
212 show a margin of error between 0.05 and 5.6 (Figure 4).

The drive 1 can be divided in two distinct beds which range from dark grey (2.5Y 4/1) to very dark grey (2.5Y 3/1). All beds are composed of a majority of quartz with varying concentrations of magnetite, feldspars and micas. The organic varies between 0 and 4 % with a peak of 5 % at a depth of 113 cm. The carbonates range from 0 to 1 %. The mean grain-size varies from 12.5 to 106.6 μm . The lowest value is observed at a depth of 50 cm while the highest at a depth of 118 cm. The standard deviation grain sorting is directly proportional to the mean grain size where it varies from 211.7 to 479.6 μm (very poorly sorted).

Sediment core chronology

The age-depth model built from the cores extracted at site North A2 uses the three radiocarbon dates from the drive 0 at depths of 26 cm, 47 cm and 88 cm (Figure 3; Table 1). South oxbow lake chronology was built using the two radiocarbon dates at depth of 44 cm (drive 0) and 84 cm depth (drive 1)(Table 1). The chronology of both North (Figure 5) and South oxbow lakes were produced using the Bayesian model Bacon program (Blaauw and Christens 2011).

Discussion

Stratigraphy analysis

The depositional environment changes from relatively higher energy fluvial environment to relatively lower energy lacustrine environment once an oxbow lake detaches from a river. In post-detachment environments, the sediments deposited are typically fine grained, rich in macrorests (Saint-Laurent 2004; Saint-Laurent and Lavoie 2004) and low in magnetisable minerals. Since coring was performed to refusal and the lower portion of the cores from all sites have coarse sediment, low organic matter and high values in magnetic susceptibility we interpret these sediments as having been deposited in fluvial depositional environment. These fluvial deposits are overlain by fine sediment, rich in organic matter and generally have lower values in

magnetic susceptibility. These fine sediments accumulated in a lacustrine environment following the detachment of the oxbow from the river.

The sediment structures of the post-detachment deposits of sites North A1 and North A2 and those from the South oxbow lake are very different from structures observed at sites North B1 and North B2. Sites North A1 and North A2 are characterized by inter-laminated fine and coarse sediment and organic matter reflecting changes of the energy at that location.

The thickness of the post-detachment deposits at sites North A1 and North A2 (160 cm) is at least twice the thickness that of sites North B1 and North B2 (80 cm and 50 cm respectively) (Figure 6). Transect Z-Z' at the North oxbow lake shows a higher topographical barrier between the river and the oxbow lake (>6 m) than transect Y-Y' supporting that transect Y-Y' is the first entry point of sediments during a flood (Figure 3B). Based on the sediments structures, the thickness of post-detachment accumulation and on the topography around the lake the most probable entry point of flooding waters would be located near the south-eastern section of the oxbow lake (Figure 3A).

Flood reconstruction

Field measurements using a theodolite showed that the river would need to rise by 2.13 m in order to flood the North oxbow lake. Using a rating curve as per Sivapragasam and Muttil (2005) it was estimated that the discharge needed to raise the level of the river sufficiently to flood the oxbow lake would be $309 \text{ m}^3 \text{ s}^{-1}$. Since no flooding has occurred in these lakes since instrumental measurements, we fitted a locally weighted regression model (a direct surface LOESS)(Cleveland et al. 1988) to the last 50 years of complete discharge data (Centre d'expertise hydrique 2014). This enabled us to estimate a recurrence interval of 1 in 432 years for a $309 \text{ m}^3 \text{ s}^{-1}$ discharge, all other parameters being equal. A recurrence interval was not

established for the South oxbow lake as there is a large plunge basin at the foot of a waterfall (Chute Rouge) a few hundred meters upstream of the study site completely changing the hydrological regime, thus making a rating curve from these values of very low confidence.

The North oxbow lake is surrounded by dense vegetation contributing to a thick layer of decomposing organic matter covering the lake bed. This presented challenges in extracting successive cores within individual bore holes because as the corer was taken out, organic material was seeping back into the hole. For example, the difference (ie. lower) in magnetic susceptibility values from sites A1 and A2 suggest that organic material from earlier deposits may have spilt into the original bore hole. The radiocarbon dates from drive zero and drive one from site A2 were not in chronological order (Table 1). The younger radiocarbon dates from samples DR1-cm13 and DR1-cm49 could have resulted from contamination by organic material falling into the borehole or from penetrating roots containing more recent carbon (Bowman 1990). Based on these issues, we only used drive zero at site A2 to establish the most reliable age-depth chronology for our flood reconstruction. The 3 chosen dates for creating the age depth model were validated with the South oxbow lake results as well as grain-size and magnetic susceptibility peaks (Figure 4).

Magnetic susceptibility peaks in a detached oxbow lake can be interpreted as floods (Wolfe et al. 2006). The South oxbow lake's most recent peak matches very well with a known historical flood occurring in 1908 on the Désert River at Maniwaki, Québec (Québec Heritage 2014), date at which the river was not yet instrumented. This provides a validation for the use of magnetic susceptibility as a proxy indicator in paleoflood reconstructions at one of our study sites.

At the North oxbow lake, five peaks in magnetic susceptibility from site North A2 (depth of 13 cm, 20 cm, 31 cm, 59 cm and 72 cm) (Table 2) match with dates all belonging to colder and more humid conditions than present (Figure 7) (Saenger et al. 2006). The two oldest peaks in

283 magnetic susceptibility are dated with the model at 831 and 709 AD (Figure 7) during a cold and
284 humid period known as the Dark Ages Cold Period (DACP; 300-800 AD) (Ljungqvist 2010).
285 After a ~300 year hiatus between peaks, the third or middle peak at 1175 AD occurs towards the
286 end of the Medieval Warm Period (MWP; 900-1200 A.D.). The two latest peaks in magnetic
287 susceptibility are dated 200 years apart at 1566 and 1366 AD (Figure 7) which is during a cold,
288 humid period known as the Little Ice Age (LIA; 1450-1850 AD) (Mann et al. 2009; Viau et al.
289 2006). At the South oxbow lake, six magnetic susceptibility peaks (depth of 9 cm, 17 cm, 25 cm,
290 36 cm, 59 cm, 78 cm) were dated with the model at 1395 AD, 1520 AD, 1655 AD, 1755 AD,
291 1817 AD and 1904 AD (Table 2). The two oldest dates of 1395 and 1520 AD match with the
292 results from the North oxbow lake, also validating the chosen radiocarbon dates. Conversely
293 minimum magnetic susceptibility such as during the MWP hiatus occurs during warmer and
294 dryer conditions (Saenger et al. 2006) where more drought conditions prevailed in the mid-
295 latitudes (Kundzewicz et al. 2007).

296 Conclusion

297 A multi-century paleoflood history was successfully reconstructed from oxbow lakes along the
298 Désert River near Maniwaki, Québec, Canada that shows that temperate region oxbow lakes are
299 well suited for studying paleofloods. The study also supports Wolfe et al. (2006) conclusion that
300 magnetic susceptibility, paired with other analyses such as grain-size and loss-on-ignition is a
301 “particularly sensitive and efficient tool” (Wolfe et al. 2006) for identifying past floods.
302 Moreover, the most recent magnetic susceptibility peak at 1904 AD from the South oxbow lake
303 matches very well with a known historical flood event on the Désert River in Maniwaki, Québec
304 in 1908. These results provide strong support for the use of magnetic susceptibility in paleoflood
305 reconstructions in temperate regions.

There are several advantages in using oxbow lakes as paleoflood proxies, including straight forward chronology building where fluvial sediments underlie post-detachment deposits which provide an absolute cut-off age and also the archival nature of oxbow lakes (Brooks and Medioli 2003). Limitations encountered in our study include unknown variations in sedimentation rates between regular alluvial sedimentation and overbank fluvial sedimentation from floods. The North and South oxbow lakes have an average of ~0.05 and ~0.1 cm of accumulation per year, respectively, which is expected due to human and agricultural activity (Davidson et al. 2004) surrounding the South oxbow lake. Considering these accumulation rates, the peaks in magnetic susceptibility could represent decadal to multi-decadal periods where increases in flood events occurred rather than a single year flood event. Our results are consistent with increases in flood events during colder and wetter periods (DACP, LIA) (Benito and Thorndycraft 2005; Fuller et al. 1998; Smith 1992) and that two major higher frequency and magnitude flood epochs “straddle” the MWP (Smith 1992).

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Table 1. Radiocarbon dates from cores extracted at the South oxbow lake and at site A2 from the North oxbow lake.

Oxbow Lake	Sample number	Lab number	Material	Core depth (cm)	Reported age (¹⁴ C yr BP)	Age (2 sigma calibrated calendar year A.D.)
North	DR0A-cm26	349813	Plant Material	26-27cm	770 ± 30	1125 ± 85
North	DR0A-cm47	342428	Plant Material	47-48cm	1070 ± 30	960 ± 60
North	DR0A-cm88	340298	Organic Material	88-89cm	1650 ± 30	385 ± 45
North	DR1A-cm13	342429	Charcoal	110-111cm	1030 ± 30	960 ± 60
North	DR1A-cm49	340299	Organic Material	146-147cm	1280 ± 30	780 ± 100
South	DR1-cm44	UOC-0436	Organic Material	44-45cm	440 ± 32	1519 ± 39
South	DR2-cm43	UOC-0437	Organic Material	84-85cm	601 ± 34	1417 ± 56

522 Table 2. Modeled age of magnetic susceptibility peaks.

Oxbow lake	cm	Age (AD)	Min age (AD)	Max age (AD)
North	13	1566	1420	1840
North	20	1366	1241	1631
North	31	1175	1066	1286
North	59	831	672	897
North	72	709	482	762
South	9	1904	1844	1974
South	17	1817	1757	1922
South	25	1755	1677	1867
South	36	1655	1586	1766
South	59	1520	1406	1561
South	78	1395	1298	1448

Draft

Figures

Figure 1. Location map of both studied oxbow lakes.

Figure 2. Studied oxbow lake still frozen with semi-abandoned meander in front of it also sheltered from the thawed river. Red dot coring site A and blue dot coring site B.

Figure 3. a) North oxbow lake bathymetry, expressed as depth in meters below lake surface. b) Transects Y-Y' and Z-Z'. Datum is lake water level. c) South oxbow lake bathymetry, expressed as depth in meters below lake surface. d) Transects A-A' and B-B'. Datum is lake water level.

Figure 4. Core length (cm), lithology, magnetic susceptibility, organic matter (%), inorganic (carbonates) (%) and mean grain-size (μm). Ages in year AD. North Oxbow (A) black line represents site North A2 and grey line North A1. North Oxbow (B) black line represents site North B1 and grey line North B2.

Figure 5. Bacon output with the 3 dates from the North oxbow lake. Accumulation rate equals 0.05cm/yr.

Figure 6. Core location within oxbow lake and depth, expressed in meters below lake surface, of fluvial deposits. Datum is lake level.

Figure 7. Black points represent the returned dates from the magnetic susceptibility peaks from North oxbow lake and orange points from the South oxbow lake. The black curve represents the temperature ($^{\circ}\text{C}$) variance over the last 2500 years (Viau et al, 2006). The grey curve represents the magnetic susceptibility from core A2 at the North oxbow lake. The dashed grey curve represents the magnetic susceptibility from the core at the South oxbow lake.

Location map of both studied oxbow lakes.
152x101mm (300 x 300 DPI)

Studied oxbow lake still frozen with semi-abandoned meander in front of it also sheltered from the thawed river. Red dot coring site A and blue dot coring site B.
231x154mm (150 x 150 DPI)

a) North oxbow lake bathymetry, expressed as depth in meters below lake surface. b) Transects Y-Y' and Z-Z'. Datum is lake water level. c) South oxbow lake bathymetry, expressed as depth in meters below lake surface. d) Transects A-A' and B-B'. Datum is lake water level.
174x132mm (150 x 150 DPI)

Core length (cm), lithology, magnetic susceptibility, organic matter (%), inorganic (carbonates) (%) and mean grain-size (μm). Ages in year AD. North Oxbow (A) black line represents site North A2 and grey line North A1. North Oxbow (B) black line represents site North B1 and grey line North B2. 273x224mm (300 x 300 DPI)

Bacon output with the 3 dates from the North oxbow lake. Accumulation rate equals 0.05cm/yr.
124x180mm (300 x 300 DPI)

Core location within oxbow lake and depth, expressed in meters below lake surface, of fluvial deposits.
Datum is lake level.
173x61mm (300 x 300 DPI)

Draft

Black points represent the returned dates from the magnetic susceptibility peaks from North oxbow lake and orange points from the South oxbow lake. The black curve represents the temperature ($^{\circ}\text{C}$) variance over the last 2500 years (Viau et al, 2006). The grey curve represents the magnetic susceptibility from core A2 at the North oxbow lake. The dashed grey curve represents the magnetic susceptibility from the core at the South oxbow lake.

284x200mm (96 x 96 DPI)