A Sault-outlet-referenced mid- to late-Holocene paleohydrograph for Lake Superior constructed from strandplains of beach ridges

John W. Johnston, Erin P. Argyilan, Todd A. Thompson, Steve J. Baedke, Kenneth Lepper, Douglas A. Wilcox, and Steven L. Forman

Abstract: The most detailed Lake Superior paleohydrograph relative to the current outlet near Sault Ste. Marie, Ontario–Michigan, was constructed from four strandplains of beach ridges. This provides a history of water-level, glacial isostatic adjustment (GIA), and the active outlet prior to monitoring and regulation. Four relative paleohydrographs that are offset and subparallel owing to differences in GIA were produced from 321 basal foreshore elevations and 56 optically stimulated luminescence ages. Subtracting modeled elevations in defined millennial lake phases between relative paleohydrographs and similarity between an inferred Sault Ste. Marie (hereinafter, Sault) paleohydrograph and data near the zero isobase corroborates rates of GIA derived from water-level gauges. A change in trend in the Sault paleohydrograph is related to the final separation of Lake Superior from Lakes Michigan and Huron and is the youngest age reported at 1060 ± 100 years. A near-horizontal trend in the Sault paleohydrograph for the past millennium has an intercept that is close to the historical average for Lake Superior. A consistently linear trend from about 2 to 1 ka suggests a relatively stable outlet similar to the past millennium, but a decreasing trend from 3 to 1 ka suggests an outlet other than the Sault. Although intercept data beyond the last millennium are similar in elevation to the reported bedrock sill near Chicago (Hansel et al. 1985), we argue that the Port–Huron outlet was the active outlet during this time and the inferred paleohydrograph of Baedke and Thompson (2000) requires reevaluation.

Résumé : Le paléo-hydrogramme le plus détaillé pour le lac Supérieur par rapport à l'exutoire actuel près de Sault Ste. Marie, Ontario–Michigan, a été construit à partir de quatre anciennes plaines intertidales de crêtes de plage. Ces données fournissent un historique du niveau de l'eau, de l'ajustement isostatique glaciaire et d'un exutoire actif avant le suivi et la régularisation. Quatre paléo-hydrogrammes relatifs, décalés et subparallèles en raison de différences d'ajustement isostatique glaciaire, ont été produits à partir de 321 élévations de base de l'estran et 56 âges déterminées par luminescence optique stimulée. La soustraction des élévations modélisées dans des phases de lac millénaires définies entre des paléo-hydrogrammes relatifs et la similitude entre un paléo-hydrogramme inféré pour le Sault Ste. Marie (« Sault ») ainsi que les données à proximité de l'isobase zéro corroborent les taux d'ajustement isostatique glaciaire dérivés de jauges de niveau d'eau. Un changement de tendance dans le paléo-hydrogramme du Sault est reliée à la séparation finale du lac Supérieur du lac Michigan–Huron et constitue le plus jeune âge rapporté, soit 1060 ± 100 ans. Une tendance presque horizontale dans le paléo-hydrogramme du Sault pour le dernier millénium a un intercepte qui est près de la moyenne historique pour le lac Supérieur. Une tendance linéaire constante depuis 2 à 1 ka suggère un exutoire relativement stable, semblable à celui du dernier millénaire mais une tendance décroissante depuis 3 à 1 ka suggère un exutoire autre que celui du Sault. Bien que les données d'intercepte au-delà du dernier millénaire aient une élévation semblable à celle rapportée pour le seuil de socle rocheux à proximité de Chicago (Hansel et al. 1985), nous proposons que l'exutoire Port–Huron constituait l'exutoire actif à cette époque et que le paléo-hydrogramme inféré de Baedke et Thompson (2002) demande à être réévalué.

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Introduction

Tectonism and glaciation are the geologic origins of Lake Superior, the largest freshwater lake in the world by surface area, third largest by water volume, and among the top 35 deepest (Beeton 2002). It stands at the head of the largest fresh surface-water system in the world, the Great Lakes – St. Lawrence drainage system, and is a vital environmental and economic

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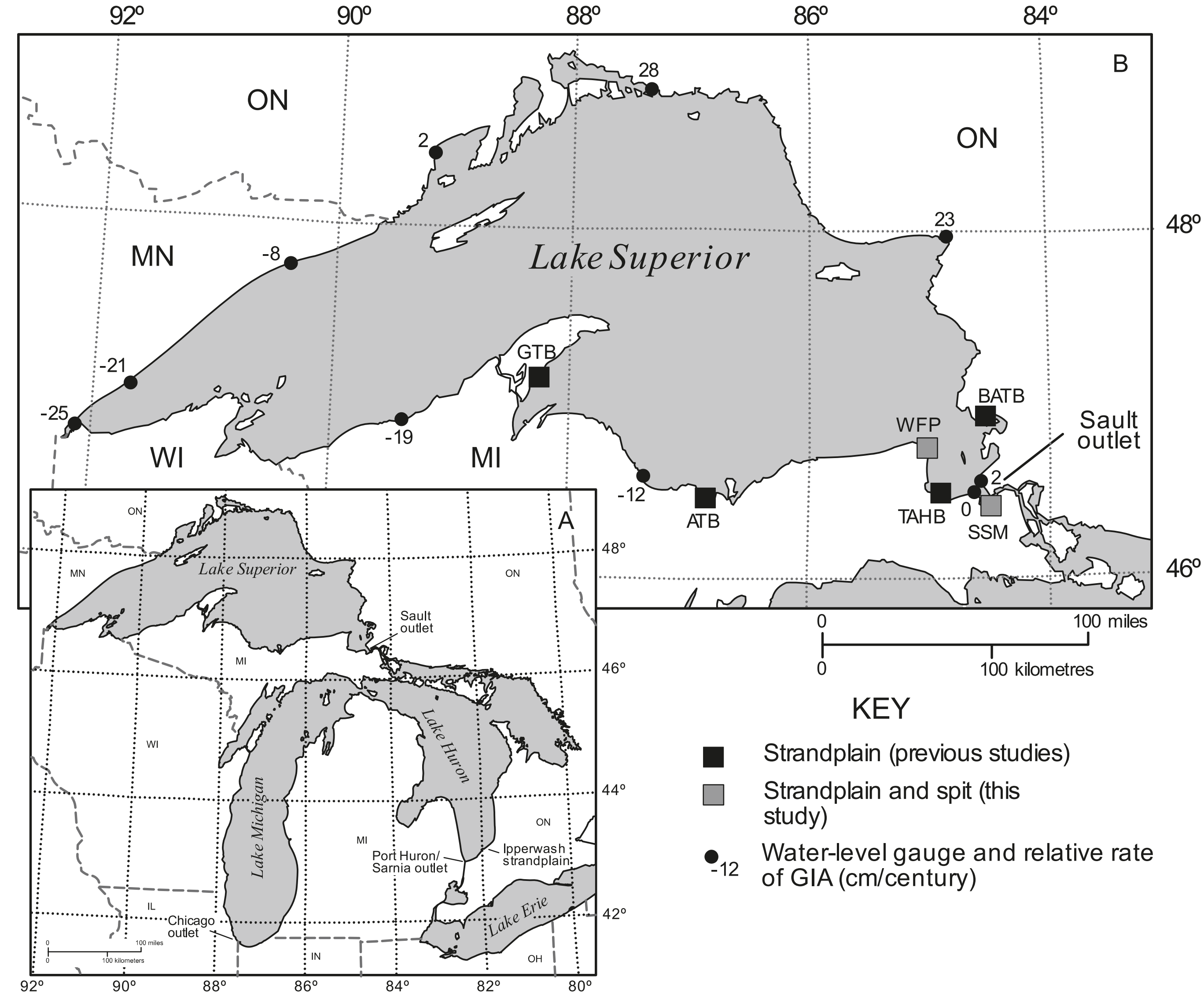


Fig. 1. Map of the upper Great Lakes showing location of the Ipperwash strandplain (Johnston 1999) and lake outlets. Map of Lake Superior, showing location of study areas (solid squares) and rates of glacial isostatic adjustment (GIA) calculated from individual water-level gauges (solid circles) by Mainville and Craymer (2005).

resource for two nations — Canada and the United States of America. Today, Lake Superior discharges across a bedrock-controlled and lock-regulated outlet near Sault Ste. Marie (Sault), Michigan–Ontario, into the Lake Huron – Michigan basin (Fig. 1). Prior to 2000 years ago (Farrand 1962), however, and possibly as late as 1200 years ago (Johnston et al. 2000, 2007*b*), water levels were confluent between the Lake Superior and Lake Michigan – Huron basins. This larger lake came into existence during the Nipissing phase of the upper Great Lakes and has been most recently defined by Thompson et al. (2011). Studies of prominent coastal features have helped define four major mid- to late-Holocene lake phases of ancestral Lake Superior — the Nipissing, Algoma, Sault, and Sub-Sault phases — in the Lake Superior basin (Stanley 1932; Farrand 1960, 1962; Cowan 1978, 1985; Farrand and Drexler 1985). However, these studies lack the submillennial-scale resolution to compare or relate to historical records.

The study of ridge and swale sequences resulted in a more detailed understanding of past lake-level change in the Lake Superior basin. Larsen's (1994) study of the strandplain at the Whitefish Point peninsula, Michigan, partially adopted the approach of Thompson (1992) but lacked sufficient subsurface data and introduced a new technique of modeling the chronology of strandplain sequence based on scattered radiocarbon ages. Johnston et al. (2000, 2001, 2004) adopted the approach of Thompson (1992) and presented the first detailed late-Holocene relative lake-level hydrograph for Lake Superior using beach ridges in the embayments of Grand Traverse Bay (GTB), Michigan, and Tahquamenon Bay (TAHB), Michigan. Difficulty correlating these relative paleohydrographs and the paucity of sufficient peat for 14C dating in swales between beach ridges in the Au Train Bay (ATB), Michigan, strandplain led to the work of Argyilan et al. (2005). That study provided a viable alternative to the radiocarbon dating of swale-organics to constrain the timing of beach ridge emplacement by using optically stimulated luminescence (OSL). Comparison of geomorphic and sedimentologic data among four Lake Superior strandplains — TAHB, GTB, and ATB, Michigan, and Batchawana Bay (BATB), Ontario (Johnston et al. 2007*b*) — provided the necessary groundwork to develop age models for this paper.

Here we construct a paleohydrograph for the Sault outlet that can be used to interpret lake level, climate, glacial isostatic adjustment, and the controlling influence of the outlet during the past five millennia. This study combines data from four Lake Superior strandplains — elevation data from Johnston et al. (2007*b*), age data from Argyilan et al. (2005), and more recent unpublished data. OSL ages are used to formulate cross-strandplain age models but geomorphic and sedimentologic data constrain and guide strandplain correlation. Analysis of glacial isostatic adjustments (GIA) among sites within major lake phases provides a new quantitative method to evaluate GIA in sites within one lake basin and to reconstruct a paleohydrograph for the outlet. The resulting paleohydrograph for the Sault outlet is compared to the Whitefish Point (WFP) data of Larsen (1994), land surveys of Cowan (1985), and new elevation data from a Nipissing spit (SSM) near Sault to check the consistency of inferred paleo lake level. An attempt to interpret the Sault paleohydrograph follows, including comparison with data from Johnston's (1999) study in Lake Huron and Baedke and Thompson's (2000) paleohydrograph for Lake Michigan.

Methods

Six sites containing beach ridges were studied along the southern and eastern shores of Lake Superior (Fig. 1). The sites include five strandplains (TAHB, GTB, ATB, and BATB, previously described in Johnston et al. (2007*b*), and WFP, reevaluated here after Larsen (1994)) and a spit (SSM, newly described here) of dune-capped beach ridges with intervening swales often filled with organics. The beach ridges at each site are onshore-to-offshore and alongshore (in the case of the spit) chronosequences of former positions of the Lake Superior shoreline, and the internal sedimentology records the elevation of the lake through time (cf. Thompson 1992). To determine these elevations, vibracores were collected along the lakeward margin of all beach ridges at TAHB, GTB, ATB, BATB, and SSM to recover basal foreshore (swash zone) deposits following the techniques of Thompson (1992). Ground penetrating radar (GPR) study of the ridges at the ATB embayment indicates that vibracores collected along the lakeward margin of the ridges recover foreshore deposits at the highest elevation within the beach ridges (Johnston et al. 2007*a*). Consequently, basal foreshore elevations are a close approximation of highstands of lake level. Core sites were surveyed topographically using an optical transit and elevations referenced to the International Great Lakes Datum of 1985 (IGLD85) (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1995). Basal foreshore contacts in core were established using genetic facies analysis following Thompson and Baedke (1997).

The age of the ridges were estimated by OSL dating of quartz separates collected from approximately every fourth to seventh beach ridge in four of the Lake Superior strandplains (TAHB, GTB, ATB, and BATB). Collection and processing of the OSL dates follows Argyilan et al. (2005) for sample designations beginning in "UIC" and Thompson et al. (2011) for those designated with "LS" prefixes (Table 1). Sediment samples were retrieved from the lakeward margin of beach ridges, within the upper part of the foreshore facies to isolate lake-level indicative deposits (Argyilan et al. 2005; Johnston et al. 2007*b*). All these sediment samples were retrieved from hand-dug soil pits, except for those samples at BATB, which were retrieved from vibracores collected through the beach-ridge crest. Calibrated radiocarbon ages of 13 peat samples retrieved by hand-coring basal wetland sediments between 27 beach ridges at SSM and recalibrated radiocarbon ages of nine organic samples collected by Larsen (1994) at WFP (Table 2) were used to check the veracity of the Sault paleohydrograph after age models were formulated and adjustments for GIA were completed for TAHB, GTB, ATB, and BATB.

Age models were formulated using OSL ages at TAHB, GTB, ATB, and BATB to assign an inferred age to each individually cored beach ridge. Because age data are relatively dispersed, we adopted the simplest model possible. A linear model was consistently applied to all sites, reflecting the dispersion in data and to avoid violating the basic tenet that beach ridges increase in age with distance from the modern shoreline. The number of age models per site was established by investigating multiple, sequential outliers seen in residual and confidence interval plots that corresponded with abrupt changes in cross-strandplain geomorphic and sedimentologic characteristics (cf. Johnston et al. 2007*b*). The veracity of age models was assessed by comparing general trends and patterns in basal foreshore elevation peaks and troughs among datasets. This approach assumes that time-equivalent beach ridges should align and merge after subtracting the effects of GIA, creating a hypothetical common water surface within the basin through time (Baedke and Thompson 2000).

Instead of estimating rates of GIA using the residual approach of Baedke and Thompson (2000), a method that is dependent upon visually inspecting the best fit between paleohydrographs and selecting an appropriate intercept value, we calculated the difference between modeled basal foreshore elevations in four different time periods. Because basal foreshore elevations were measured at unequal intervals between sites, modeled elevations were used to quantify rates of GIA between sites. Linear models were used because they approximate well the process of GIA in the last several millennia (Baedke and Thompson 2000) and best fit the data in discrete time periods. Data sets were evaluated in four different time periods because incomplete and time-varying relative paleohydrographs analyzed over five millennia caused intercept value divergence among linear models. In other words, partial records of water-level change about a consistent rate of GIA in the youngest and oldest data would not allow for the computation of a common intercept required for GIA estimation among sites. Determining this common intercept is important because it indicates a current-day elevation important for past water-level regulation. Historical observations of the Sault outlet may help interpret sparse data of the last millennium, but not prior to the final separation of Lake Superior from Lake Michigan – Huron (Johnston et al. 2007*b*). Isolating the data in four different time periods allowed us to better determine this intercept value from common linear trends observed in relative paleohydrographs within specific time periods. Pat-

Table 1. Optically stimulated luminescence age data collected at the Lake Superior strandplains.

Distance (m)	Ridge	Core	Depth (m)	Lab	Aliquots	Equivalent dose (Gy)	U (ppm)	Th (ppm)	K_2O (%)	H_2O (%)	Dose rate (mGy/year)	Optical (year)
Tahquamenon Bay (TAHB)												
34	1	901	0.94	LS901	14/93	0.5±0.06	0.4±0.1	1.2±0.1	0.96±0.07	25±5	0.87±0.06	580±90
129	6	906	0.78	LS906	24/71	0.4±0.07	0.3±0.1	0.9±0.1	0.67±0.05	30±5	0.64±0.04	580±120
245	11	911	0.67	LS911	32/96	1.4±0.08	0.4±0.1	0.8±0.1	0.84±0.06	25±5	0.80±0.05	1780±190
374	14	912	0.70	LS912	39/94	2.0±0.15	0.3±0.1	0.7±0.1	1.45±0.08	30±5	1.09±0.08	1830±220
524	18	916	0.75	UIC905	24/30	2.5±0.2	0.4±0.1	1.2±0.1	1.49±0.01	30±5	1.29±0.09	1940±220
714	23	921	0.95	UIC885	23/30	2.2±0.2	0.4±0.1	1.5±0.1	1.02±0.01	25±5	1.03±0.07	2140±250
993	31	928	0.55	UIC1107	27/30	3.3±0.3	0.4±0.1	0.7±0.1	1.33±0.01	25±5	1.21±0.09	2740±330
1136	37	934	0.61	UIC896	28/30	3.3±0.2	0.4±0.1	1.6±0.1	1.44±0.01	25±5	1.34±0.09	2470±250
1258	41	938	0.80	UIC1109	28/30	3.4±0.2	0.4±0.1	1.4±0.1	1.79±0.01	25±5	1.58±0.11	2410±240
1428	46	943	0.72	UIC906	28/30	3.5±0.3	0.4±0.1	1.0±0.1	1.47±0.01	30±5	1.27±0.09	2760±320
1516	50	947	0.78	UIC1108	29/30	3.5±0.2	0.5±0.1	1.6±0.1	1.51±0.01	30±5	1.35±0.09	2600±250
1686	56	953	0.75	UIC912	26/30	4.3±0.3	0.4±0.1	1.1±0.1	1.52±0.01	25±5	1.37±0.10	3150±340
1809	61	958	1.15	UIC903	25/30	3.9±0.3	0.4±0.1	1.3±0.1	1.35±0.01	30±5	1.20±0.08	3250±360
2162	72	965	1.07	UIC1110	17/20	2.5±0.2	0.4±0.1	0.9±0.1	0.56±0.01	30±5	0.63±0.04	3940±430
2230	77	970	1.07	UIC913	28/30	4.0±0.2	0.5±0.1	1.4±0.1	0.93±0.01	30±5	0.94±0.07	4280±390
Grand Traverse Bay (GTB)												
110	4	800	0.85	UIC922	28/30	1.0±0.1	0.7±0.1	2.1±0.1	1.79±0.01	10±5	1.95±0.14	510±70
212	7	803	0.50	UIC923	27/30	1.3±0.1	0.6±0.1	1.8±0.1	1.47±0.01	10±2	1.64±0.12	790±80
314	12	807	0.48	UIC924	29/30	1.6±0.1	0.6±0.1	2.2±0.1	1.66±0.01	25±5	1.57±0.11	1020±100
479	19	812	0.54	UIC925	26/30	1.9±0.1	0.7±0.1	2.2±0.1	1.88±0.01	30±5	1.67±0.12	1140±110
675	27	819	1.50	UIC960A	27/30	2.3±0.1	0.7±0.1	2.2±0.1	1.56±0.01	30±5	1.45±0.10	1590±140
675	27	819	1.50	UIC960B	27/30	2.2±0.3	0.7±0.1	2.2±0.1	1.56±0.01	30±5	1.45±0.10	1520±240
887	35	826	0.90	UIC961	30/30	3.5±0.2	0.8±0.1	2.7±0.1	2.40±0.01	30±5	2.07±0.14	1690±170
1005	41	831	1.01	UIC929	9/11	2.3±0.1	0.6±0.1	1.9±0.1	1.33±0.01	30±5	1.26±0.09	1830±160
1146	47	837	0.47	LS837	90/95	5.0±0.2	0.9±0.1	2.2±0.2	2.57±0.19	15±3	2.10±0.14	2370±210
1233	51	841	0.98	UIC926A	25/30	3.0±0.2	1.0±0.1	3.3±0.1	1.03±0.01	25±5	1.26±0.09	2390±230
1233	51	841	0.98	UIC926B	25/30	3.1±0.2	1.0±0.1	3.3±0.1	1.03±0.01	25±5	1.26±0.09	2470±240
1413	58	848	1.33	UIC928	28/30	3.6±0.2	0.9±0.1	3.3±0.1	1.76±0.01	25±5	1.76±0.12	2040±190
1586	62	852	0.90	UIC927	27/30	4.8±0.3	0.8±0.1	2.7±0.1	2.16±0.01	25±5	2.00±0.14	2400±240
1625	63	853	0.75	LS853	81/96	4.8±0.2	0.8±0.1	3.3±0.3	2.30±0.17	30±5	1.81±0.11	2680±270
1853	67	857	0.73	LS857	86/96	4.9±0.2	0.8±0.1	2.9±0.2	2.20±0.16	30±5	1.71±0.10	2880±270
Au Train Bay (ATB)												
94	1	1001	1.05	UIC1129	29/30	1.2±0.1	0.5±0.1	1.7±0.1	1.85±0.01	10±2	1.74±0.12	690±80
198	5	1005	1.44	UIC1131	30/30	2.2±0.1	0.5±0.1	1.9±0.1	2.56±0.01	20±5	2.29±0.16	960±90
285	11	1011	1.54	UIC1188	28/30	2.0±0.2	0.6±0.1	2.2±0.1	2.21±0.01	25±5	2.06±0.14	970±130
362	14	1014	1.10	UIC974-30	29/30	3.3±0.1	0.6±0.1	1.8±0.1	2.52±0.01	30±5	2.07±0.15	1590±160
362	14	1014	1.10	UIC974-60	16/20	3.0±0.2	0.6±0.1	1.8±0.1	2.52±0.01	30±5	2.07±0.15	1450±150
416	17	1017	0.64	UIC1189	30/30	2.9±0.2	0.6±0.1	2.2±0.1	2.38±0.01	20±5	2.00±0.14	1450±150
503	21	1020	0.67	UIC1130	29/30	3.7±0.2	0.6±0.1	2.0±0.1	2.57±0.01	30±5	2.11±0.15	1760±170
587	26	1025	1.17	UIC1132	28/30	4.5±0.3	0.5±0.1	2.0±0.1	2.86±0.01	30±5	2.31±0.16	1950±210
661	31	1030	1.09	UIC1191	29/30	4.0±0.2	0.6±0.1	2.0±0.1	2.45±0.01	30±5	2.03±0.14	1970±190
698	33	1032	0.53	UIC979	28/30	3.0±0.2	0.5±0.1	1.8±0.1	1.81±0.01	20±5	1.71±0.12	1750±190
698	33	1032	0.92	UIC1187	29/30	3.3±0.2	0.6±0.1	2.2±0.1	2.29±0.01	30±5	1.93±0.14	1710±170
822	38	1038	0.91	UIC980	30/30	3.6±0.3	0.6±0.1	2.1±0.1	2.73±0.01	20±5	2.45±0.17	1470±170
822	39	1038	1.05	UIC1190	30/30	3.5±0.2	0.6±0.1	2.0±0.1	2.45±0.01	30±5	2.03±0.14	1720±170
822	39	1038	1.05	UIC1190B	28/30	4.6±0.2	0.6±0.1	2.0±0.1	2.45±0.01	30±5	2.03±0.14	2260±210
893	44	1043	1.76	UIC975	30/30	3.6±0.2	0.5±0.1	1.7±0.1	1.98±0.01	20±5	1.84±0.13	1960±200
Batchawana Bay (BATB)												
113	5	1105	2.90	UIC1339	29/30	1.5±0.1	0.6±0.1	2.4±0.1	2.18±0.01	30±5	1.87±0.13	780±70
222	10	1110	6.60	UIC1274A	29/30	2.3±0.1	0.6±0.1	2.3±0.1	1.73±0.01	30±5	1.51±0.11	1490±130
323	15	1115	1.70	UIC1284	27/30	3.1±0.1	0.5±0.1	2.1±0.1	1.83±0.01	30±5	1.61±0.11	1930±170
805	30	1130	2.10	UIC1278	30/30	4.7±0.2	0.7±0.1	3.1±0.1	1.84±0.01	30±5	1.69±0.12	2760±240
943	35	1135	2.80	UIC1279	30/30	4.2±0.2	0.5±0.1	2.0±0.1	1.80±0.01	25±5	1.64±0.12	2560±240

Table 1 (*concluded*).

Distance (m)	Ridge	Core	Depth (m)	Lab	Aliquots	Equivalent dose (Gy)	U (ppm)	Th (ppm)	K_2O (%)	H_2O (%)	Dose rate (mGy/year)	Optical (year)
1079	40	1140	3.10	UIC1341	30/30	3.6±0.2	0.4±0.1	1.6±0.1	1.78±0.01	30±5	1.51±0.11	2370±230
1219	45	1145	2.60	UIC1391	28/30	1.3±0.1	0.7±0.1	2.5±0.1	2.14±0.01	30±5	1.87±0.13	2550±230
1548	55	1155	2.60	UIC1328	29/30	4.5±0.2	0.6±0.1	2.2±0.1	1.55±0.01	25±5	1.49±0.10	3020±270
2036	66	1166	6.40	UIC1304	20/20	5.6±0.2	0.6±0.1	2.8±0.1	1.46±0.01	30±5	1.35±0.10	4140±350
2150	70	1170	2.55	UIC1340	29/30	6.6±0.3	0.6±0.1	2.4±0.1	1.60±0.01	30±5	1.47±0.10	4500±400
2225	74	1174	0.95	UIC1424	28/30	5.7±0.3	0.8±0.1	2.6±0.1	1.38±0.01	30±5	1.38±0.10	4100±400

Note: All OSL ages were determined form the 150–250 μm size quartz fraction.

terns in basal foreshore elevations and previously reported lake phases of Lake Superior were used to establish four time periods of about a millennium in length. Stanley (1932), Farrand (1960, 1962), Cowan (1978, 1985), and Farrand and Drexler (1985) documented major lake phases in Lake Superior and referred to them as “Nipissing,” “Algoma,” “Sault,” and “Sub-Sault.” Here, we consider the end of the Nipissing phase as ca. 2800 cal. years BP, Algoma phase as ca. 2000 cal. years BP, and Sault phase as ca. 1000 cal. years BP.

Results and discussion

Elevation data

Site and genetic facies characteristics of four of the study areas TAHB, GTB, ATB, and BATB are presented in Johnston et al. (2007*b*). We compiled 321 basal foreshore elevations from four sites (71 TAHB, 60 GTB, 81 ATB, and 82 BATB) to identify common trends among sites (Fig. 2). They were used in conjunction with cross-strandplain geomorphic and sedimentologic trends, described in Johnston et al. (2007*b*), to formulate age models.

Age data

We used 56 OSL dates from four Lake Superior strandplains to produce ages for each individually cored beach ridge. Argyilan et al. (2005) reported on 23 of these ages, whereas 33 of these ages are first reported here (Table 1). We used 15 ages from TAHB, GTB, and ATB and 11 ages from BATB to formulate age models at each of the four study sites (Figs. 3–6). Because 25% of the cored beach ridges were age-dated at GTB, this site may be considered more reliable than the other sites at 21% (TAHB), 20% (ATB), and 14% (BATB). However, age models for each site must be created and evaluated individually.

Tahquamenon Bay age model

We used 15 OSL ages to create a chronology for the TAHB strandplain (Fig. 3). This chronology includes four additional ages (Table 1) not reported in Argyilan et al. (2005). These additional data were collected to investigate an apparent age reversal between the two age models of Argyilan et al. (2005) and an anomalously high rate of average timing of beach-ridge development in their youngest age model. Six OSL ages reported in Argyilan et al. (2005) were excluded from this analysis because of inconsistencies with the new ages. Ages produced by Argyilan et al. (2005) were consistently older than ages produced by subsequent analyses at TAHB by ~500 years, although the relation of individual ages to each other remained consistent between the two datasets. Samples UIC1106 (ridge 8; 2360 ± 290 years) and UIC907 (ridge 11; 2120 ± 210 years) yielded ages that were approximately 1000 years older than lakeward ridges (Argyilan et al. 2005). The same offset in ages was observed in the newer OSL data. While the cause of the apparently older ages from Argyilan et al. (2005) is currently under analysis, possible sources of error include the relatively coarse grain size (250–355 μm) of samples UIC880 and UIC834, which is less than ideal for single aliquot regeneration (SAR) analysis (Argyilan et al. 2005). Samples UIC833 (3020 ± 410 years) and UIC850 (1670 ± 170 years) were collected from a vibracore at ridge 27, which also may have produced sampling errors (Argyilan et al. 2005).

Here, we propose two new age models, separated by about one millennium, that are coincident with a change in cross-strandplain geomorphic and sedimentologic characteristics from the landward to lakeward set of beach ridges (Johnston et al. 2007*b*). A linear function constrained by 13 ages was used to assign an age for 60 ridges cored in the landward set of beach ridges. Ages span approximately 2200 years from 3900 to 1700 cal. years BP, assuming a constant progradation rate of 0.88 m/year and 34 ± 3 years between adjacent ridges. Owing to the close similarity in the two lakeward ages, ages were calculated for 11 ridges cored in the lakeward set by using an average of the two lakeward ages and the slope of the landward set of beach ridges. Lakeward ages span about 200 years, with no beach ridges preserved in the previous 1000 years between landward and lakeward sets and during the last 470 cal. years BP.

Grand Traverse Bay age model

Fifteen OSL ages were used to create a chronology for the GTB strandplain (Fig. 4). Three additional ages (Table 1) not reported in Argyilan et al. (2005) were collected to investigate a possible gap in the record. This gap was supported by geomorphic and sedimentologic evidence (Johnston et al. 2007*b*) but it could not be deciphered because of an abrupt increase in scattered ages between 1050 and 2175 m distance from the modern shoreline (Johnston et al. 2000; Argyilan et al. 2005). Here, we propose two new linear age models separated at 1050 m, not the 350 m distance landward from the modern shoreline used by Argyilan et al. (2005). This improves the model fit, with a majority of the seven oldest ages within the 95% confidence limits, and better matches in elevation peaks and troughs in other relative paleohydrographs after GIA was extracted. A separate age model at 1050 m was developed to remedy intersecting paleohydrographs (TAHB and GTB), which are inconsistent with strandplain develop-

Table 2. Calibrated radiocarbon age data collected at Whitefish Point (Larsen 1994) and Sault Ste. Marie, Michigan.

Lab	Material	Distance (m)	Reported age (years BP)	Calibrated two sigma (95.4%) age range	Relative area under distribution	Median probability
Whitefish Point						
TO-3288	Peat	8315	2350±50	2180–2239	0.051	2394
TO-3288	Peat	8315	2350±50	2303–2502	0.859	2394
TO-3288	Peat	8315	2350±50	2532–2536	0.002	2394
TO-3288	Peat	8315	2350±50	2595–2613	0.016	2394
TO-3288	Peat	8315	2350±50	2637–2695	0.073	2394
TO-3289	Peat	8164	1050±50	800–812	0.013	966
TO-3289	Peat	8164	1050±50	827–864	0.042	966
TO-3289	Peat	8164	1050±50	902–1066	0.945	966
TO-3290	Peat	7560	3010±50	3044–3045	0.001	3212
TO-3290	Peat	7560	3010±50	3063–3358	0.999	3212
TO-3291	Peat	5670	1600±50	1379–1607	1.000	1481
TO-3292	Peat	4914	2210±60	2061–2089	0.032	2223
TO-3292	Peat	4914	2210±60	2098–2345	0.968	2223
TO-3293	Peat	4385	2150±50	2001–2212	0.691	2147
TO-3293	Peat	4385	2150±50	2220–2310	0.309	2147
TO-3296	Peat	2608	800±50	663–796	0.977	722
TO-3296	Peat	2608	800±50	873–896	0.023	722
TO-3297	Peat	2419	480±50	334–349	0.017	520
TO-3297	Peat	2419	480±50	439–448	0.007	520
TO-3298	Peat	1436	270±50	1–13	0.025	340
TO-3298	Peat	1436	270±50	148–188	0.106	340
TO-3298	Peat	1436	270±50	189–211	0.012	340
TO-3298	Peat	1436	270±50	269–479	0.857	340
Sault Ste. Marie						
GX-30560	Peat	8423	3300±70	3385–3689	1.000	3533
GX-30559	Peat	8503	3760±80	3924–3954	0.031	4133
GX-30559	Peat	8503	3760±80	3956–4360	0.928	4133
GX-30559	Peat	8503	3760±80	4365–4408	0.040	4133
GX-30558	Peat	8558	3900±90	4006–4033	0.011	4324
GX-30558	Peat	8558	3900±90	4081–4572	0.989	4324
GX-30557	Peat	8627	2170±60	2005–2025	0.031	2182
GX-30557	Peat	8627	2170±60	2037–2330	0.969	2182
GX-30556	Peat	8732	1470±60	1289–1424	0.842	1367
GX-30556	Peat	8732	1470±60	1427–1445	0.027	1367
GX-30556	Peat	8732	1470±60	1456–1517	0.131	1367
GX-30555	Peat	8879	1720±70	1419–1463	0.034	1634
GX-30555	Peat	8879	1720±70	1512–1820	0.966	1634
GX-30554	Peat	8975	1890±70	1629–1654	0.022	1830
GX-30554	Peat	8975	1890±70	1691–1993	0.978	1830
GX-30553	Peat	9057	3070±70	3076–3412	0.982	3278
GX-30553	Peat	9057	3070±70	3423–3442	0.018	3278
GX-30552	Peat	9227	3590±90	3643–3664	0.013	3897
GX-30552	Peat	9227	3590±90	3683–4102	0.959	3897
GX-30552	Peat	9227	3590±90	4109–4148	0.028	3897
GX-30551	Peat	9339	3800±80	3976–4419	1.000	4195
GX-30550	Peat	9446	3330±70	3396–3720	0.996	3565
GX-30550	Peat	9446	3330±70	3803–3809	0.004	3565
GX-30549	Peat	9495	2890±70	2851–3248	1.000	3035
GX-30548	Peat	9558	4130±90	4434–4844	1.000	4658

Note: Radiocarbon dates were calibrated to calendar years BP using the program CALIB (version 6.0; Stuiver and Reimer 1993) with the calibration data set of Reimer et al. (2009). Sample designations beginning in "TO" are reported from Isotrace Radiocarbon Laboratory at the University of Toronto and recalibrated from Larsen (1994). Sample designations beginning in "GX" are reported from Geochron Laboratories, Inc., Cambridge, Massachusetts. For all Sault Ste. Marie data, 8400 m distance was added to compare with Whitefish Point data.

Fig. 2. Graph of distance from the modern shoreline versus elevation above IGLD85 of subsurface basal foreshore contacts in individual beach ridges from four different Lake Superior strandplains. Arcs represent common general patterns observed between study sites that align after adjustments for age and GIA are completed.

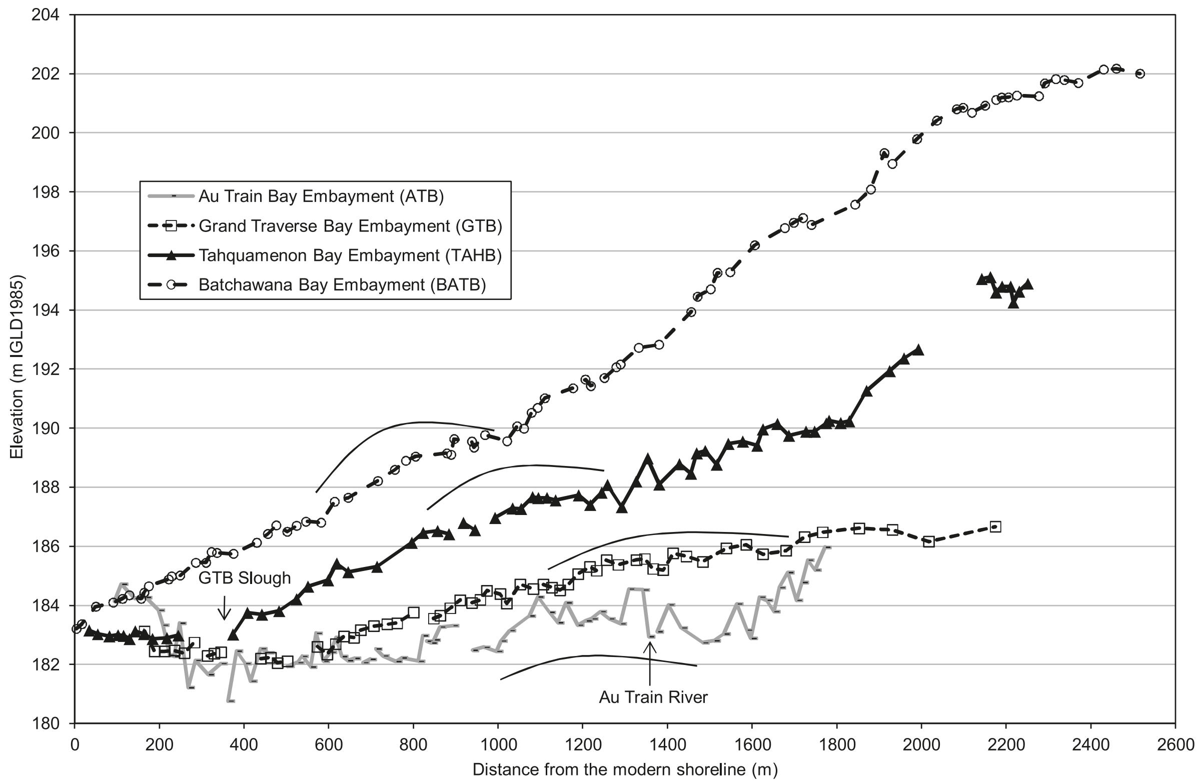


Fig. 3. Graph of distance from the modern shoreline versus basal foreshore elevations, OSL ages, and age model for the Tahquamenon Bay strandplain. SAR, single aliquot regeneration.

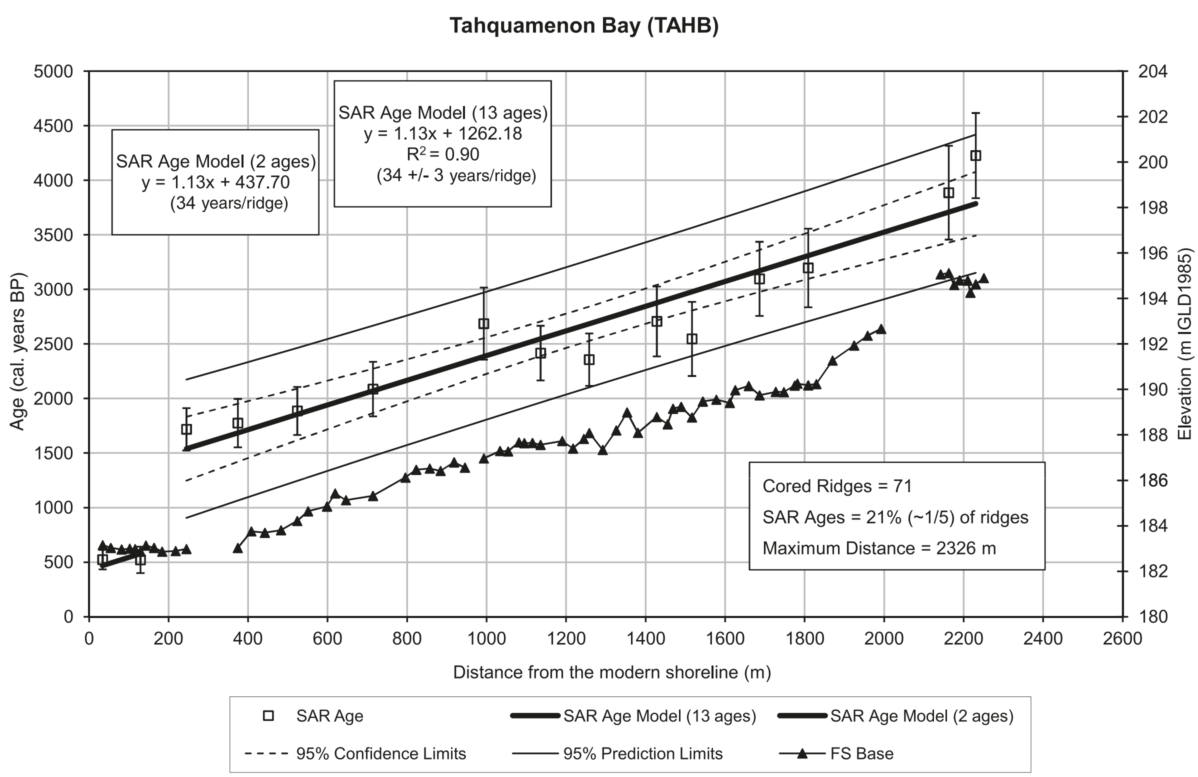
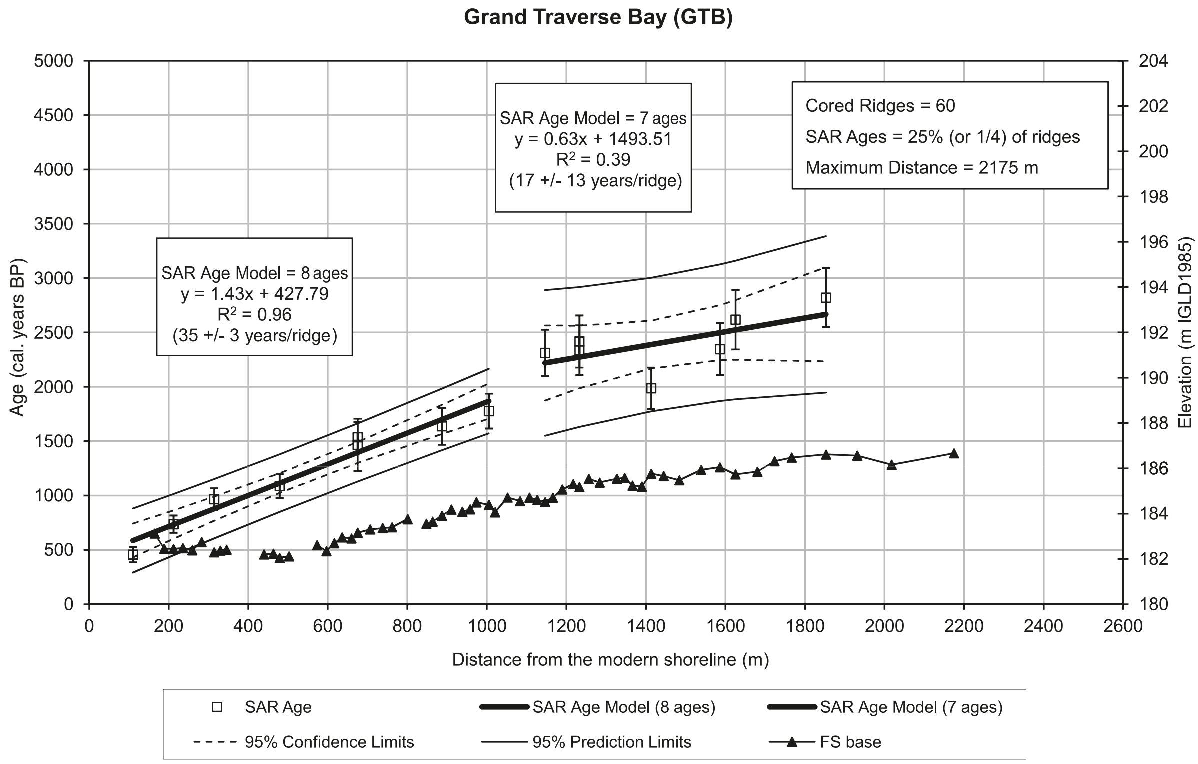


Fig. 4. Graph of distance from the modern shoreline versus basal foreshore elevations, OSL ages, and age model for the Grand Traverse Bay strandplain.



ment unless tectonism occurred (Johnston et al. 2004). Ages for 28 ridges cored between 1050 and 2175 m distance from the modern shoreline were derived from a linear age-model constrained by seven OSL ages (Fig. 4). These ridges span ca. 700 years from 2900 to 2200 cal. years BP, with an average time span of 17 ± 13 years per ridge and an average progradation rate of 1.58 m/year. Age estimates for the 32 cored ridges between the modern shoreline and 1021 m landward were calculated by a linear age model constrained by eight of the youngest OSL ages. The inferred ages span ca. 1400 years from 1900 to 500 cal. years BP, with an assumed constant accretion rate of about 35 ± 3 years per ridge and an average progradation rate of 0.70 m/year. These two new age models for GTB yield a twofold increase in the average rate of beach accretion, whereas the average progradation rate is halved with a hiatus of about 300 years centered at 2000 cal. years BP.

Au Train Bay age model

Age estimates for all 81 ridges for the ATB strandplain were derived from a linear age model constrained by 15 OSL ages (Fig. 5; Table 1). One age model was used instead of two separated at 350 m landward from the modern shoreline, because elevation peaks and troughs between 1000 and 1500 m distance from the modern shoreline better matched other Lake Superior paleohydrographs after subtraction of GIA. The inferred ages span ca 2300 years from 3200 to 900 cal. years BP, assuming an average rate of progradation of 0.72 m/year and 25 years per ridge for the entire ATB strandplain.

Batchawana Bay age model

Age estimates for the 82 recognized ridges for the BATB strandplain were derived from a linear model based on 11 OSL ages (Fig. 6; Table 1). Disparity between ages, including apparent age reversals, made it difficult to justify multiple age models while aligning elevation peaks and troughs to other paleohydrographs after GIA was extracted. The inferred ages for the BATB strandplain span ca. 3600 years from approximately 1000 to 4600 cal. year BP, assuming an average rate of progradation of 0.69 m/year and 45 years per ridge for the entire BATB strandplain. Because 14% of the cored beach ridges were age-dated at BATB, the fewest among all study sites, and observed disparity between ages at BATB, alignment of common patterns among sites was used to evaluate the BATB chronology. However, strandplain records must be differentially adjusted for GIA to best evaluate alignment of these common patterns.

Calculation of GIA of study sites

The sequence of GIA analysis among lake phases was determined by age and elevation data. Because the majority of the age (71%) and elevation (69%) data are within the Sault and Algoma phases, we investigated these first. Although the Algoma phase contains more elevation data than the Sault phase (41% versus 28%), the Sault phase contains more age data than the Algoma phase (39% versus 32%). Given that paleohydrograph elevations are measured and ages are modeled, the Sault phase was studied first. The linear nature of the data in the Sault phase (BATB, GTB, and ATB) also supports

Fig. 5. Graph of distance from the modern shoreline versus basal foreshore elevations, OSL ages, and age model for the Au Train Bay strandplain.

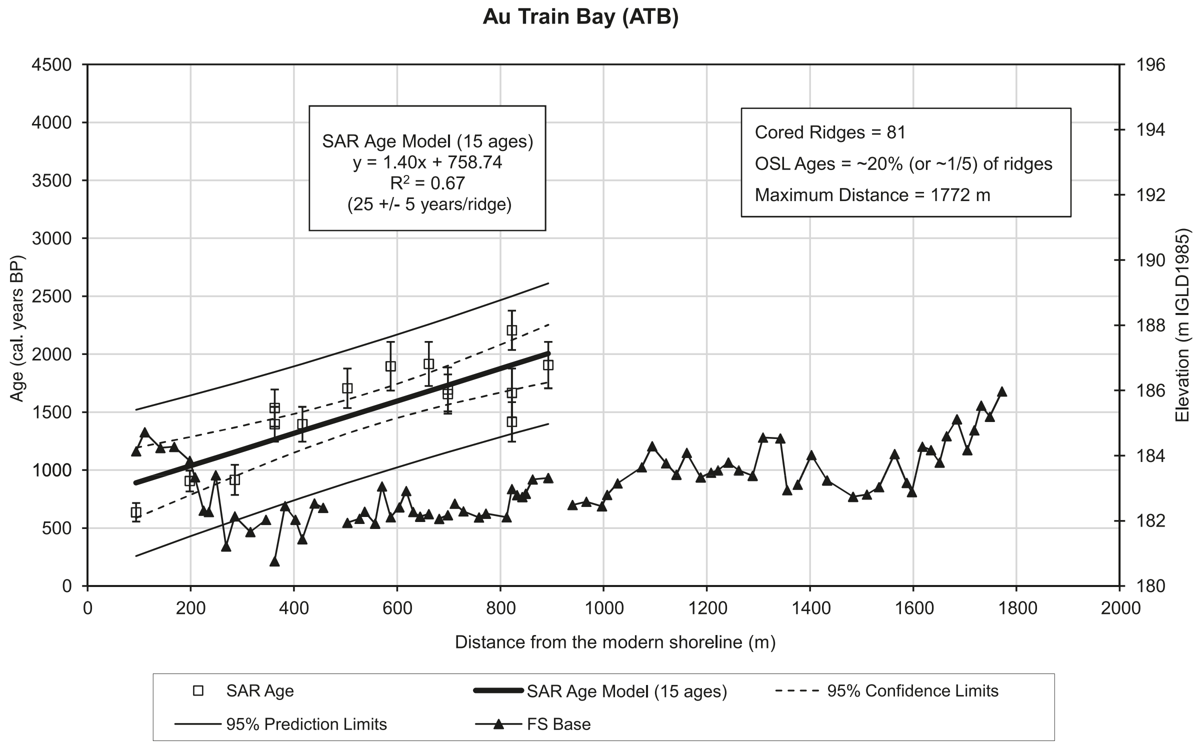


Fig. 6. Graph of distance from the modern shoreline versus basal foreshore elevations, OSL ages, and age model for the Batchawana Bay strandplain.

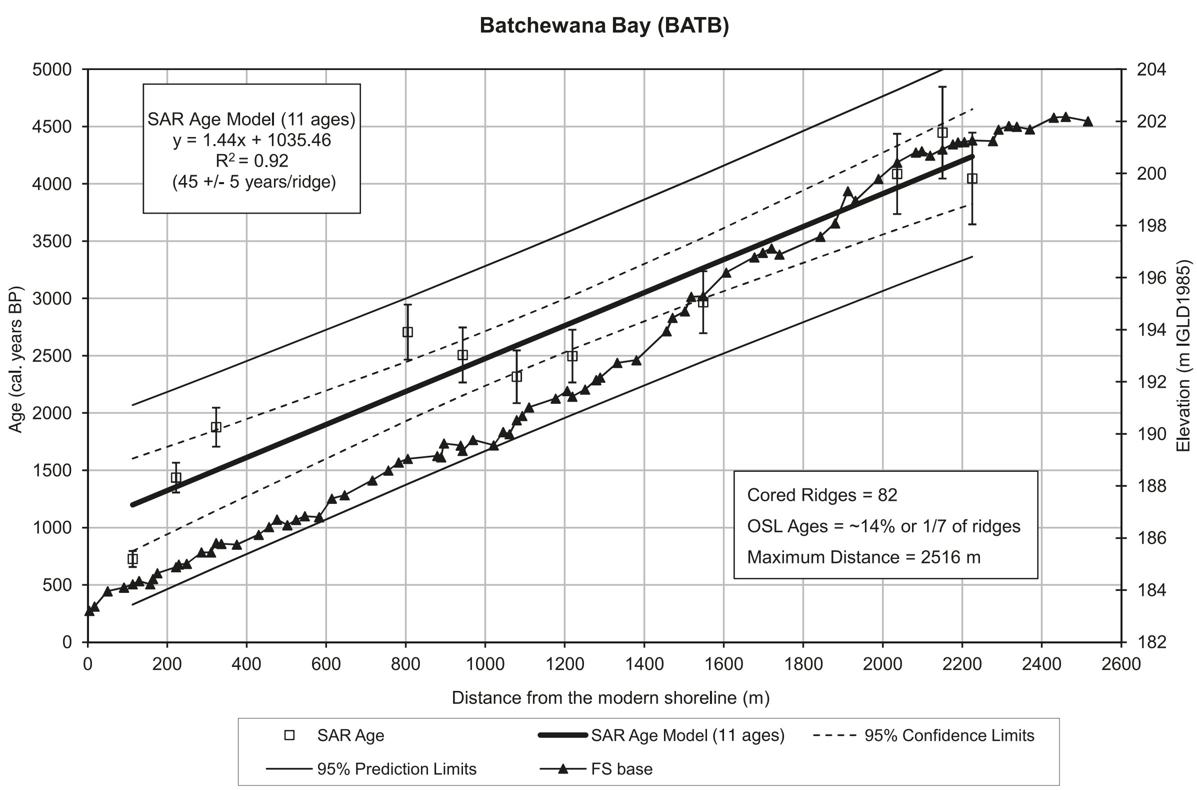
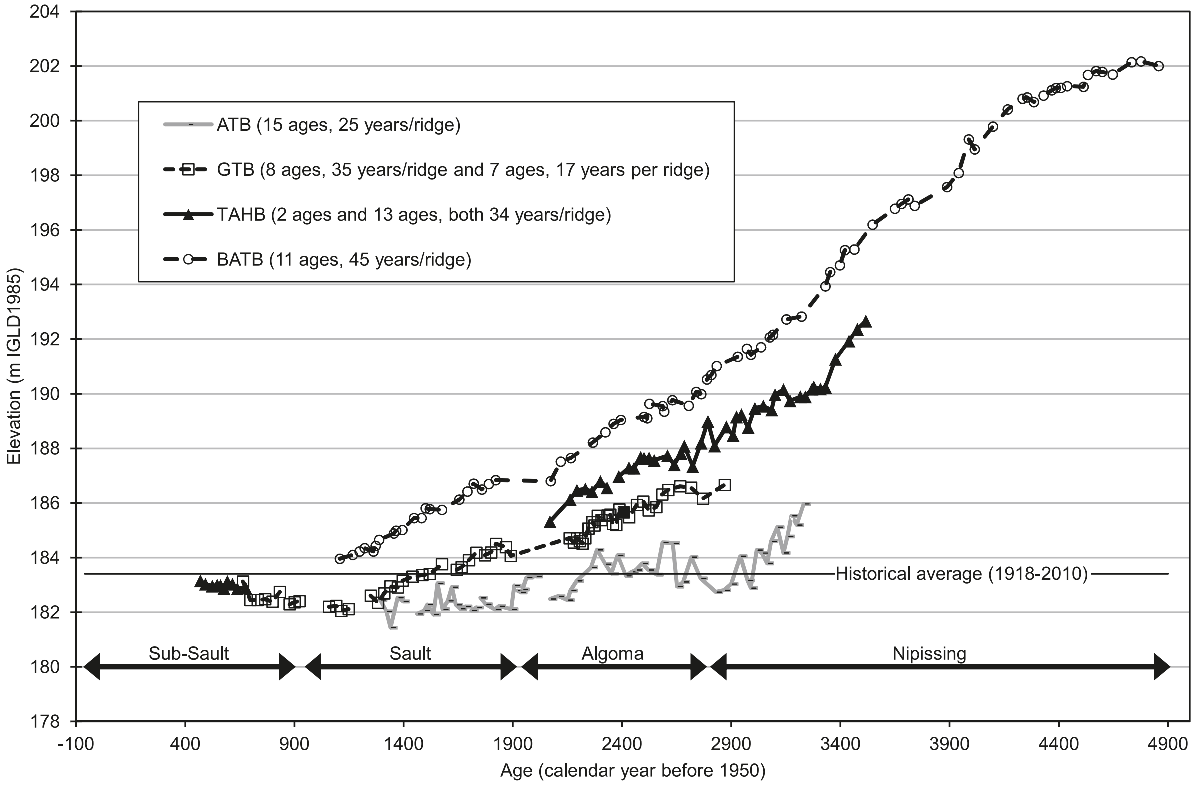


Fig. 7. Relative paleohydrographs of four different Lake Superior strandplains. Also shown is the historical average of water-level gauge data (1918–2010) for Lake Superior extended to five millennia.



studying this first because it may best represent a long-term linear trend of GIA that can be used to help determine a common intercept among paleohydrographs (Fig. 7). The Nipissing phase was analyzed after the Sault and Algoma phases and was followed by the Sub-Sault phase. Analysis of each lake phase is described later and compared with the most recent compilation of rates of GIA calculated from water-level gauge data (Mainville and Craymer 2005).

Sault phase

The Sault phase contains three relative paleohydrographs (BATB, GTB, and ATB) that are offset and subparallel owing to differences in GIA (Fig. 7). A linear function was calculated to represent the long-term trend in each data set and allow reproduction of a modeled elevation at equal intervals to be subtracted between sites. Because the age model can influence the linear model, we selected the dataset having the best age control to determine the common intercept value required to calculate GIA among sites. The GTB age model fit these criteria where *r*-squared values approach 1.0, the standard error decreases toward zero, and the *F*-statistic goes toward infinity in plots of distance from the modern shoreline versus OSL age. A linear model through 23 GTB data points in a plot of age versus elevation generates an intercept of 178.97 ± 0.21 m. This is similar to the intercept of 179.09 ± 0.31 m produced modeling 18 BATB data points in the Sault phase. General consistency between these two sites was used to assign an intercept value of 179 m (rounded down from an average of 179.03 m) for calculation of GIA among sites. The difference among modeled slopes with a fixed intercept of 179 m is 15 cm/century between BATB and GTB, 9 cm/century between GTB and ATB, and 24 cm/century between BATB and ATB. The only rate of GIA where strandplain records correspond to water-level gauge records is between BATB and GTB (Fig. 1). This supports use of 6 cm/century between the Sault outlet (bedrock sill near the head of the St. Mary's River) and BATB and –9 cm/century between the Sault outlet and GTB from approximately 2000 to 1000 cal. years BP. Rates of GIA calculated between ATB and the other two sites are at least 6 cm/century greater than estimates from water-level gauges. This value is at least double the standard error among sites when intercept values are not assigned. The discrepancy among rates of GIA inferred between ATB and the other sites may be related to errors in the ATB age model or may argue for reevaluation of contoured rates of historic GIA where relatively few water-level gauge records exist near ATB (Mainville and Craymer 2005). Analysis of GIA among study sites in other time periods may help to resolve the discrepancy of the proposed –17 cm/century instead of –12 cm/century (Mainville and Craymer 2005) between the Sault outlet and ATB from approximately 2000 to 1000 cal. years BP.

Algoma phase

The Algoma phase contains four relative paleohydrographs (BATB, TAHB, GTB, and ATB) that are offset and subparallel owing to differences in GIA (Fig. 7). Relative paleohydrographs in the Algoma phase are differentiated from those in the Sault phase by a general arcuate shape rather than a linear form (Figs. 2, 7). The arcuate pattern generally aligns among all sites except for BATB. BATB was fine-tuned to better match the other data sets by adding 200 years, approximately half of the BATB age model, 95% confidence interval during the Algoma phase. To keep consistent with the analysis of data in the Sault phase, GIA among study sites was calculated using linear models. Interestingly, a linear model through TAHB data without an assigned intercept value was 178.96 ± 0.81. This is consistent with the assignment of an intercept value of 179 m that was used to calculate rates of GIA during the Sault phase. Similar to the GTB age model in the Sault phase, the TAHB age model is the most well-constrained among study sites in the Algoma phase. During the Algoma phase, the TAHB age model contains the greatest number of ages and the narrowest confidence interval, 95%, among study sites. A consistent intercept in two different lake phases where age models are the most well-constrained among study sites supports use of 179 m between 2800 and 1000 cal. years BP (Algoma and Sault phases). Comparisons of rates of GIA after assigning an intercept of 179 m were within 3 cm/century, which is within the statistical error of the linear models. After assigning a 179 m intercept, the calculated differences of GIA among all four datasets during the Algoma phase support the findings in the Sault phase. The newly calculated rates of GIA between ATB and the other sites are almost two contours (6 cm/century) different than those calculated using water-level gauge records (Mainville and Craymer 2005), while the rate of GIA between the other three sites corresponds with gauge data. An additional strandplain record within the Algoma phase suggests that the rate of GIA between the Sault outlet and TAHB was approximately –3 cm/century.

Nipissing phase

The Nipissing phase contains three relative paleohydrographs (BATB, TAHB, and ATB) that are offset and subparallel because of differences in GIA (Fig. 7). Data were modeled using linear equations having a fixed intercept of 179 m between approximately 2800–3200 and 3200–3800 cal. years BP and 2800–3800 cal. years BP. Differences between these linear interpolations through strandplain data of BATB and TAHB were consistent with rates of GIA of about 9 cm/century from water-level gauge data (Mainville and Craymer 2005). Differences between linear equations through ATB and BATB or TAHB data from 2800 to 3200 cal. years BP support a greater rate of at least 5 cm/century for ATB (Mainville and Craymer 2005).

Sub-Sault phase

Two relative paleohydrographs were analyzed in the Sub-Sault phase to estimate a rate of GIA between TAHB and GTB (Fig. 7). Although the datasets do not overlap, a linear function was used to determine a common intercept. A linear model through 11 TAHB data points in a plot of age versus elevation generates an intercept of 183.35 ± 0.22 m. This is similar to an intercept of 183.80 ± 0.70 m produced modeling nine GTB data points. A common intercept at the historical average lake-level elevation of 183.41 m (1918–2010) produces a rate of GIA that is similar to those from water-level gauge records of 6 cm/century (Mainville and Craymer 2005). Although robust datasets are lacking within the Sub-Sault phase, a preliminary analysis supports commonality with estimates of GIA from gauge records (Mainville and Craymer 2005).

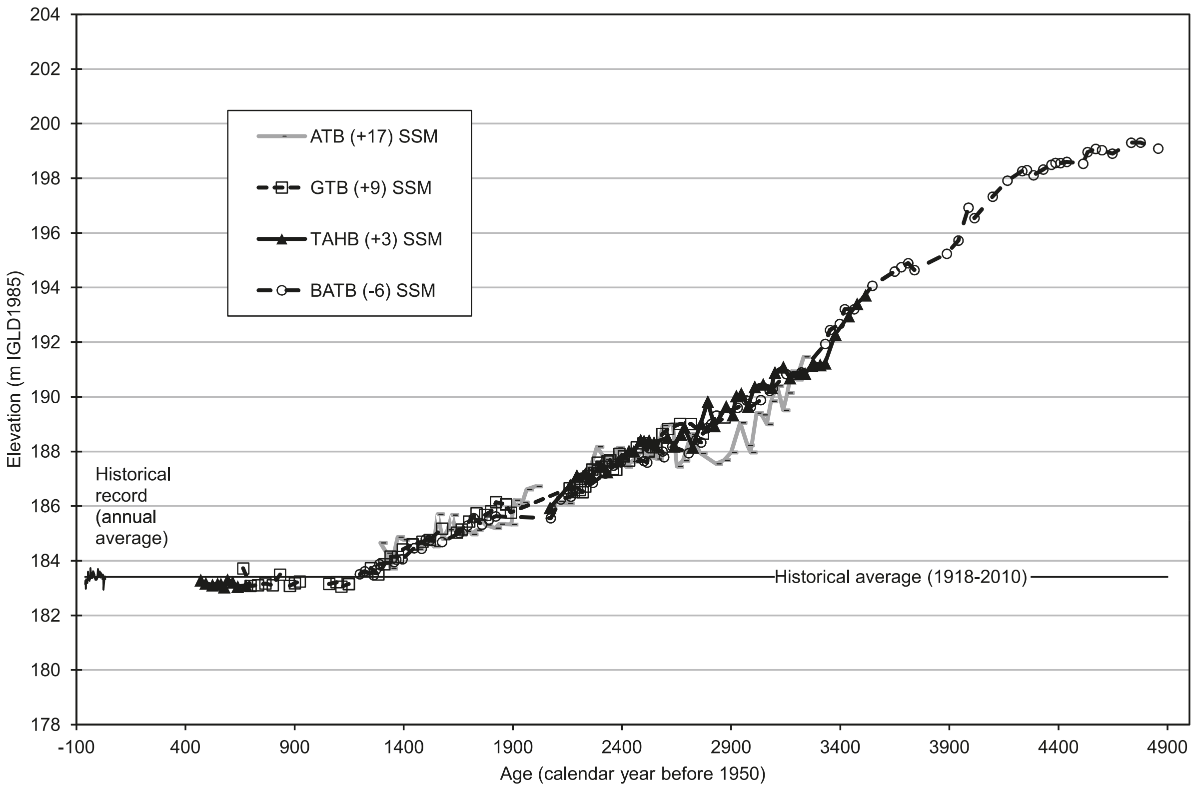
Lake Superior paleohydrograph, relative to the Sault outlet

Successful compilation of data from disparate strandplains into one paleohydrograph for Lake Superior requires accurate age and elevation data that are appropriately adjusted for GIA. Horizontal alignment is primarily constrained by numerical limitations associated with formulated age models at each site and recognition of common patterns or trends in cross-strandplain geomorphic or sedimentologic characteristics among sites (Johnston et al. 2007*b*). Vertical alignment is primarily constrained by adjustments, either positive or negative, to account for GIA at each site through time. Here, we use the calculated differences in GIA among Lake Superior strandplains and pattern of GIA (Mainville and Craymer 2005) to adjust each dataset vertically to the Sault outlet. GIA was subtracted from sites north and east of the outlet (or zero relative isobase) to account for a rising ground surface that is greater at the study site than at the outlet through time. GIA was also added to sites south and west of the outlet to account for a rising ground surface that is greater at the outlet than at the study site through time. A linear function was used to adjust the elevation of each cored beach ridge by using the rate of GIA relative to the outlet for the slope, current elevation of the subsurface basal foreshore contact as the intercept, and modeled age for the *x*-value. The resultant elevation reconstructs the water surface at each unique time period for the Sault outlet. GIA rates of –6 cm/century were used for BATB, while 3, 9, and 17 cm/century were used for TAHB, GTB, and ATB, respectively. These rates of GIA calculated among study sites correspond to rates of GIA estimated from gauge data (Mainville and Craymer 2005) at all sites except ATB. Outliers in the data were identified and removed to refine the final inferred paleohydrograph.

Refinement of the inferred paleohydrograph for Lake Superior's current outlet

General alignment of the datasets suggests that age models and GIA adjustments are sufficient except in four areas where individual datasets seem to diverge from others. These areas were investigated to refine the reconstructed paleohydrograph for the Sault outlet. Relatively high elevations were recognized in the Nipissing phase at TAHB and Sault phase at ATB, whereas relatively low elevations were recognized in the Sault phase at TAHB and BATB. Although correction of each of the divergent trends was suggested, insufficient age data or uncertainties associated with elevations preclude adoption, so these data were removed. Elevated elevations and absolute ages older than modeled ages for the eight oldest cored ridges at TAHB suggest that these ridges should be at least a century or more older and would better align with BATB (Figs. 2, 3, 7). Because the BATB and TAHB datasets aligned well between 2000 and 3500 cal. years BP, the current age model was kept and the eight oldest data points were removed. Nine TAHB cored ridges were omitted from the Sault phase because elevations were abnormally low and over-steepened compared to the other three sites. Even after additional age controls were collected and elevations recollected and verified from field data, it remains unclear as to why this occurs, so this divergent trend was removed and requires further investigation. At BATB, a relatively low elevation and large discrepancy between modeled ages and one absolute age in the youngest part

Fig. 8. A Sault-referenced paleohydrograph compiled from age and elevation data from individual beach ridges at four study sites along Lake Superior. Also shown is the historical water-level record (annual average) for Lake Superior and 92 year historical average extended to five millennia.



of the BATB strandplain suggests that the lakeward set of beach ridges should be in the modern phase of Lake Superior (Figs. 2, 6, 7). An alternative age model for the lakeward set of beach ridges was explored by using the one lakeward age and slope of the landward age model. Because this produced a much greater divergence from the Sault paleohydrograph, these data were removed and must be investigated further. At ATB, 14 of the youngest cored ridges were omitted because of abnormally high elevations and the apparent over-steepening that was noted earlier (Figs. 2, 5, 7).

In summary, 40 of the 321 data points or 12% of the data were removed to create the most robust and consistent paleohydrograph from four Lake Superior strandplains to date. Seventeen data points were removed from TAHB, 14 from ATB, and nine from BATB. Although this included removal of data in all lake phases except the Algoma, these data were mostly near the youngest or oldest part of the strandplain records. Many of these discrepancies may be related to insufficient age and elevation data required to recognize patterns of change. Despite these discrepancies, a large and robust data set (Fig. 7) was used to create an inferred paleohydrograph for Lake Superior's current outlet (Fig. 8) constructed from four strandplains within the lake basin.

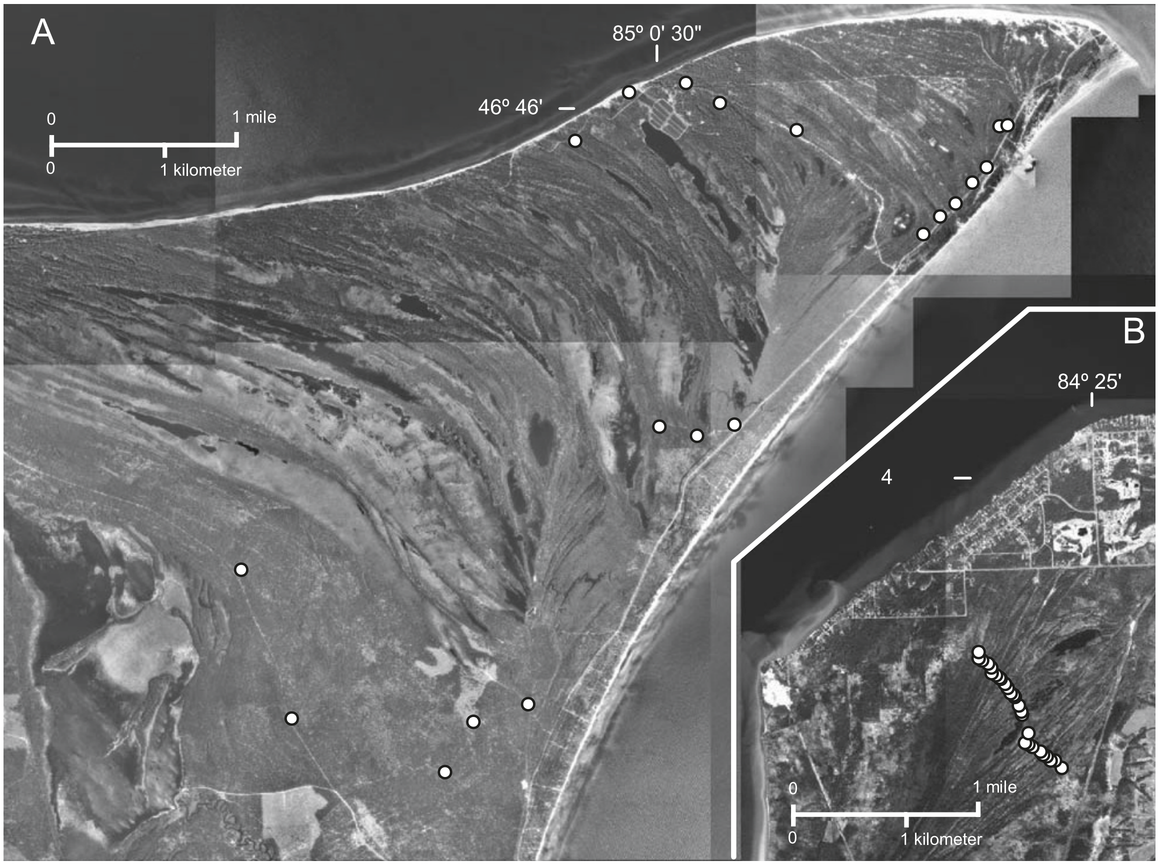
Validation of the inferred paleohydrograph for Lake Superior's current outlet

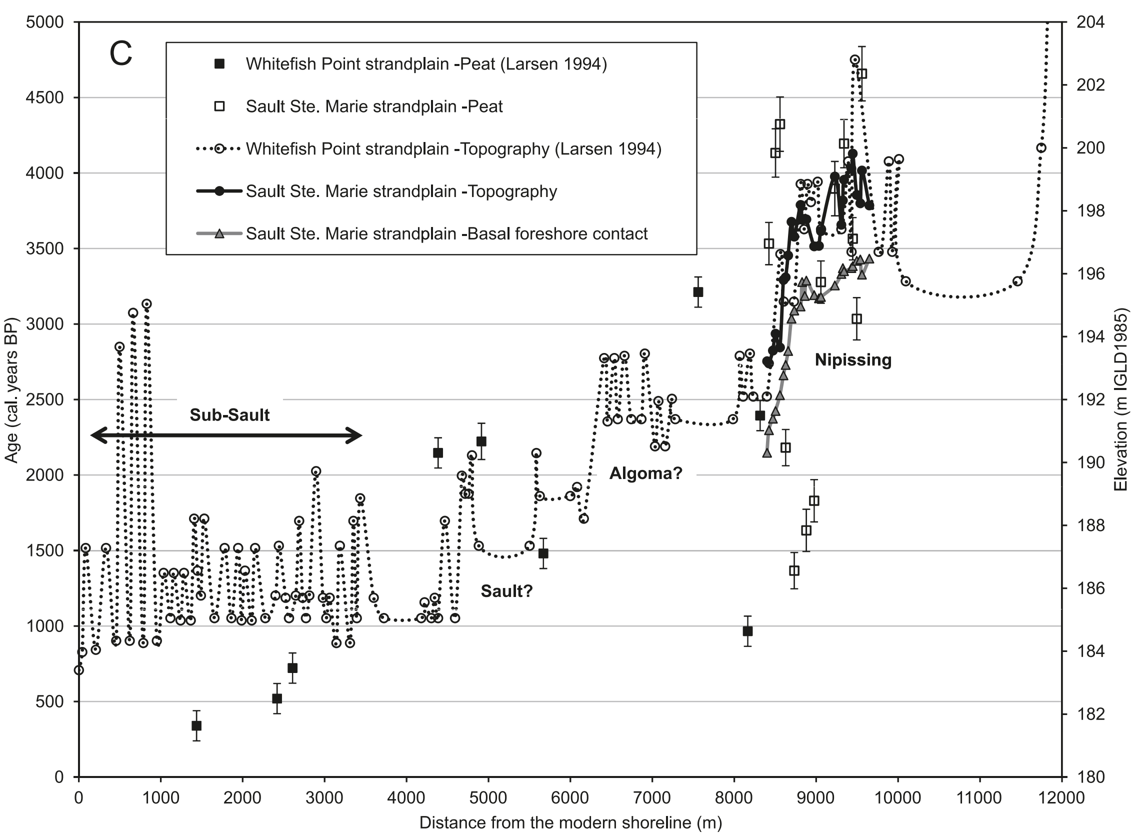
The resultant paleohydrograph reconstructed from four spatially disconnected strandplains shows a common trend that represents water level at the outlet over the past 4900 years (Fig. 8). These data indicate that the Sault outlet experienced a long-term relative lake-level fall of approximately 16 m in 3900 years, followed by a relatively stable lake level during the last millennium. Verification of this inferred paleohydrograph for the Sault outlet requires comparison with data near the outlet. Spatially distant data may also be used for validation, but the best data for comparison would be from a site that experienced a similar rate of GIA through time and shared a common water surface within one basin.

Cowan's (1985) detailed land surveys on shorelines at Sault Ste. Marie, Ontario, identified a well-developed Nipissing beach at 198 m. Correspondence with elevations in the oldest part of the paleohydrograph substantiates a rate of GIA approximately 6 cm/century between BATB and the Sault outlet. A similar rate calculated from gauge data (Mainville and Craymer 2005) suggests a consistent rate of GIA from the present to 5 ka along the eastern shore of Lake Superior. The only other elevation Cowan (1985) mentioned that was lower than the Nipissing beach was 183 m, the modern water-level surface. The youngest part of the inferred Sault paleohydrograph seems to follow a consistent trend close to this value but will be discussed in detail later after comparison with updated historical records.

Data from two additional strandplains were compared with the Sault paleohydrograph, one previously published by Larsen (1994) from WFP and another new record near Sault Ste. Marie, Michigan (SSM) (Fig. 9). Contoured rates of GIA (Mainville and Craymer 2005) suggest that both sites have

Fig. 9. Air photograph and core locations of a study site at (A) Whitefish Point (WFP) from Larsen (1994) and (B) Sault Ste. Marie (SSM), Michigan. (C) Graph of elevation and age data from WFP (Larsen 1994) and SSM. To align WFP and SSM, 8400 m was added to the SSM data.





experienced a rate of GIA similar to the ground surface at the Sault outlet. Consequently, the sites should contain basal foreshore elevations similar to the inferred paleohydrograph constructed here. However, both study sites are difficult to interpret owing to age variability produced from dated peat (Table 2; Fig. 9C) and inconsistencies from different elevation measurement methods. Thompson (1992) calculated a linear trend through the data, while Larsen (1994) estimated a linear trend bounding the upper limit of the data to derive individual ages for beach ridges. Thompson (1992) collected basal foreshore elevations, while Larsen (1994) compiled ground-surface elevations from topographic maps and collected a few upper foreshore elevations within beach ridges to infer past water-level elevations. Here, we reevaluate the data of Larsen (1994) at WFP with the help of newly collected data at SSM to validate the inferred paleohydrograph for Lake Superior's current outlet.

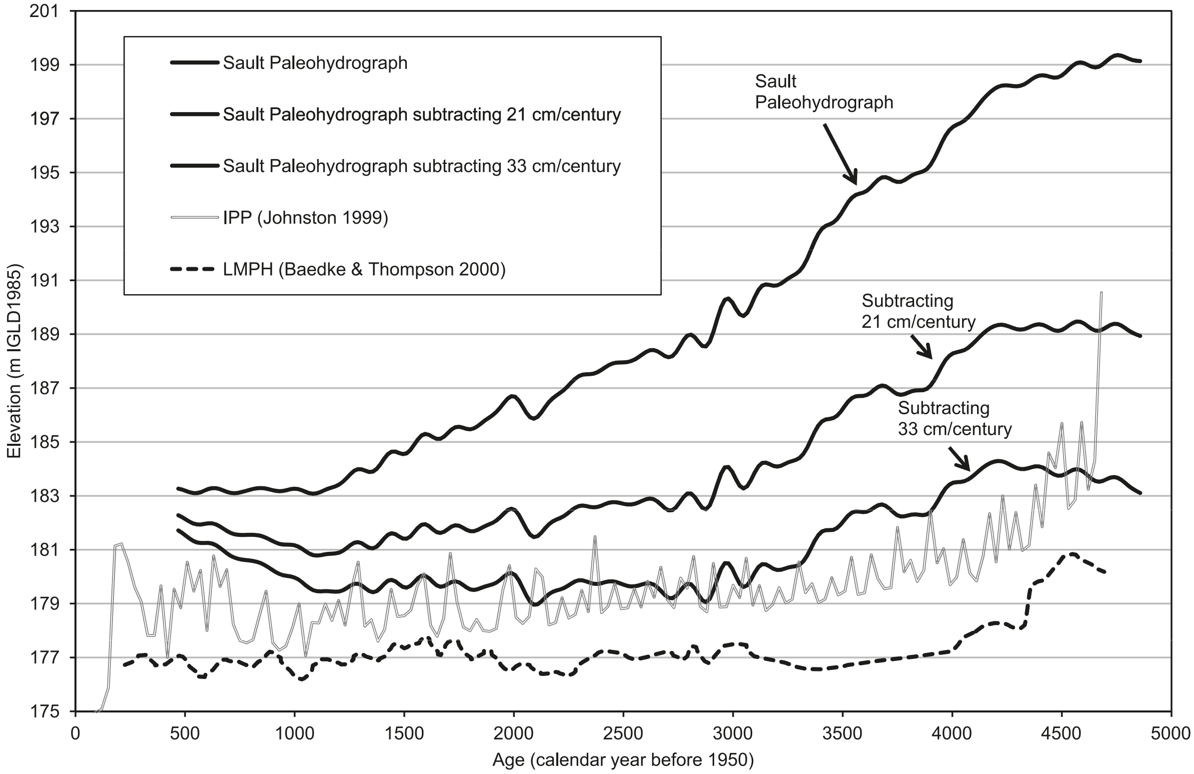
Published data of upper foreshore deposits at WFP (Larsen 1994) show a long-term relative lake-level fall followed by a relatively stable lake level up to the present. This overall pattern is similar to the pattern identified by Johnston et al. (2007*b*) and our paleohydrograph, but varies in timing by about one millennium. Argyilan et al. (2005), comparing OSL ages from beach ridge sand to 14C ages on swale organics, showed a nearly 1:1 correspondence between 14C ages and OSL ages for ridge ages younger than 2000 cal. years BP, but for ridges older than 2000 cal. years BP, the correspondence is less significant. At WFP, a cross-strandplain change in topography and increased variability between 14C ages at about 4 km distance landward from the modern shoreline substantiates this observation, questioning the reliability of the ages assigned to individual beach ridges older than 2000 cal. years BP (Fig. 9C). Further investigation of Larsen's (1994) age data at WFP suggested the creation of two age models separated at about 4 km distance from the modern shoreline. A linear trend through the youngest three calibrated ages established a relatively stable lake level during the last millennium. Although formulating an age model using the remaining five 14C ages at WFP is problematic because of scattering among ages, a linear trend through all five data points, following the approach of Thompson (1992), produced a relative paleohydrograph that extends from about 3400 to 1900 cal. years BP. Following the approach of Larsen (1994), bounding the upper limit of 14C ages with a linear trend produced a relative paleohydrograph that extends from about 4500 to 1800 cal. years BP. However, Larsen assigned an age of 5300 cal. years BP, calculated from an average of seven radiocarbon ages in the Lake Michigan basin to one of the oldest landforms surveyed at WFP, which extended the age of the peak Nipissing phase roughly 800 years older. Regardless of the age model approach of Thompson (1992) or Larsen (1994), the two new age models suggest a hiatus of about one millennium where beach ridges were created and then destroyed or not created at all during the Sault phase. An age of about 2000 cal. years BP corresponds to Larsen's (1994) reported age at the cross-strandplain change in topography (4 km distance from the modern shoreline), but the separate age model of the three youngest 14C ages suggests a millennium of preserved sediment deposited during the Sub-Sault phase followed a hiatus during the Sault phase. Topographic elevations in the Sub-Sault phase are at least 2 m above the inferred paleohydrograph elevations but seem to correspond to the sporadic and variable subsurface elevations collected by Larsen (1994) in cores and the general relationship between topographic and basal foreshore elevations found at SSM (Figs. 8, 9C). Difficulty comparing Nipissing phase elevations between WFP and the inferred paleohydrograph stems from inadequate age and elevation control. SSM was studied to improve this and help validate the inferred paleohydrograph.

Some elevations and ages collected at WFP and SSM compare (Fig. 9C). Remarkably, topographic elevations are similar, while basal foreshore elevations in the SSM strandplain compare with inferred Sault paleohydrograph elevations between approximately 3000 and 4000 cal. years BP (Figs. 8, 9C). More than a three-millennia spread in 14C ages across the SSM spit corresponds to Argyilan et al. (2005) and questions the reliability of using basal organics in swales to provide true ages for the ridges at this site. Despite the scatter in 14C ages at SSM, comparison of elevations between WFP, SSM (Fig. 9C), and the Sault paleohydrograph (Fig. 8) better supports the age model approach of Thompson (1992) than Larsen (1994) and differs from ages reported in Larsen (1994). Applying the general relationship found at SSM by subtracting about 2 m from topographic elevations to determine basal foreshore elevations or past lake-level elevations at WFP produces similar elevations of the Sault paleohydrograph during the last four millennia. Although data at WFP appear to extend to the recent, these data were not used for paleohydrograph reconstruction because of uncertainties related to elevations and 14C ages.

Interpretation of the Sault paleohydrograph

The general long-term tendency of the Sault paleohydrograph is a decreasing trend lasting about 4000 years followed by a relatively horizontal trend during the last millennium (Fig. 8). These trends are more apparent after data sets of all four sites (TAHB, GTB, ATB, BATB) were combined (Fig. 8) and a 20% Fourier smoothing was applied (cf. Baedke and Thompson 2000) (Fig. 10). The horizontal trend is expected when the outlet is controlling water levels in the basin, whereas deviations from this trend may be associated with an alternative outlet or modifications of the outlet (i.e., erosion or sedimentation) or climate (i.e., water gain or loss to the basin). Little change in water level for the youngest part of the Sault paleohydrograph indicates that the Sault outlet exclusively controlled water levels within the Lake Superior basin for at least the past millennium. A linear function through both GTB and TAHB data between 1000 and 500 cal. years BP (Sault phase) produced a slope close to zero (–0.000 085 9 m/year) and an intercept of 183.21 ± 0.10 m. Although this intercept value is within the range of annual water levels for Lake Superior from 1918 to 2010 (183.73–182.94 m), it is lower than the annual average (183.41 m) and very close to the current chart datum of 183.20 m for Lake Superior (available from http://www.waterlevels.gc.ca/C&A/historical_e.html; Fig. 8). Increasing the intercept of the linear regression through GTB and TAHB data to the last multidecadal high lake-level stage, following the procedure of Baedke and Thompson (2000), indicates that water levels were relatively low approximately 1000–500 cal. years BP but were within the range of historical variability. This means that the relatively rare low lake levels experienced during historical times

Fig. 10. Smoothed paleohydrograph of Lake Superior with 21 and 33 cm/century GIA removed to reconstruct an outlet paleohydrograph south of the Sault. Inferred paleohydrographs for the Port Huron – Sarnia outlet derived by compiling data from five strandplains along Lake Michigan (LMPH; Baedke and Thompson 2000) and data adjusted from the Ipperwash (IPP) strandplain in southern Lake Huron (Johnston 1999). Adjustments include assigning an age of 30 years per ridge and subtracting 2 m from topographic elevations collected across the IPP strandplain.



(five percent of the record below the low-water datum) were more common after the final separation of Lake Superior from Lakes Michigan and Huron. However, accounting for the fact that subsurface elevations recorded within beach ridges preserve multidecadal highstands in lake level (Thompson and Baedke 1995; Johnston et al. 2007*a*), average lake levels between 1000 and 500 cal. year BP were about 183 m, assuming the regulated and natural range compare. This elevation is similar to the two lowest lake levels recorded by Lake Superior water-level gauges in 1926 and 2007 and is 41 cm lower than the historical average. Although a decrease in lake level of this magnitude seems relatively small, the volume of water is large, as Lake Superior has the third largest surface volume of any freshwater lake in the world and the largest surface area. A surface area of about 82 000 km^2 and a water loss of about 0.41 m is equivalent to 33.62 km^3 of water. A very large surface area and a relatively stable bedrock sill at the outlet of Lake Superior may suggest that climate has been the driving mechanism of water-level variation for at least the last millennium. Drought-induced modes over North America, and specifically the Great Lakes region, that lasted several decades to centuries during the Medieval Climate Anomaly and transition into the Little Ice Age described by Booth et al. (2006) and Woodhouse et al. (2010) may be related to the relatively low lake levels described for Lake Superior from 1000 to 500 cal. years BP. Minimal variation about this relatively low lake level may be related to a stable bedrock sill at the outlet for Lake Superior during the last millennium and preferential preservation of multidecadal highstands of lake level in beach ridges. Closer examination of OSL age data in this paper along with geomorphic and sedimentologic data of Johnston et al. (2007*b*) from GTB suggests that the start of this time period was approximately 1060 ± 100 cal. years BP. This is the youngest published age for the final separation of Lake Superior from Lakes Michigan and Huron and establishes the modern phase of Lake Superior back to 1060 cal years BP.

A general long-term decreasing trend in the Sault paleohydrograph from ca. 5000 to 1000 cal. years BP could be attributed to an outlet other than the Sault, erosion of the Sault outlet, or water-level loss in the basin related to climate (Figs. 8, 10). The slope and intercept of the Sault paleohydrograph within individual lake phases provides insight for resolving this question. A linear function through data from 2800 to 2000 cal. years BP produced a slope of about 33.5 ± 2.4 cm/century and intercept of 179.54 ± 0.59 m, while the data from 2000 to 1000 cal. years BP produced a slope of about 33.8 ± 1.3 cm/century and intercept of 179.55 ± 0.21 m. The common slope among phases is similar to the rate of GIA between the Sault and Chicago outlets calculated from gauge data (Mainville and Craymer 2005). This suggests that the Chicago outlet was the active outlet that helped regulate water levels in the Lake Superior basin during the Algoma and Sault phases. Removing 33 cm/century of GIA from the Sault paleohydrograph creates a near-horizontal trend centered about 179.55 m during the Algoma and Sault phases (Fig. 10). Although the intercept compares to the current elevation of the bedrock sill reported by Hansel et al. (1985) of 180 m at the Chicago outlet, beach ridges record multidecadal highstands in lake level (Thompson and Baedke 1995; Johnston et al. 2007*a*), suggesting a lower present-day elevation for the active outlet during the Algoma and Sault phases. A difference of about 4 m between the current elevation of the bedrock sill at the Sault outlet (179.30 m; Scott Rose USACE, personal communication 2011) and the historical average of Lake Superior water levels since 1918 suggests a lower outlet elevation than the Chicago sill and more similar to the unconsolidated base of the outlet at Port Huron – Sarnia. However, the result of removing either 21 cm/century suggested by gauge data or 33 cm/century suggested by the ICE-3G global postglacial rebound model from the Sault paleohydrograph is higher than the inferred levels of Baedke and Thompson (2000) for the Port Huron – Sarnia outlet (Fig. 10). Removing an additional 17 from 21 cm/century or 5 from 33 cm/century or total of 38 cm/century from the Sault paleohydrograph would better match reconstructed Nipissing levels of Baedke and Thompson (2000) and Thompson et al. (2011). However, post-Nipissing topographic elevations derived by Johnston (1999) from the closest strandplain (Ipperwash) to the Port Huron – Sarnia outlet are elevated above the paleohydrograph created by Baedke and Thompson (2000) from five sites in Lake Michigan. Accounting for an average foreshore thickness of about 2 m, extrapolated from core data of Johnston (1999), and a similar relationship derived at SSM and an assumed average rate of ridge formation of 30 years per ridge, the relative paleohydrograph derived from Ipperwash (IPP) seems to better match the Sault paleohydrograph after 33 cm/century of GIA was removed (Fig. 10). This suggests either that Baedke and Thompson (2000) removed too much GIA from their five respective relative paleohydrographs or that IPP has experienced more than zero relative movement with respect to the Port Huron – Sarnia outlet; however, these data are not supported by Mainville and Craymer (2005). To resolve this, subsurface elevations and ages within ridges must be collected from the IPP strandplain or a similar strandplain near the Port Huron – Sarnia outlet.

Conclusions

Lake levels on timescales of decades to millennia that are recorded within beach ridge strandplains are mainly influenced by three key factors: GIA, outlet modification, and climate. GIA influences the ground surface at the outlet for Lake Superior, altering the elevation of the water plane within the basin over time and the elevation of the shorelines. Each study site has experienced a unique rate of GIA that can be calculated between sites, but more importantly, also relative to the lake's outlet because the outlet helps regulate water within the basin through time. Studying the common trend that emerges among study sites after properly accounting for GIA allows one to investigate outlet modification and climate. Outlet modification may include a change in the location of the outlet or a change in the channel dimension through erosion or sedimentation. Although deviations from a horizontal trend in the outlet paleohydrograph may represent either of these, records from other lake basins and other possible outlets are required to resolve this. Difficulty matching paleohydrographs produced from data in Lake Superior (presented here) to data in Lake Huron (Johnston 1999) and Lake Michigan (Baedke and Thompson 2000) may stem from a lack of subsurface elevations and ages at IPP and different types of age data used in Lake Michigan (14C) and Lake Superior (OSL). Collection of OSL age data from Michigan basin strandplains may improve these efforts, but data within the Huron basin are needed, especially near the Port Huron – Sarnia outlet. Collecting subsurface elevation and age data near the outlet would best mimic what was experienced at the outlet through time; this is required to provide context for all other paleohydrographs. Because IPP contains the greatest number of beach ridges and hence the longest record near the Port Huron – Sarnia outlet, an extension of Johnston (1999) must be pursued to collect more subsurface information from ridges, especially samples for OSL age-dating and cores for basal foreshore elevation analysis. Sites closer to the outlet may help complete part of the record not found at IPP or may help to validate the IPP record.

The Lake Superior paleohydrograph presented in this paper represents the first detailed lake-level record relative to the current outlet near Sault Ste. Marie and the youngest age for the separation of Lake Superior from Lakes Michigan and Huron (1060 ± 100 cal. years BP). Paleohydrograph reconstruction in this paper provides better resolution than previous attempts in the number of individual ages and elevations, precision of elevations representing lake level and ages representing each ridge's age, and compilation efforts between multiple sites. Unique compilation efforts in this study involved linearly interpolating data within defined millennial lake phase to explore for common intercepts required to calculate GIA between sites of unequal data intervals. Attempts were not made to assign a modern-day intercept value for the data before relative paleohydrographs were adjusted for GIA, as in Baedke and Thompson (2000), but were determined by extrapolating trends from each Lake Superior data set to the present. Two modern-day elevations derived from sets of ancient shorelines are critical for interpreting the active outlet and relationship between the water plane and ground surface at the outlet during different lake stages. A modern-day elevation of about 179.5 m is important in interpreting Lake Superior's history from 3 to 1 ka. Similar modern-day elevations of the bedrock sills near Sault Ste. Marie and Chicago seem to suggest that these outlets were important from 3 to 1 ka. However, a modern-day elevation derived from data (within the last millennium that best corresponds with the low-water datum for Lake Superior, and not the Sault sill elevation) suggests an alternative outlet of lower elevation, such as the one at Port Huron – Sarnia, was important from 3 to 1 ka. This cannot be resolved here and must be investigated using data adjacent to Lake Huron, near the Port Huron – Sarnia outlet. The similar linearity in the data from 2 to 1 ka and within the last millennium seems to suggest a stable outlet and also needs further investigation. This compilation is one critical step in deciphering the role of GIA, outlet modification, and climate on lake levels of the Upper Great Lakes from decades to millennia during present regulation reviews by the International Joint Commission. This study of ancient shorelines supports calculated rates of GIA derived from water-level gauge data of Mainville and Craymer (2005) within the Lake Superior basin and establishes the Sault outlet as the active outlet for the past millennium. Evaluation of data older than a millennium and extrapolation to other basins requires data from the Lake Huron basin, especially near the Port Huron – Sarnia outlet.

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