

Historical and paleolimnological evidence for expansion of Lake Athabasca (Canada) during the Little Ice Age

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Abstract A multi-proxy paleolimnological record obtained from a small, lowland closed-drainage basin located in the Peace-Athabasca Delta (Alberta, Canada), 10 km northwest of the present-day shore of Lake Athabasca, captures evidence of pronounced hydroecological changes over the past ~400 years. Consistent with historical maps produced by early European explorers of western Canada, paleolimnological data support the existence of a Lake Athabasca highstand during the Little Ice Age (LIA), c. 1600–1900 Common Era (CE). This contrasts with interpretations from previous analyses on sediment cores from an upland closed-drainage basin located centrally within the Peace sector of the delta that

indicate low water levels during this interval. The different paleohydrological records at these two basins reflect the relative influence of different controls on the lake water balances. During the LIA, the lowland site was influenced by high levels in Lake Athabasca, whereas the elevated basin was outside the range of water-level rise in the lake and its distributaries, and was instead controlled by dry atmospheric conditions that led to evaporative draw-down. Integration of paleolimnological records and historical sources demonstrates that the ecosystem has undergone marked climate-driven hydroecological change over the past century, which is important information for effective management.

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Introduction

Deltas are amongst the most complex of natural environments because they exist in a transitional zone where numerous processes on the land, air and water meet, creating a continually changing landscape. Climate, water and sediment discharge, river-mouth processes, waves, currents, winds, shelf slope, subsidence and geometry of the receiving basin all potentially contribute to the formation and evolution of

deltas (Bhattacharya and Walker 1992). The interplay of these factors also generates highly productive terrestrial, wetland and aquatic habitats that encompass a broad range of hydroecological conditions. These natural attributes create a mosaic of ecosystems that are difficult to manage effectively because efforts can be confounded by additional watershed stressors such as industrial development, agriculture and urbanization.

Effective management has been a challenge for the Peace-Athabasca Delta (PAD), northern Alberta, Canada, where we have employed a range of spatial and temporal analyses to further the understanding of its hydroecological evolution, and to address long-standing concerns regarding the relative roles of multiple stressors on this freshwater ecosystem (Wolfe et al. 2005, 2006, 2007b, 2008a, b; Yi et al. 2008). Since its construction near the headwaters of the Peace River in 1968 to produce hydroelectricity, the WAC Bennett Dam has been blamed for lowered water levels in Lake Athabasca and reduction in the frequency and magnitude of ice-jam floods that help to recharge delta wetlands and lakes (Peters and Prowse 2001). More recent concerns have focused on consumption of Athabasca River water to extract bitumen in tar sand deposits (Schindler and Donahue 2006; Schindler and Smol 2006; Wolfe et al. 2008b). Although the latter has recently been identified as a much more serious threat to the delta's ecological integrity (Wolfe et al. 2008b), new studies have revealed complex relations among climate, quantity and seasonality of river discharge and lake levels in the PAD over the past millennium (Wolfe et al. 2008a). For example, comparisons of paleohydrological records from multiple proxies measured in lake sediment cores obtained from several sites within the PAD and one site in a lagoonal pond on Bustard Island in Lake Athabasca indicated divergent responses to regional climatic conditions during the Little Ice Age (LIA; c. 1600–1900 CE; Edwards et al. 2008). While some sites experienced reduced flood frequency or increased evaporative drawdown, others were affected by high water levels on Lake Athabasca.

Here we provide a detailed examination of the hydroecological changes that took place during and subsequent to the LIA in a small basin near Lake Athabasca. Based on comparison to a previously published paleolimnological record in an elevated region of the PAD (Wolfe et al. 2005), results illustrate complex landscape responses to regional climate

change. In this study, we use multi-proxy (biological, geochemical and physical) paleolimnological records as well as historical maps and air photos to elucidate the relative roles of drivers of hydroecological change in the central low-lying and northern upland regions of the PAD over the past ~400 years. Integration of this information contributes to a growing understanding of the dynamic processes that shape the system, a fundamental requirement for development of effective management practices.

Study area

The PAD is located at the confluence of the Peace, Athabasca and Birch Rivers in northern Alberta, Canada (Fig. 1). The PAD consists of two distinct sectors. The Peace sector in the north is a relict deltaic landscape. It is presently bypassed by the Peace River under normal flow conditions and only receives widespread flooding from river water during periodic ice-jam flood events that cause flow reversals on the Rivière des Rochers, Revillon Coupé and Chenal des Quatre Fourches. The Athabasca sector consists of both a relict deltaic landscape and an active deltaic margin that is currently prograding into Lake Athabasca. These areas receive frequent flood inputs from the Athabasca River and its tributaries. The Peace and Athabasca sectors are separated by a central lowland corridor occupied mainly by the large and shallow lakes Claire and Mamawi. Elsewhere, numerous smaller basins, active and inactive channels, and vast wetland areas characterize the 3,900 km² delta. The basins can largely be categorized by the degree to which river water influences the lake water balance. Open-drainage basins have a constant river connection, restricted-drainage basins have periodic river connection during periods of elevated flow and closed-drainage basins receive river inputs only during ice-jam flood events (Wolfe et al. 2007b).

PAD 9 (informal name; 58°46.46'N, 111°19.48'W, 209.8 m a.s.l) is a small (~12 ha), shallow (maximum depth ≈1 m), closed-drainage, open-water wetland, located ~10 km northwest of Lake Athabasca in a lowland portion of the delta (Fig. 1). Between PAD 9 and Lake Athabasca is a large (~70 km²) flood-prone sedge meadow known locally as Fort Chipewyan Bay. The catchment vegetation around PAD 9 consists primarily of willow (*Salix*) shrubs, except for a small

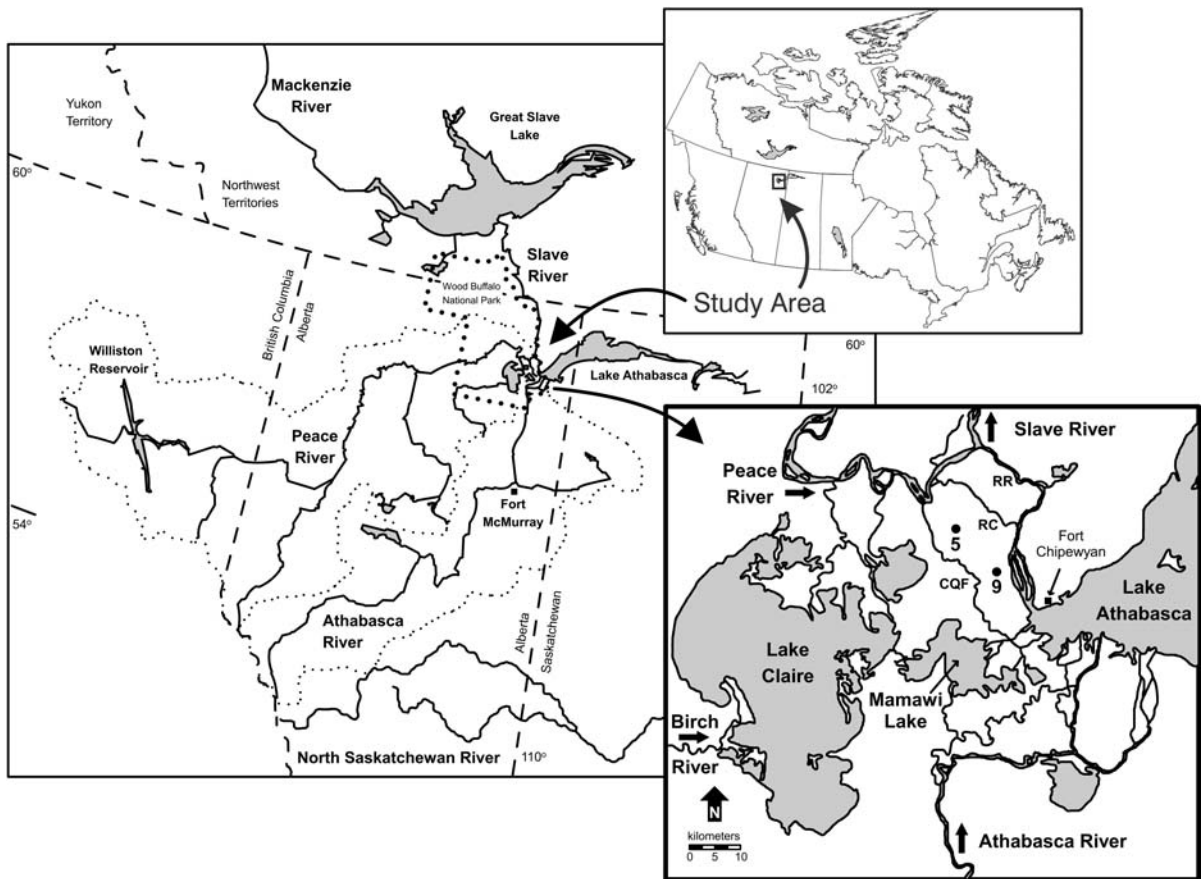


Fig. 1 The Peace-Athabasca Delta (northern Alberta, Canada), a UNESCO World Heritage Site and Ramsar Wetland of International Significance, is situated largely within Wood Buffalo National Park. Paleolimnological records referred to in

the text are from PAD 5 and PAD 9. Abbreviated river names described in text include *RR* for Rivière des Rochers, *RC* for Reillon Coupé and *CQF* for Chenal des Quatre Fourches

($\sim 400 \text{ m}^2$) forested bedrock outcrop along the south shore which is dominated by white spruce (*Picea glauca* (Moench) Voss), trembling aspen (*Populus tremuloides* Michaux) and jack pine (*Pinus banksiana* Lambert). Dominant aquatic and emergent vegetation include *Ceratophyllum* and filamentous algae, sedges (*Carex*) and cattail (*Typha*). The presence of dead willow fringes around the PAD 9 indicates the basin has experienced recent water level fluctuations.

Methods

Collection of archival maps

Historical maps of the PAD from 1814, 1827, 1884, 1897, 1917, 1927 and 1955 were obtained from

Vandermaelen (1827), Selwyn (1884), Dawson (1897), Tyrrell (1916), Fortin (1917) and Mollard et al. (2002). The maps were traced and converted to similar scales to examine historical evidence of changes in water level in the PAD over the past ~ 200 years. These provide key benchmarks for testing and refining our interpretations of the paleolimnological record from PAD 9.

Collection of lake sediment cores and preliminary analyses

Four sediment cores (Length: KB1 = 30 cm; KB2 = 29 cm; KB4 = 33 cm; KB5 = 32 cm) were collected from near the centre of PAD 9 in June 2001 using a gravity corer (Glew 1989). Each core was sectioned into 0.5-cm stratigraphic increments within 48 h after

transfer to the field base in Fort Chipewyan by helicopter. Multiple cores were obtained to provide sufficient material for analyses. KB1 was used for geochemical analyses, KB2 was used for macrofossil analyses, KB4 was used for ^{210}Pb and diatom analyses, and KB5 was used for mineralogical analyses. All cores were analyzed for loss-on-ignition at 0.5-cm intervals at temperatures of 85, 550 and 950°C (Heiri et al. 2001). A longer sediment sequence was also collected using a Russian corer to provide material for radiocarbon dating.

Core chronology

Contiguous sediment samples (1–3 g) from core KB4 between 0 and 29 cm depth were analyzed for ^{210}Pb using alpha spectrometry at the Environmental Radiochemistry Laboratory, Freshwater Institute (Winnipeg, Canada). Sediments were analyzed for ^{210}Pb by leaching in 6 N HCl in the presence of a ^{209}Po tracer, autoplating Po onto a silver disc (Flynn 1968), and counting the disc on an alpha spectrometer to determine ^{210}Pb using its ^{209}Po successor. Resulting dates were modelled using cumulative dry sediment weight and the Constant Rate of Supply model (CRS), which assumes a constant rate of ^{210}Pb supply to the sediment while allowing for changing sedimentation rates (Appleby 2001).

AMS radiocarbon dating of plant macrofossils retrieved from the longer Russian core sequence at depths 74.5 and 79.0 cm was carried out at Beta Analytic Inc. (Miami, Florida; Table 1). Samples were washed in distilled water, dried in an oven at 75°C and submitted for analysis. Radiocarbon dates were calibrated to calendar years before present by the probability distribution method using the Intcal98 calibration curve (Stuiver et al. 1998). All dates are reported as CE.

Diatom analyses

Contiguous samples from core KB4 were prepared for diatom analyses using acid digestion following standard techniques (Hall and Smol 1996). A minimum of 400 valves was counted per sample at 1000× magnification under oil immersion with the aid of several taxonomic sources (Foged 1981; Krammer and Lange-Bertalot 1986–1991; Cumming et al. 1995). Diatom taxa were summed into categories of closed- and open-drainage hydrological indicators based on contemporary relations between diatom taxa and environmental variables determined from a surface-sediment dataset spanning 52 basins along a hydrological gradient in the PAD (Hall et al. 2004). Closed-drainage indicator taxa include the epiphytes *Achnanthes lanceolata* subsp. *frequentissima* (Brebisson) Grunow, *Achnanthidium minutissimum* (Kützing) Czarnecki, *Cocconeis placentula* Ehrenberg, *Epithemia adnata* (Kützing) Brebisson, *Fragilaria capucina* var. *mesolepta* Rabenhorst, *Gomphonema angustum* Agardh, *G. parvulum* (Kützing) Kützing, *Navicula cryptocephala* Kützing, *N. minima* Grunow in Van Heurch, *N. pupula* Grunow in Van Heurch, *Nitzschia amphibia* Grunow, *N. palea* (Kützing) W. Smith, *Sellaphora seminulum* (Grunow) D.G. Mann. Open-drainage indicator diatom taxa include *Aulacoseira ambigua* (Grunow) Simonsen, *Cyclostephanos* cf. *tholiformis* Stoermer, Hakånsson and Theriot, *C. sp. PADI*, *Pseudostaurosira brevistriata* (Grunow in Van Heurch) D.M. Williams and Round, *Staurosira construens* var. *venter* (Ehrenberg) P. B. Hamilton and *Staurosirella pinnata* (Ehrenberg) D. M. Williams and Round.

Macrofossil analyses

Samples from core KB2 were washed through a 125- μm mesh screen with warm tap water. Material

Table 1 Radiocarbon data for PAD 9

Lab number	Material	Sediment core depth (cm)	Reported age (^{14}C year BP)	Calibrated 2σ age range (Cal year AD)
Beta-193586	<i>Sparganium</i> , <i>Carex</i> , <i>Scirpus</i> and <i>Rumex</i> seeds	74.5	1,540 \pm 40	420–620
Beta-193585	<i>Carex</i> and <i>Scirpus</i> seeds	79.0	1,830 \pm 40	90–260

Median calibrated ages were used in depth-age calculation. Radiocarbon dates were calibrated to calendar years before present by the probability distribution method using the Intcal98 calibration curve (Stuiver et al. 1998)

retained on the sieve was sorted in water using a binocular dissecting microscope at 8–40× magnification. Macro-remains were identified and counted with the aid of modern reference specimens and several keys (Bertsch 1941; Martin and Barkley 1961; Berggren 1969, 1981; Montgomery 1977; Artjuschenko 1990) and are expressed as the number of remains per 10 cm³ of wet sediment.

Geochemical analyses

Contiguous sediment samples from core KB1 were analyzed for bulk organic carbon content and oxygen isotope composition of the cellulose fraction following procedures detailed in Wolfe et al. (2001, 2007a). A subsample of the fine fraction obtained during the cellulose extraction procedure was analyzed for elemental organic carbon content using an elemental analyzer at University of Waterloo-Environmental Isotope Laboratory (UW-EIL). Cellulose oxygen isotope composition was measured on a continuous flow isotope ratio mass spectrometer system at UW-EIL. Oxygen isotope results are expressed in standard delta (δ) notation representing per mil (‰) deviations from Vienna Standard Mean Ocean Water (VSMOW) on a scale normalized such that Standard Light Antarctic Precipitation has a value of -55.5‰ in $\delta^{18}\text{O}$ (Coplen 1996). Analytical uncertainties are $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}$. Lake water $\delta^{18}\text{O}$ was inferred from cellulose $\delta^{18}\text{O}$ using a cellulose-water oxygen isotope fractionation factor of 1.028 (Wolfe et al. 2001).

Mineral analyses

Contiguous sediment samples from core KB5 were analyzed for mineral composition. All samples were air dried at room temperature, disaggregated with a mortar and pestle and passed through a 62.5- μm sieve following removal of organic matter by hydrogen peroxide treatment. Bulk mineralogy was determined using standard X-ray diffraction techniques (Last 2001). Mineral percentages were estimated from the bulk mineral diffractograms using the intensity of the strongest peak for each. Duplicate samples were analyzed for bulk mineralogy in one of every 50 samples and indicated precision of $\sim \pm 8\%$.

Results and interpretation

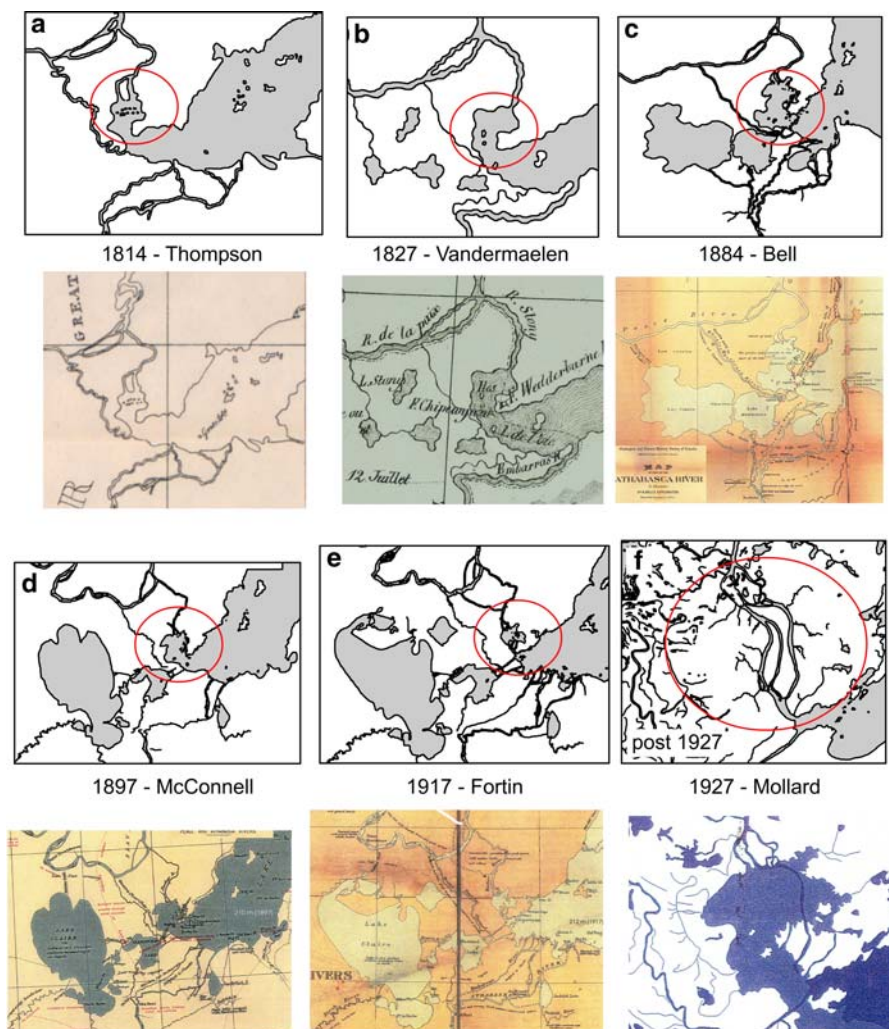
Archival map record

We have assembled several historical maps and aerial photographs that provide useful spatial and temporal context of hydrological change over the past two centuries. A key feature of early historical maps from the 1800s is evidence of markedly higher water levels relative to present at the west end of Lake Athabasca (Fig. 2a, b). The first comprehensive and coherent map of western Canada was completed in 1814 by David Thompson (Tyrrell 1916). Thompson's account of the southern end of Rivière des Rochers indicated a highstand on Lake Athabasca and submergence of the large embayed area known as Fort Chipewyan Bay (Fig. 2a). All other historical maps that we have obtained document an embayed area or expansion of Lake Athabasca into the PAD including Vandermaelen's Atlas Universel (1827; Fig. 2b) and maps by Bell (Fig. 2c; Selwyn 1884) and McConnell (Fig. 2d; Dawson 1897). Fortin's (1917) map (Fig. 2e) is compiled from geological field work from 1889 to 1915. This map indicates that the embayed area had decreased in size by this time, establishing the modern fluvial network of the Rivière des Rochers evident in maps derived from aerial photographs from 1927 to the present (Fig. 2f; Mollard et al. 2002).

Fort Chipewyan Bay has remained prone to periodic flooding in recent decades. Satellite images captured significant open-water (1990) and ice-jam floods in 1974 and 1996 that submerged the embayment (Peters et al. 2006). Although the extent of previous flood stages is uncertain, Peters et al. (2006) used the earliest peak in Lake Athabasca's water-level gauge record (1935) with a digital elevation model to infer the areal inundation via lake expansion. The 1935 event submerged the embayed area in addition to other low-lying areas adjacent to the central lakes in the PAD (Peters et al. 2006). Surficial mapping confirmed the presence of fine-grained lacustrine material in the embayed area in excess of one metre in thickness (Fig. 3; Bednarski 1999). A longer-term submergence and multiple reoccupation is evident from a well-developed strandline delineating the western edge of the embayed area and abruptly ending ancient fluvial courses connected to the Chenal des Quatre Fourches (Fig. 3). Although

Fig. 2 Traced extent of water bodies (rivers and lakes) in the PAD based on early maps from 1814 to 1917 (a–e) and from aerial photographs (f). The westward expansion of Lake Athabasca into an embayed area on the PAD is outlined by a circle.

Modified from Thompson's mapping (Tyrrell 1916) in **a**, Vandermaelen (1827) in **b**, Bell's mapping (Selwyn 1884) in **c**, McConnell's mapping (Dawson 1897) in **d**, Fortin's compilation (1917) in **e** and aerial photographs (Mollard et al. 2002) in **f**



the study site (PAD 9) is not within the delineated embayment boundary, it is within a sub-basin of low elevation in proximity to the embayed area as well as the Rivière des Rochers that has likely responded similarly. Evidence obtained from the cartographic sources was used to refine interpretations of paleolimnological results from PAD 9 cores, as described below.

Multi-proxy paleolimnological record

Chronologies for the sediment cores were based on ^{210}Pb analysis of core KB4 combined with ^{14}C dates from a longer sequence collected with a Russian corer. Below 3 cm core depth, total ^{210}Pb activity generally declined exponentially with depth reaching

constant ^{210}Pb values (0.034 Bq/g) at 21.25 cm. Similar values of supported ^{210}Pb have been obtained from analysis of sediment cores from other lakes in the PAD (Wolfe et al. 2005, 2008a, b). Linear interpolation assuming constant sedimentation rate was used between the oldest age provided by the CRS-modelled ^{210}Pb dates and ^{14}C dates obtained from seed and emergent plant matter taken from 74.5 cm depth in the Russian long core (Table 1, Fig. 4). Linear interpolation between the CRS-modelled dates and the ^{14}C dates provided a basal date for KB4 of c. 1579. The resulting chronology provided a mean sampling resolution of 6.4 years per 0.5-cm interval between 0 and 21.25 cm (c. 1866) and a mean sampling resolution of ~ 25.0 years per 0.5-cm interval from 21.25 cm to the base of the core. A rise

Fig. 3 Surficial geology (*R* bedrock, *S* shoreline, *L1* lacustrine, *L1d* lacustrine-deltaic and *A* fluvial deposits) modified from Bednarski (1999), water bodies (*black*), embayed area (*shaded*) and location of study lake PAD 9

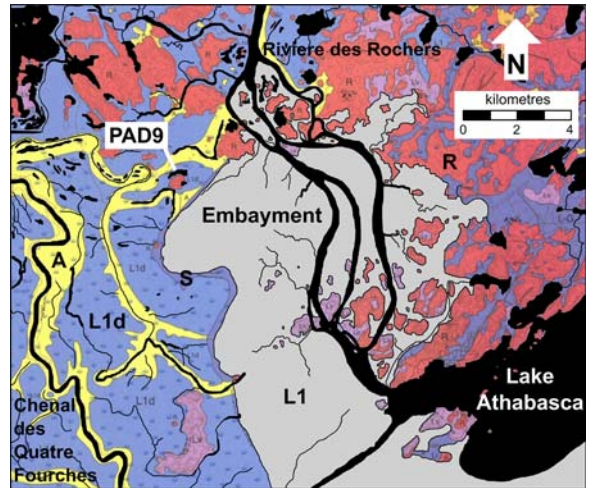
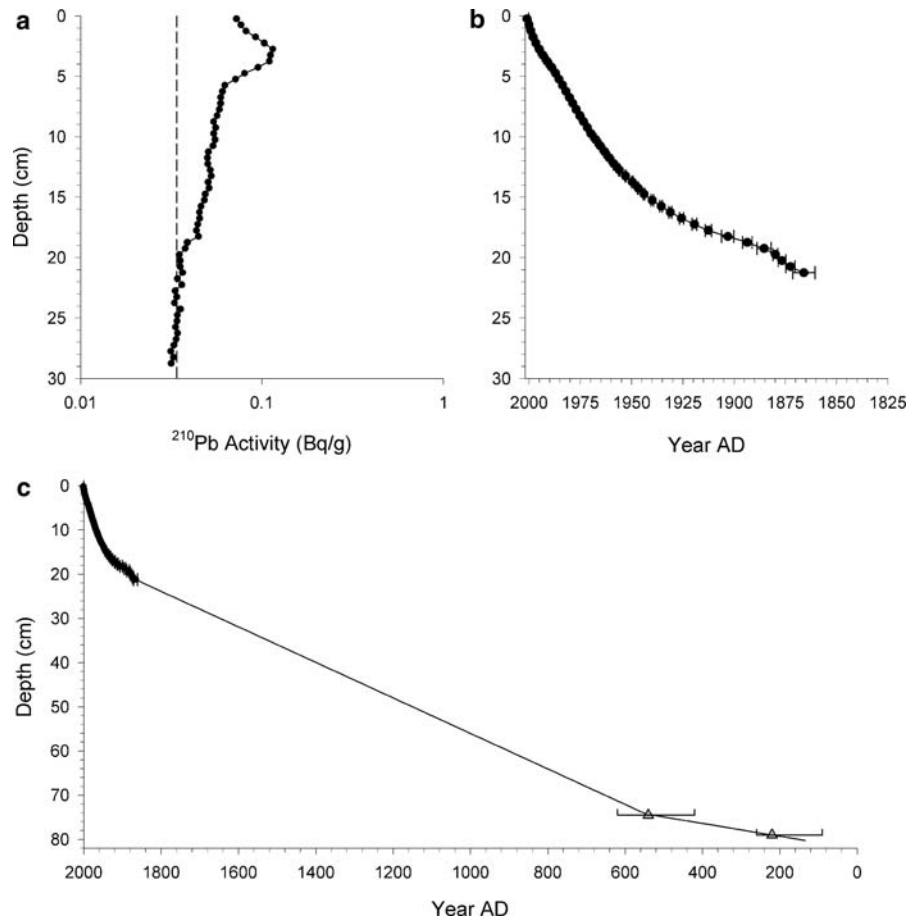


Fig. 4 **a** ^{210}Pb activity versus depth. **b** PAD 9 sediment core chronology (KB4). **c** Interpolation between ^{210}Pb dates and radiocarbon dates



in sedimentation rate occurs after c. 1925 (Fig. 4b). Age-depth relationships for the other KB cores were estimated by matching a prominent stratigraphic change in the loss-on-ignition profile dated at 1940 in the KB4 core (Fig. 5). This identified an offset of

only 0.5–1.0 cm among cores, and thus we assumed that supported ^{210}Pb activity was reached at the same depth (i.e. 1866) in all cores. Basal dates for these cores were as follows: c. 1654 (KB1), c. 1679 (KB2) and c. 1605 (KB5).

Biological, geochemical and physical profiles depict marked changes in hydroecological conditions in PAD 9 (Fig. 6). These include: (1) diatom taxa *Stausirella pinnata* and *Stausira construens* var. *venter*, which are indicators of open-drainage conditions and summed totals of the percent abundance of closed-drainage indicator diatom taxa (consisting mainly of *Cocconeis placentula*, *Epithemia adnata* and *Fragilaria capucina* var. *mesolepta*); (2) ostracod shells, *Chara* oospores, *Typha latifolia* seeds and *Salix* seeds identified from macrofossil analyses; (3) organic carbon content and cellulose-inferred lake water $\delta^{18}\text{O}$; and (4) quartz content. These stratigraphic profiles have been selected from a large number of analyses conducted on the PAD 9 sediment cores (Hall et al. 2004), and include a wide variety of indicators proven to be most sensitive to hydroecological change in shallow lakes in this ecosystem (Wolfe et al. 2005, 2008a, b). For example, cellulose-inferred lake water $\delta^{18}\text{O}$ records have been effective at tracing lake water balance history while diatom indicator taxa have provided complementary information on changing hydrological conditions. Results from analyses of the PAD 9 sediment cores identify three distinct hydroecological

phases over the past ~ 400 years, consistent with evidence from the historical maps and aerial photographs (Fig. 2a–f).

Phase 1—Lake Athabasca highstand and embayment

In the earliest part of the record, at c. 1600, abundance of diatom taxa indicative of closed-drainage conditions (e.g. *Cocconeis placentula*, *Epithemia adnata*, *Nitzschia amphibia*) declined by 10–20% to values generally less than 15% of the diatom sum (Fig. 6). Between c. 1600 and c. 1875, diatom assemblages were dominated (70–80%) by taxa indicative of open-drainage lake conditions (*Stausirella pinnata* and *Stausira construens* var. *venter*). These sediments also contained moderate amounts of quartz (~ 10 –15%) and high concentrations of *Chara* oospores (75–150/10 cm^3). Cellulose-inferred lake water $\delta^{18}\text{O}$ values (-17.9 to -15.6 ‰) were similar to those of present-day Lake Athabasca $\delta^{18}\text{O}$ values (-16.8 to -14.8 ‰). Overall, these paleolimnological indicators imply open-drainage conditions from c. 1600–1875, which corresponds with evidence from the earliest historical maps (1814, 1827; Fig. 2a, b) that Lake Athabasca

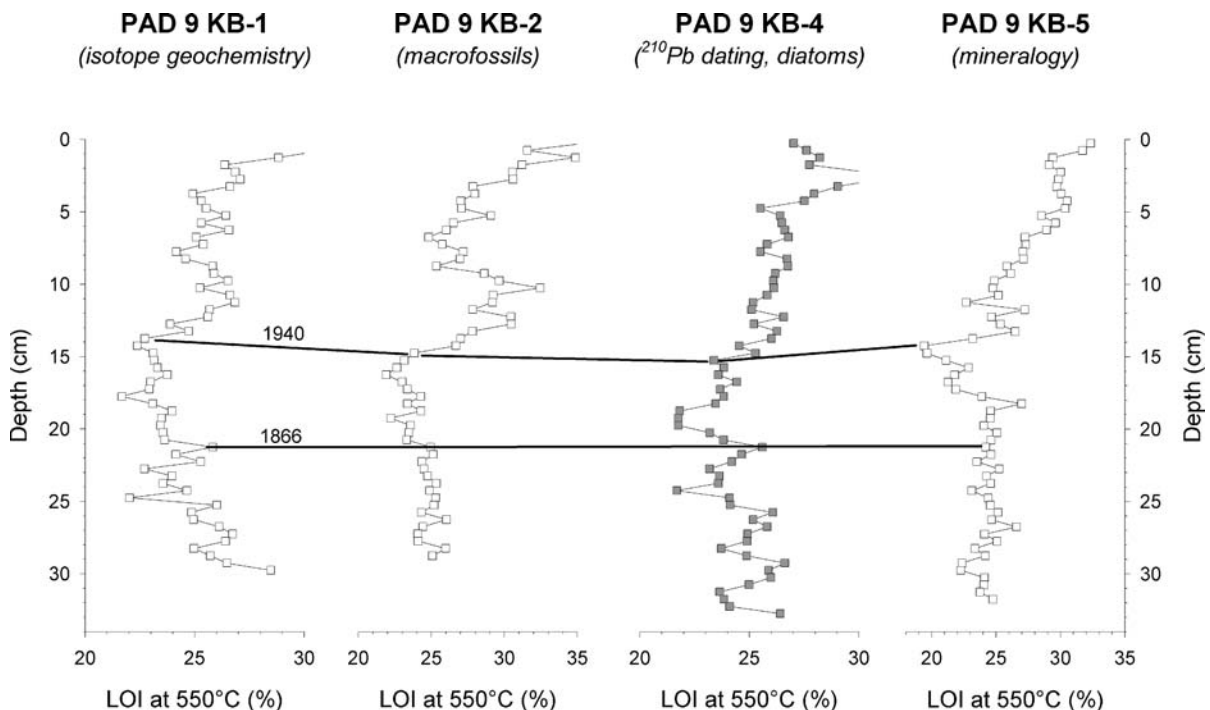


Fig. 5 Loss-on-ignition profiles used to align the dated core KB4 with the other KB gravity cores

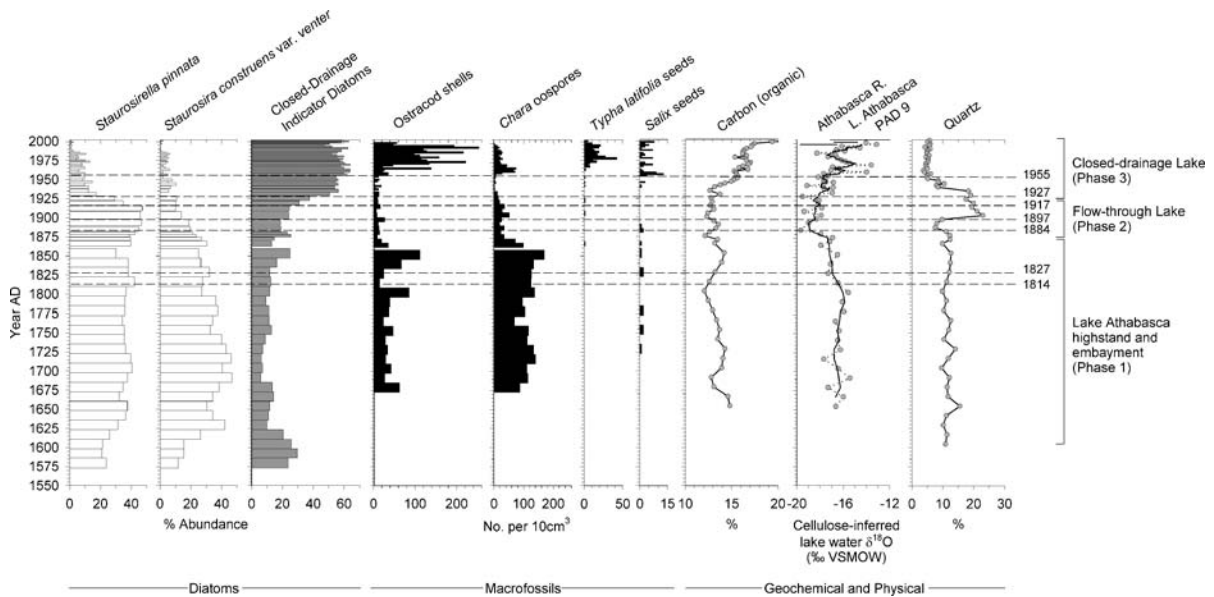


Fig. 6 Summary of key paleolimnological indicators at PAD 9. Diatom profiles indicate the two most abundant open-drainage indicator taxa (*open*) and a sum of closed-drainage indicator taxa (*grey*). Macrofossil profiles (*black*) show terrestrial taxa (*Salix* spp.), emergent aquatic taxa (*Typha latifolia*), submerged aquatic taxa (*Chara* oospores), and invertebrates (ostracods). Geochemical and physical profiles show percent organic carbon, cellulose-inferred lake water

$\delta^{18}\text{O}$ (including raw data and three-point running mean) and sedimentary quartz content. *Solid horizontal lines* at the top of the cellulose-inferred lake water $\delta^{18}\text{O}$ plot are modern ranges of water from Lake Athabasca, the Athabasca River and PAD 9 based on multiple samples obtained between 2000 and 2006. *Dashed horizontal lines* indicate years of maps in Fig. 2. *Brackets on the right* identify hydroecological phases, as described in the text

perennially or intermittently inundated large areas at the westward margin that are presently exposed. This highstand of Lake Athabasca would have generated elevated discharge along some outflow channels, which evidently led to frequent and protracted flooding of the PAD 9 basin.

Phase 2—flow-through lake

A marked hydroecological shift began between c. 1875 and c. 1900 and lasted until sometime between c. 1925 and c. 1950 based on prominent changes in several proxy indicators (Fig. 6). Notably, quartz content nearly doubled from 12 to >20%. Cellulose-inferred lake water $\delta^{18}\text{O}$ values declined by ~ 2 ‰ to values (-19.4 to -17.9 ‰) more similar to those of present-day Athabasca River water (-19.7 to -16.5 ‰). Abundance of ostracod remains and *Chara* oospores declined markedly. The presence of a quartz peak likely indicates fast-moving water with energy sufficient to transport suspended sediment. Prominent declines in both *Chara* and ostracod remains, along with very low abundances of aquatic

plant macrofossils, are consistent with a response to high turbidity associated with open-drainage hydrological conditions. This evidence indicates a high-energy environment, consistent with evidence depicted on the map from c. 1917 showing the former embayment of Lake Athabasca as an active flow-through lake connected to Lake Athabasca by a channel (Fig. 2e).

Phase 3—closed-drainage lake

Analyses indicate that another major change in hydroecological conditions began sometime between c. 1925 and c. 1950, and was associated with increasing sedimentation rate (Fig. 6). At c. 1925, the abundance of closed-drainage diatoms (mainly *Cocconeis placentula*) increased rapidly from <38 to >50%. After c. 1950, the abundance of ostracod shells increased substantially from ~ 20 to ~ 100 – $200/10\text{ cm}^3$. Remains of emergent aquatic and terrestrial plants (*Typha latifolia* Linnaeus and *Salix* spp.) also increased. This most recent phase is also characterized by a large increase in percent organic carbon, decline in percent quartz and an increase in

cellulose-inferred lake water $\delta^{18}\text{O}$ values (-19.4 to -13.1 ‰) that are similar to PAD 9 lake water $\delta^{18}\text{O}$ values (-17.1 to -8.8 ‰) measured on samples collected during the early thaw season between 2001 and 2006. Overall, paleolimnological results identify that this third phase was characterized by productive, low-energy aquatic conditions, in agreement with the closed-drainage hydrological setting depicted on the 1927 map (Fig. 2f) and the basin's current state.

Discussion and conclusions

Paleolimnological analyses of sediment cores from PAD 9 revealed three major hydroecological phases over the past ~ 400 years (Fig. 6). From c. 1600 to c. 1875, a highstand on Lake Athabasca formed an embayment at the west end of the lake and PAD 9 was affected by periodic low-energy flooding from Lake Athabasca outflow. Sometime between c. 1875 and c. 1900, lowering of Lake Athabasca briefly established a high-energy flow-through basin which influenced PAD 9 until sometime between c. 1925 and c. 1950. Finally, further reduction in Lake Athabasca water levels led to closed-drainage hydrological conditions at PAD 9 which commenced between c. 1925 and c. 1950 and have continued to the present. Historical maps extending back to 1814 also document three similarly timed hydrological phases at the west end of Lake Athabasca (Fig. 2). While availability of the historical maps contributed substantially to the interpretation of the paleolimnological record, our sediment core results identify that the maps produced by early explorers of the region captured persistent hydrological conditions beyond their record of observation.

Comparison of the paleohydrological record from PAD 9 with the paleohydrological record from a nearby closed-drainage lake (PAD 5) in an elevated portion of the northern Peace sector of the delta demonstrates clear differences during the LIA (Fig. 7). Contemporaneous with the Lake Athabasca highstand, the cellulose-inferred lake water $\delta^{18}\text{O}$ record from PAD 5 indicates that this basin experienced substantial evaporative drawdown leading to seasonal or periodic desiccation (Wolfe et al. 2005, 2008a). Although these results appear to be contradictory, they can readily be explained by considering the prevailing climatic conditions and their effect on

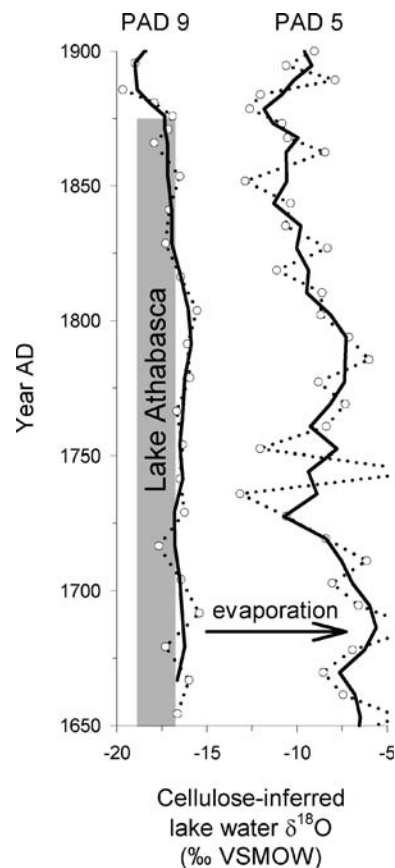


Fig. 7 Comparison of cellulose-inferred lake water $\delta^{18}\text{O}$ records (raw data and three-point running mean) from PAD 5 (Wolfe et al. 2005, 2008a) and PAD 9 during the Little Ice Age

streamflow generation at the headwaters of the Athabasca River in the eastern Rocky Mountains. While hydroclimatic conditions were variable in western Canada during the LIA (St. George et al. 2009), a cool and dry climate appears to have dominated in the upper Mackenzie River system (Edwards et al. 2008). The record at PAD 5 reflects a predictable hydrological response of this basin to these atmospheric conditions because it is elevated and removed from the influence of Lake Athabasca and the open-drainage network of the PAD. Concurrently, cooler LIA conditions delayed and prolonged snowmelt in the headwaters of the Athabasca River, sustaining greater streamflow during the summer (Case and MacDonald 2003; Edwards et al. 2008; Wolfe et al. 2008a). This ultimately raised the water level of Lake Athabasca and adjacent basins like PAD 9 that are located near the open-drainage

network of the PAD. Although we have recognized the strong role of non-climatic drivers such as geomorphic changes in Athabasca River distributary flow affected late twentieth century hydroecological conditions in the active Athabasca sector of the delta (Wolfe et al. 2008b), we have no comparable evidence to suggest this is the cause of water-level change in Lake Athabasca over the past four centuries, nor the contrasting paleohydrological records of PAD 9 and PAD 5 during the LIA.

The contrasting hydrological responses of PAD 9 and PAD 5 to regional climate conditions that prevailed during the LIA demonstrate the spatial complexity of the deltaic landscape in which they are located. While confirming that deltaic landscapes are complex is hardly surprising, long-term records derived from paleolimnological analyses have provided new insight into the relative roles of key drivers like changes in climate and river discharge that account for this spatial heterogeneity. This is crucial knowledge in systems like the PAD, where for more than 40 years hydroecological changes have been attributed primarily to anthropogenic stressors (i.e. flow regulation) due to limited understanding of the importance of natural drivers (PADPG 1973; PADTS 1996; MRBB 2004). As a result, management strategies, such as installation of expensive water-level control structures in the PAD, continue to attempt to mitigate the perceived effects of regulation. Our studies provide both the temporal context and spatial perspective required to identify climate as the main driver of hydroecological variability (Wolfe et al. 2005, 2006, 2008a). Importantly, our findings suggest that the dominant perception of ‘normal’ conditions in the PAD may have formed during the late 1800s and early 1900s when flood frequency (Wolfe et al. 2006) and water levels, including Lake Athabasca, in the vicinity of the Fort Chipewyan settlement were anomalously high in the context of the past 400 years, due to elevated discharge in the Peace and Athabasca rivers at the conclusion of the LIA - a factor that may have contributed to the long-held paradigm that the delta is drying and dying by unnatural causes (Timoney 2002). This evolving knowledge base is an important resource for public agencies responsible for effective stewardship of the PAD.

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