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Optically stimulated luminescence dating of late Holocene raised strandplain sequences adjacent to Lakes Michigan and Superior, Upper Peninsula, Michigan, USA

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Abstract

This study evaluates the accuracy of optically stimulated luminescence to date well-preserved strandline sequences at Manistique/Thompson bay (Lake Michigan), and Tahquamenon and Grand Traverse Bays (Lake Superior) that span the past ~4500 yr. The single aliquot regeneration (SAR) method is applied to produce absolute ages for littoral and eolian sediments. SAR ages are compared against AMS and conventional ^{14}C ages on swale organics. Modern littoral and eolian sediments yield SAR ages <100 yr indicating near, if not complete, solar resetting of luminescence prior to deposition. Beach ridges that yield SAR ages <2000 yr show general agreement with corresponding ^{14}C ages on swale organics. Significant variability in ^{14}C ages >2000 cal yr B.P. complicates comparison to SAR ages at all sites. However, a SAR age of 4280 ± 390 yr (UIC913) on ridge77 at Tahquamenon Bay is consistent with regional regression from the high lake level of the Nipissing II phase ca. 4500 cal yr B.P. SAR ages indicate a decrease in ridge formation rate after ~1500 yr ago, likely reflecting separation of Lake Superior from lakes Huron and Michigan. This study shows that SAR is a credible alternative to ^{14}C methods for dating littoral and eolian landforms in Great Lakes and other coastal strandplains where ^{14}C methods prove problematic.

Keywords: Optically stimulated luminescence; Littoral sediments; Great Lakes water levels; Radiocarbon; Beach ridges

Introduction

Strandplains that commonly occur in coastal embayments of the Laurentian Great Lakes are comprised of beach ridges, sandy depositional features consisting of waterlain nearshore deposits commonly capped by eolian sediments (Thompson, 1992; Thompson and Baedke, 1997). The combination of regional glacioisostatic uplift, rapid lake-level fluctuations, and abundant sediment supply trapped in coastal embayments results in a prograding shoreline with progressive abandonment of beach ridges, creating chronosequences of beach ridges and associated landforms (Olson, 1958; Thompson, 1992; Thompson and Baedke, 1997). Strandplain deposition in the upper Great Lakes reflects a long-term regression from the Nipissing II phases about 4500 yr ago, when lake level was ~4.1 m higher than the historical average (Baedke and Thompson, 2000). Chronologic control on beach-ridge formation coupled with sedimentological data from cores is critical to quantify rates and magnitudes of water-level fluctuations and to partition the effects of glacioisostasy, variations in sediment supply, and climate on late Holocene lake-level variability.

Previously, the lake-level history of Lake Michigan during the past ~4700 yr was reconstructed from the ages and elevations of beach ridges in five strandplain

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sequences (Baedke and Thompson, 2000; Thompson and Baedke, 1997). Strandplains preserve a record of fluctuations in Great Lakes water levels, preferentially reflecting highstands. Paleo-water level is determined from the elevation of basal foreshore sediments in individual beach ridges sampled through vibracoring (Thompson, 1992). Given the historical range of water-level fluctuation in the Great Lakes, the foreshore facies is typically within 0.3 m of the corresponding lake level, providing a sensitive metric to reconstruct water-level changes (Thompson and Baedke, 1997). Thompson and Baedke (1997) created age models to determine the average timing of beach-ridge formation at sites in Lake Michigan by regressing calendar-corrected conventional ^{14}C ages on bulk basal peat from inter-ridge swales against ridge number from the modern shoreline. Data from lakes Michigan and Superior suggest the presence of quasi-periodic, climate-driven fluctuations of ~30 and ~150 yr (Baedke and Thompson, 2000; Johnston, 2004; Johnston et al., 2000, 2004; Thompson and Baedke, 1997).

Age control for Great Lakes strandplains has principally relied on ^{14}C dating of peats from wetlands that commonly form in swales between beach ridges. Formation of a lakeward beach ridge effectively impounds or restricts drainage, providing favorable conditions for the establishment of hydrophilic plants and organic matter accumulation. Ideally, basal peat can provide a close minimum limiting age for beach-ridge formation in embayments that support groundwater focusing (Thompson and Baedke, 1997). However, some strandplains adjacent to Lake Michigan show an unclear relation between the age of basal peats and ridge distance from the present shoreline (e.g., Larsen, 1994). Radiocarbon ages often cluster, indicating peat formation at a particular interval after strandplain development, likely reflecting changes in local hydrology (Larsen, 1994). In turn, there is the potential for organics of various ages to accumulate within swales through multiple washover events (Lichter, 1995). Consequently, uncertainty remains on the timing between beach-ridge establishment and the accumulation of organic matter in swales or wetland environments (Lichter, 1997).

Questions surrounding ^{14}C dating of coastal strandplains, and a general lack of organic matter in many coastal embayments, illustrate a need for an alternate geochronometer, like optically stimulated luminescence (OSL), to determine ages of individual beach ridges in strandplains. OSL is an advantageous approach because it provides discrete, absolute ages for quartz sand grains from littoral and eolian depositional sequences. In the past decade, there have been significant advances in OSL dating, particularly with the advent of single-aliquot regeneration (SAR) approaches (Duller, 1996; Murray and Wintle, 2000, 2003). Recent studies indicate that this analytical approach can provide accurate ages for middle Holocene dunes in the Upper Peninsula of Michigan (Arbogast et al., 2002). SAR dating of littoral and eolian sediments in other coastal environments has yielded ages in agreement with ^{14}C control spanning the past 5000 yr (e.g., Bailey et al., 2001; Murray-Wallace et al., 2002; Wilson et al., 2001).

This study is designed to assess the accuracy and precision of using SAR procedures to date strandplain landforms adjacent to Lakes Superior and Michigan. SAR is used to date modern and paleo-littoral and eolian sediments in a well-preserved standplain sequence adjacent to Lake Michigan at Manistique–Thompson bay, and two strandplains along the southern shore of Lake Superior at Grand Traverse and Tahquamenon bays (Fig. 1). SAR ages on quartz-grain separates from paleo-littoral sediments are evaluated against conventional and AMS ^{14}C ages on swale organic matter at each site (Johnston, 2004; Johnston et al., 2000, 2004; Thompson and Baedke, 1997). The accuracy and precision of SAR and ^{14}C dating results are evaluated and the potential implications for generating strandplain age-models are evaluated. This study gives insight on the suitability of SAR-OSL to date late Holocene strandplains adjacent to large lakes or oceans and ultimately to refine and resolve water-level history.

Radiocarbon dating

Radiocarbon chronologic control is provided by accelerator mass spectrometry (AMS) dating of plant macrofossils or charcoal, and by conventional dating of bulk peat samples collected at or near the basal littoral-sand to peat contact in areas of maximum accumulation in swales (Table 1). Organic samples are collected as close as possible to transects established for sediment cores from

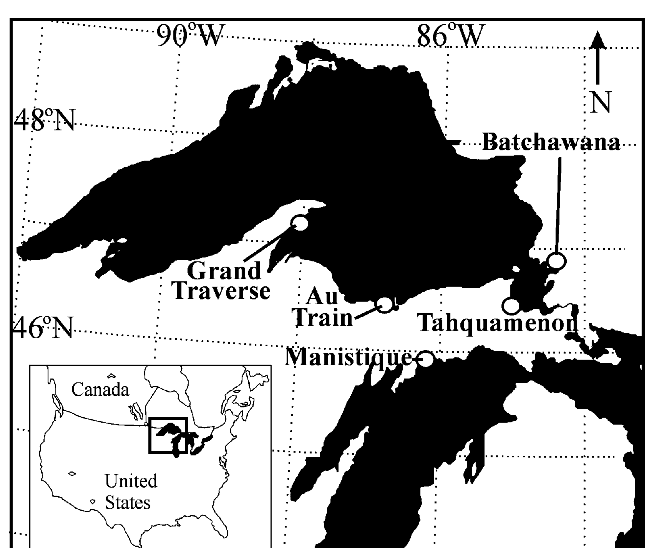

Figure 1. Map of Lake Superior and Lake Michigan study sites.

Table 1
Radiocarbon ages and data for organic material collected from swales in strandplains at Grand Traverse Bay, MI and Tahquamenon Bay, MI, USA adjacent to Lake Superior

Ridge number	Distance landward (m)	Material dated	Laboratory reported ^{14}C Age, ^{14}C yr B.P.	Calendar-corrected age range, cal yr B.P.	Laboratory number	Corresponding SAR age yr (lab; ridge number)
Manistique/Thompson Bay, MI						
8	288	peat	1248 ± 65	1242–1043	GX-18153	
10	432	peat	1633 ± 65	1583–1443	GX-18154	
11	488	peat	1313 ± 65	1323–1123	GX-18155	1320 ± 120 (UIC1154; 13)
19	765	peat	1883 ± 65	1883–1683	GX-18157	
21	831	peat	1678 ± 115	1743–1403	GX-18158	
24	931	peat	2718 ± 125	2923–2773	GX-18159	2060 ± 220 (UIC1155; 25)
25	975	peat	2648 ± 70	2813–2773	GX-18160	2060 ± 220 (UIC1155; 25); 1520 ± 180 (UIC1156; 28)
31	1252	peat	3318 ± 70	3623–3443	GX-18161	2060 ± 220 (UIC1155; 25); 1520 ± 180 (UIC1156; 28)
32	1297	peat	3313 ± 130	3683–3403	GX-18162	2060 ± 220 (UIC1155; 25); 1520 ± 180 (UIC1156; 28)
33	1330	peat	2988 ± 130	3373–2923	GX-18163	2110 ± 210 (UIC1024; 32)
35	1463	peat	3013 ± 70	3273–3043	GX-18164	
36	1518	peat	2938 ± 70	3163–2933	GX-18165	
37	1563	peat	3253 ± 70	3523–3413	GX-18166	
38	1629	peat	3033 ± 70	3313–3063	GX-18167	
39	1663	peat	3238 ± 130	3603–3313	GX-18168	
41	1740	peat	3547 ± 70	3893–3693	GX-18169	
44	1873	peat	3443 ± 70	3753–3543	GX-18170	
47	2028	peat	3338 ± 70	3633–3463	GX-18171	
54	2302	peat	3183 ± 90	3513–3273	GX-19335	
55	2328	peat	3243 ± 85	3523–3393	GX-19336	
56	2359	peat	1693 ± 80	1663–1465	GX-19337	3550 ± 360 (UIC1027; 57)
57	2385	peat	3837 ± 110	4403–4033	GX-19338	3550 ± 360 (UIC1027; 57)
58	2400	peat	4117 ± 165	4853–4203	GX-19339	3550 ± 360 (UIC1027; 57)
63	2488	peat	2247 ± 145	2403–2043	GX-19340	
65	2516	peat	4043 ± 90	4593–4363	GX-19341	
78	2666	peat	3828 ± 90	4323–4043	GX-19342	
81	2726	peat	4513 ± 175	5373–4893	GX-19343	
84	2788	peat	3193 ± 145	3523–3223	GX-19344	3070 ± 290 (UIC1028; 86)
86	2837	peat	2088 ± 160	2333–1863	GX-19345	3070 ± 290 (UIC1028; 86)
Grand Traverse Bay, MI						
8	236	peat	1343 ± 70	1342–1224	GX-25929	790 ± 80 (UIC923; 7)
9	259	peat	1328 ± 75	1340–1143	GX-25930	
10	283	peat	1493 ± 75	1460–1342	GX-25931	1020 ± 100 (UIC924; 12)
17	440	peat	1113 ± 75	1108–979	GX-25932	
18	463	peat	1463 ± 70	1403–1335	GX-25933	
19	479	peat	1193 ± 60	1221–1021	GX-25934	1140 ± 110 (UIC925; 19)
19	479	Needles: *Picea; Larix laricina*	1523 ± 40	1460–1362	NSRL-10865	1140 ± 110 (UIC925; 19)
20	502	peat	1403 ± 75	1362–1237	GX-25935	
24	616	peat	1653 ± 70	1607–1463	GX-25936	
24	616	Needles*: Picea*	1433 ± 55	1379–1322	NSRL-10864	
26	659	peat	1863 ± 120	1929–1620	GX-25937	1590 ± 140 (UIC960A; 27); 1520 ± 240 (UIC960B; 27)
29	738	peat	1493 ± 70	1459–1343	GX-25938	1590 ± 140 (UIC960A; 27); 1520 ± 240 (UIC960B; 27)
31	801	peat	1953 ± 120	2041–1760	GX-25939	
36	911	peat	1893 ± 75	1923–1686	GX-25940	1690 ± 170 (UIC961; 35)
36	911	charcoal	2053 ± 40	2045–1949	NSRL-10533	1690 ± 170 (UIC961; 35)
40	973	peat	1663 ± 120	1742–1405	GX-25941	1830 ± 160 (UIC929; 41)
42	1021	Needles: *Picea; L. laricina*	463 ± 55	566–390	NSRL-10534	1830 ± 160 (UIC929; 41)
42	1021	Needles: *Picea; Pinus strobus; L. laricina*	673 ± 35	704–586	NSRL-1103	1830 ± 160 (UIC929; 41)
43	1052	charcoal	3113 ± 75	3404–3137	NSRL-10644	1830 ± 160 (UIC929; 41)

Table 1 (*continued*)

Ridge number	Distance landward (m)	Material dated	Laboratory reported ^{14}C Age, ^{14}C yr B.P.	Calendar-corrected age range, cal yr B.P.	Laboratory number	Corresponding SAR age yr (lab; ridge number)
Grand Traverse Bay, MI						
43	1052	peat	3223 ± 80	3522–3325	GX-25942	1830 ± 160 (UIC929; 41)
44	1083	Needles: *Pinus banksiana; Picea; L. laricina*	1413 ± 35	1350–1320	NSRL-10537	1830 ± 160 (UIC929; 41)
45	1083	charcoal	1843 ± 40	1859–1682	NSRL-10535	
46	1127	charcoal	3483 ± 80	3880–3632	NSRL-10536	
46	1127	peat	1563 ± 110	1578–1350	GX-25943	
47	1146	peat	2953 ± 120	3292–2920	GX-25944	
52	1256	peat	3003 ± 75	3295–3020	GX-25945	2390 ± 230 (UIC926A; 51); 2470 ± 240 (UIC926B; 51)
52	1256	charcoal	2773 ± 45	2906–2826	NSRL-10645	2390 ± 230 (UIC926A; 51); 2470 ± 240 (UIC926B; 51)
53	1284	charcoal	2503 ± 45	2762–2410	NSRL-10646	2390 ± 230 (UIC926A; 51); 2470 ± 240 (UIC926B; 51)
53	1284	peat	2743 ± 130	2976–2792	GX-25946	2390 ± 230 (UIC926A; 51); 2470 ± 240 (UIC926B; 51)
56	1366	peat	2223 ± 130	2393–2007	GX-25947	2040 ± 190 (UIC928; 58)
59	1444	charcoal	2703 ± 80	2896–2794	NSRL-10538	2040 ± 190 (UIC928; 58)
60	1484	Cyperaceae (achenes)	3723 ± 45	4138–3978	NSRL-10539	2040 ± 190 (UIC928; 58)
60	1484	peat	1603 ± 120	1607–1362	GX-25948	2040 ± 190 (UIC928; 58)
62	1586	peat	2263 ± 120	2400–2097	GX-25949	2400 ± 240 (UIC927; 62)
63	1625	peat	3883 ± 140	4473–4042	GX-25950	
63	1625	Cyperaceae (achenes)	3733 ± 70	4196–3952	NSRL-10540	2400 ± 240 (UIC927; 62)
66	1766	peat	2043 ± 70	2053–1924	GX-25951	
Tahquamenon Bay, MI						
8	163	Seeds:*Betula alleghaniensis* Needles: *L. laricinia; Picea*	1633 ± 35	1577–1465	NSRL-11678	2360 ± 290 (UIC1106; 8)
14	374	peat	2523 ± 80	2789–2409	GX-25952	
15	408	peat	2053 ± 120	2170–1875	GX-25953	
16	442	peat	2503 ± 70	2766–2410	GX-25954	
17	483	Needles: *L. laricina; P. strobus*	2233 ± 35	2355–2175	NSRL-11556	1940 ± 220 (UIC905; 18)
17	483	peat	2693 ± 120	2905–2676	GX-25955	
18	524	peat	2863 ± 70	3045–2847	GX-25956	1940 ± 220 (UIC905; 18)
23	714	Needles: *L. laricina*	3163 ± 35	3427–3321	NSRL-11557	2140 ± 250 (UIC885; 23)
23	714	peat	2943 ± 120	3289–2907	GX-25957	2140 ± 250 (UIC885; 23)
24	796	peat	3163 ± 80	3490–3266	GX-25958	2140 ± 250 (UIC885; 23)
29	945	peat	3003 ± 80	3297–3017	GX-25959	3020 ± 410 (UIC833; 27) 2740 ± 330 (UIC1107; 31)
37	1136	Needles: *L. laricina; P. strobus*	2623 ± 50	2803–2675	NSRL-11558	2470 ± 250 (UIC896; 37)
37	1136	*Carex viridula*	1423 ± 35	1356–1329	CURL-6007	
37	1136	peat	2823 ± 120	3050–2819	GX-25960	2470 ± 250 (UIC896; 37)
38	1190	peat	3213 ± 130	3600–3267	GX-25961	2470 ± 250 (UIC896; 37)
40	1244	peat	3043 ± 130	3410–3008	GX-25962	2410 ± 240 (UIC1109; 41)
41	1258	peat	3223 ± 80	3522–3325	GX-25963	2410 ± 240 (UIC1109; 41)
42	1292	Needles: *L. laricina; P. strobus*	3043 ± 40	3296–3132	NSRL-11680	2410 ± 240 (UIC1109; 41)
43	1326	charcoal	3623 ± 45	4009–3881	NSRL-11559	2410 ± 240 (UIC1109; 41)
45	1380	peat	3243 ± 80	3435–3227	GX-25964	2760 ± 320 (UIC906; 46)
46	1428	peat	2933 ± 80	3213–2927	GX-25965	2760 ± 320 (UIC906; 46)
48	1469	peat	3783 ± 80	4280–3985	GX-25966	2760 ± 320 (UIC906; 46); 2600 ± 250 (UIC1108; 50)
51	1544	charcoal	3803 ± 35	4203–4066	NSRL-11560	2760 ± 320 (UIC906; 46); 2600 ± 250 (UIC1108; 50)
51	1544	peat	2893 ± 100	3209–2847	GX-25967	2760 ± 320 (UIC906; 46); 2600 ± 250 (UIC1108; 50)

(*continued on next page*)

Table 1 (*continued*)

Ridge number	Distance landward (m)	Material dated	Laboratory reported ^{14}C Age, ^{14}C yr B.P.	Calendar-corrected age range, cal yr B.P.	Laboratory number	Corresponding SAR age yr (lab; ridge number)
Tahquamenon Bay, MI						
52	1578	peat	3213 ± 130	3600–3267	GX-25968	2760 ± 320 (UIC906; 46); 2600 ± 250 (UIC1108; 50)
54	1625	peat	3283 ± 130	3684–3327	GX-25969	3150 ± 340 (UIC912; 56)
55	1659	peat	3143 ± 60	3430–3266	GX-25970	3150 ± 340 (UIC912; 56)
56	1686	peat	3373 ± 130	3746–3445	GX-25971	3150 ± 340 (UIC912; 56)
59	1775	peat	2943 ± 80	3254–2939	GX-25972	3250 ± 360 (UIC903; 61)
61	1809	peat	3583 ± 100	4015–3698	GX-25973	3250 ± 360 (UIC903; 61)
61	1809	Needles: *L. laricina; P. strobus*	3893 ± 35	4400–4206	NSRL-11561	3250 ± 360 (UIC903; 61)

beach ridges. To ease discussion, ridges are numbered consecutively from the present shoreline (Johnston, 2004). Radiocarbon ages potentially provide minimum limiting ages on the ridge that formed immediately lakeward of the corresponding wetland. All ^{14}C ages are calendar-corrected (Stuiver et al., 1998) and reported with 1-σ age ranges. ^{14}C ages are referred to A.D. 1950, whereas SAR ages are referred to the time of measurement, resulting in an ~50 yr offset between ^{14}C and SAR ages. We acknowledge this offset and its importance when comparing younger ages. However, for this study, ^{14}C ages are unadjusted because the ~50 yr is well within the 1-σ errors associated with SAR ages, and there is a lack of ^{14}C control on the youngest ridges.

The strandplain adjacent to Manistique–Thompson bays is a control site because of the abundance of ^{14}C ages on swale organic matter and because the Holocene ridge-age distance model is well established (Thompson and Baedke, 1997). Radiocarbon ages for Grand Traverse and Tahquamenon bays adjacent to Lake Superior include AMS ^{14}C ages on plant macrofossils (Johnston, 2004; Johnston et al., 2000, 2004) (Table 1).

Luminescence dating

Optically stimulated luminescence geochronology is based on the time-dependent dosimetric properties of silicate minerals, predominately feldspar and quartz (Aitken, 1998). Single-aliquot regenerative (SAR) dating procedures (Murray and Wintle, 2000) are used in this study to estimate the equivalent dose of the 150–250 μm or 250–355 μm quartz fractions from littoral and dune sands. The quartz fraction is isolated by density separations using Na-polytungstate, and a 40-min immersion in HF is applied to etch the outer 10+ microns of grains, which are affected by alpha radiation (Mejdahl and Christiansen, 1994). The purity of the quartz separate is evaluated by petrographic inspection and point counting of a representative aliquot. Samples that showed >1% of non-quartz minerals are retreated with HF and checked petrographically. Littoral and eolian sands from the upper Great Lakes often contain >85% quartz, and obtaining a pure quartz separate is straightforward.

An Automated Risø TL/OSL reader (Bøtter-Jensen, 1997) is used for single aliquot measurements. Blue light excitation (470 ± 30 nm) is from an array of 30 light-emitting diodes that delivers ~15 mW/cm^2 to the sample position at 90% power. Photon emissions are measured by a Thorn EMI 9235 QA photomultiplier tube coupled with three 3-mm-thick Hoya U-340 detection filters that transmit between 290 and 370 nm. Laboratory irradiations use a calibrated ^{90}Sr/^{90}Y beta source coupled with the Risø reader, and the experimental sequences are executed using Risø TL/OSL software for Windows (version 4.0). All emissions are integrated over the first 0.8 s of stimulation out of 500 s of measurement, with background based on emissions for the last 90- to 100-s interval. Before the application of SAR protocols, a series of experiments are employed to evaluate the effect of preheating at 180°, 200°, 220°, and 240°C on the regenerative signal (Murray and Wintle, 2000). These experiments show that preheat temperatures of 220°C yield consistent equivalent doses; thus, aliquots are preheated at this temperature for 10 s for the SAR protocols. Tests for dose recovery are performed on all samples, and the last dose coincides well with the initial dose (at 1-σ errors).

A critical analysis for luminescence dating is the dose rate (D_r), which is an estimate of the exposure of the sediment to ionizing radiation during the burial period (Tables 2 and 3). Most ionizing radiation in sediment is from the decay of isotopes in the U and Th decay chains and ^{40}K. The U and Th contents are determined by inductively coupled plasma-mass spectrometry (ICP-MS) analyzed by Activation Laboratory LTD, Ontario, Canada. The radioactive potassium component (^{40}K) is determined from the assayed K_2O content of the sediment by ICP-MS. The beta and gamma dose is adjusted according to grain diameter to compensate for mass attenuation (e.g., Fain et al., 1999). A modest cosmic-ray component, 0.17 ± 0.01 Gy/10^3 yr is included in the estimated dose rate (Prescott and Hutton, 1994).

Estimated water content for the burial period is included in dose-rate calculations. Compressed core samples retrieved below the water table have moisture contents ranging from 22% to 28% (by weight) and are considered

Table 2
Single aliquot regeneration ages and data for modern littoral and dune sediments for study sites adjacent to Lake Superior

Facies	Laboratory number	Number of aliquots[a]	Equivalent dose (Gy)	U (ppm)[b]	Th (ppm)[b]	K_2O (%)[b]	H_2O (%)[c]	Dose rate (Gy/ky)[d]	SAR age (yr)
Grand Traverse Bay, MI									
Dune	UIC861	20/20	0.24 ± 0.18	0.7 ± 0.1	2.1 ± 0.1	1.79 ± 0.01	10 ± 2	1.95 ± 0.14	120 ± 90
Swash	UIC863	20/20	0.42 ± 0.23	0.7 ± 0.1	2.1 ± 0.1	1.79 ± 0.01	25 ± 5	1.62 ± 0.11	260 ± 140
Au Train Bay, MI									
Dune	UIC864	20/20	0.25 ± 0.21	0.49 ± 0.1	1.66 ± 0.1	1.85 ± 0.01	10 ± 2	1.93 ± 0.14	130 ± 110
Swash	UIC869	29/30	0.15 ± 0.12	0.49 ± 0.1	1.66 ± 0.1	1.85 ± 0.01	25 ± 5	1.67 ± 0.12	90 ± 70
Batchawana Bay, Ontario									
Dune	UIC995	18/20	0.05 ± 0.02	0.5 ± 0.1	1.8 ± 0.1	1.66 ± 0.01	10 ± 2	1.75 ± 0.12	30 ± 10
Backshore	UIC996	17/20	0.13 ± 0.03	0.5 ± 0.1	1.9 ± 0.1	1.77 ± 0.01	20 ± 2	1.69 ± 0.12	80 ± 20
Swash	UIC997	17/20	0.08 ± 0.02	0.6 ± 0.1	2.0 ± 0.1	1.94 ± 0.01	25 ± 5	1.69 ± 0.12	50 ± 10
Nearshore Bar	UIC998	18/20	0.06 ± 0.02	0.6 ± 0.1	2.0 ± 0.1	1.75 ± 0.01	30 ± 5	1.55 ± 0.11	40 ± 10

[a] Number of aliquots used to calculate final D_e as a ratio to total aliquots analyzed.
[b] U and Th values and percent Potassium determined by ICP-MS on a homogenized, 50 g aliquot by Activation Laboratories LTD, Ontario Canada.
[c] Water content (by weight) estimated from actual laboratory measurement with consideration of water loss during sampling.
[d] Dose rate value includes a contribution from cosmic radiation of 0.17 ± 0.01 Gy/10^3 yr. (Prescott and Hutton, 1994).

minima because some water is lost during coring. An uncompressed sediment sample from the saturated zone yields a water-content value of 34%. Consequently, saturated sediment is assigned a water content of 30 ± 5%. Sediments from the unsaturated zone are assigned water contents of 10 or 25%, reflecting field moisture conditions assessed upon collection and laboratory measurement (Tables 2 and 3). Conservative estimates of error (2–5%) are applied, acknowledging uncertainty in water content changes during burial.

A single SAR age is calculated from D_e determinations on 20 to 40 separate aliquots, each containing ~2000–4000 quartz sand grains. The D_e frequency distributions of sample aliquots typically conform to a normal distribution (Fig. 2). However, a number of frequency distributions of D_e values show modest analytical scatter, often 20–40% more than eolian sands dated in other contexts (e.g., Forman and Pierson, 2003; Murray-Wallace et al., 2002), which is one reason that ages have errors between 8 and 14%. Increased analytical scatter in D_e distributions (compared to eolian sand) is documented for other waterlain sediments (e.g., Clarke et al., 1999; Wallinga et al., 2001). Box plots are used to identify aliquots that are outliers of the data distribution. Aliquots identified as outliers are excluded from final age-calculation analysis. Typically, <15% of the generated data are considered outliers (Table 3). The final mean D_e is based on the individual error for each aliquot and weighted for the lowest associated error.

The precision of SAR ages range from 8 to 14% of the mean reflecting errors associated with the D_e and D_r determinations. The errors from D_e determination are approximately 6–7% of the mean for sediments >400 yr and reflect analytical variations associated with SAR measurements and random errors. The largest and dominant errors for the D_r are from uncertainties in moisture contents during burial; therefore, conservative estimates of error (2–5%) are applied. The U (<1 ppm) and Th (<3.3 ppm) content of sediments is relatively low, with 60–70% of the dose from ^{40}K, which is mineralogic and is not readily altered at depths below pedogenesis that are sampled for SAR dating.

Sedimentologic and geomorphic setting

Sediments for SAR dating are mostly from the foreshore facies of individual beach ridges. Foreshore sediments are identified by decreased sorting and coarser grain size, relative to the overlying eolian facies, and by mm- to cm-scale lakeward-dipping laminae (e.g., Johnston, 2004; Thompson, 1992; Thompson and Baedke, 1997). The eolian cap on beach ridges is greater at the Manistique–Thompson embayment than at either of the Lake Superior sites (Fig. 1). In cases where extensive eolian deposition precluded sampling of waterlain sediments, SAR ages reflect timing of dune development and thus yield a minimum constraining age on the subjacent beach ridge.

Beach ridge excavation often reveals extensive soil development in the upper 0.5–1.0 m. Where possible, OSL samples are collected in excavations >10 cm below the zone of pedogenesis, in the C horizon where primary sedimentary structures are evident. An indurated, ortstein-like layer that masks primary sedimentary structures is commonly encountered at depth (e.g., Barrett, 2001). Within low-relief ridges, the ortstein-like layer acts as an aquiclude, confining the uppermost limit of the saturated zone. Development of this layer may influence infiltration and the flow of water within and between wetlands. A 7.5-cm-diameter percussion corer is used to penetrate the sesquioxide horizon and access subjacent, pedogenically unaltered littoral sediments. SAR samples collected below

Table 3
Single aliquot regeneration ages and data for sediments from individual beach ridges in strandplains at Manistique–Thompson Bay, MI, Grand Traverse Bay, MI and Tahquamenon Bay, MI, USA adjacent to Lake Superior

Ridge number	Laboratory number	Distance landward (m)	Aliquots analyzed	Equivalent dose (Gy)	U (ppm)[a]	Th (ppm)[a]	K_2O (%)[a]	H_2O (%)	Dose rate (Gy/ky)[b]	SAR age (yr)
Manistique/Thompson Bay, MI										
2	UIC1026	33	17/20	0.1 ± 0.03	0.4 ± 0.1	1.4 ± 0.1	2.78 ± 0.01	10 ± 2	2.67 ± 0.19	40 ± 10
5	UIC1025	166	26/30	1.0 ± 0.1	0.4 ± 0.1	1.3 ± 0.1	1.43 ± 0.01	10 ± 2	1.53 ± 0.11	660 ± 80
13	UIC1154	576	27/30	2.1 ± 0.1	0.6 ± 0.1	1.4 ± 0.1	1.75 ± 0.01	25 ± 5	1.59 ± 0.11	1320 ± 120
25	UIC1155	975	29/30	2.9 ± 0.2	0.5 ± 0.1	1.5 ± 0.1	1.52 ± 0.01	25 ± 5	1.41 ± 0.10	2060 ± 220
28	UIC1156	1097	23/30	2.3 ± 0.2	0.5 ± 0.1	1.5 ± 0.1	1.67 ± 0.01	25 ± 5	1.52 ± 0.11	1520 ± 180
32	UIC1024	1297	29/30	4.4 ± 0.3	0.5 ± 0.1	1.5 ± 0.1	2.06 ± 0.01	10 ± 2	2.09 ± 0.15	2110 ± 210
57	UIC1027	2384	30/30	4.9 ± 0.2	0.5 ± 0.1	1.5 ± 0.1	1.57 ± 0.01	30 ± 5	1.38 ± 0.10	3550 ± 360
86	UIC1028	3837	29/30	3.7 ± 0.2	0.5 ± 0.1	1.6 ± 0.1	1.23 ± 0.01	25 ± 5	1.21 ± 0.09	3070 ± 290
Grand Traverse Bay, MI										
4	UIC922	110	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
7	UIC923	212	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
12	UIC924	314	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
19	UIC925	479	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
27	UIC960A	675	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
27	UIC960B	675	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
35	UIC961	887	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
41	UIC929	1005	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
51	UIC926A	1233	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
51	UIC926B	1233	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
58	UIC928	1413	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
62	UIC927	1586	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
Tahquamenon Bay, MI										
1	UIC880[c]	34	27/30	1.0 ± 0.1	0.4 ± 0.1	1.2 ± 0.1	1.04 ± 0.01	30 ± 5	0.95 ± 0.07	1050 ± 230
4	UIC834[c,d]	102	18/20	1.3 ± 0.1	0.4 ± 0.1	2.0 ± 0.1	1.41 ± 0.01	30 ± 5	1.24 ± 0.09	1050 ± 115
8	UIC1106	163	27/30	2.1 ± 0.2	0.4 ± 0.1	1.3 ± 0.1	0.84 ± 0.01	25 ± 5	0.89 ± 0.06	2360 ± 290
11	UIC907	245	23/30	1.7 ± 0.1	0.3 ± 0.1	1.0 ± 0.1	0.77 ± 0.01	25 ± 5	0.80 ± 0.06	2120 ± 210
18	UIC905	524	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
23	UIC885	714	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
27	UIC833[d]	884	39/40	3.6 ± 0.4	0.4 ± 0.1	1.4 ± 0.1	1.31 ± 0.01	25 ± 5	1.19 ± 0.08	3020 ± 410
27	UIC850[d]	884	28/30	3.4 ± 0.2	0.4 ± 0.1	1.6 ± 0.1	2.40 ± 0.01	25 ± 5	2.03 ± 0.14	1670 ± 170
31	UIC1107	993	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
37	UIC896	1136	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
41	UIC1109	1258	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
46	UIC906	1428	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
50	UIC1108	1516	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
56	UIC912	1686	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
61	UIC903	1809	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
72	UIC1110	2162	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
77	UIC913	2230	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

[a] U and Th values and percent Potassium determined by ICP-MS on a homogenized, 50 g aliquot by Activation Laboratories LTD, Ontario Canada.
[b] Dose rate value includes a contribution from cosmic radiation of 0.17 ± 0.01 Gy/10^3 yr. (Prescott and Hutton, 1994).
[c] SAR ages determined for the 250–355 μm quartz fraction.
[d] Samples were collected from within a vibracorre collected on the lakeward margin of the beach ridge.

this surface are considered water-saturated (30 ± 5%) throughout their burial history.

Results

SAR ages on modern beach sediments

Initial analyses concentrate on modern littoral and dune sediments from the strandplains at Grand Traverse and Au Train Bays to evaluate the precision and accuracy of SAR (Table 2). Eolian systems are ideal for OSL dating because processes of sediment transport such as saltation, allow ample opportunity for solar resetting of luminescence (Clarke et al., 1999). A potential complication in fluvial and littoral systems occurs if transport processes in aqueous environments allow light exposure that is insufficient to reset the OSL signal of all grains completely prior to deposition (Wallinga et al., 2001). Richardson (2001) finds that solar resetting is incomplete for green and blue stimulated luminescence for quartz grains from modern, turbid coastal environments of England and Wales. Partial solar resetting

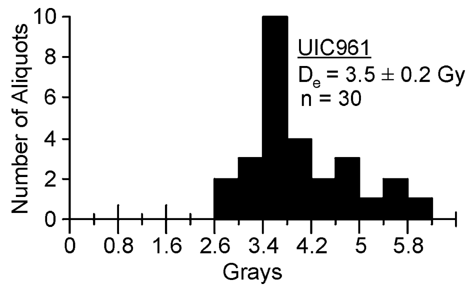

Figure 2. Distribution of the equivalent dose (D_e) for individual aliquots from SAR sample UIC961 from ridge 35 at Grand Traverse Bay (C).

would result in a portion of grains containing a remnant luminescence signal (Clarke et al., 1999) and may result in significant scatter (>25%) about the mean D_e, leading to older SAR ages.

There is a wide range of D_e values among individual aliquots of modern samples at Grand Traverse and Au Train Bays. For example, individual aliquots vary from ~0.1 to 37.0 Gy for dune sand (UIC861) and ~0.01 to 34.0 Gy for swash zone sand (UIC869). Scatter among aliquots from Grand Traverse and Au Train Bays, Michigan may reflect contamination by glass. Sediment collected from the youngest dated beach ridge (UIC922) at Grand Traverse, which would be void of modern glass, exhibits significantly less scatter in D_e, than the modern beach. However, within individual samples, aliquots of modern sand exhibit negatively skewed distributions with clear clustering around a D_e <0.2 Gy (Fig. 3A). Age calculation based on the weighted mean D_e for each sample after outliers are removed yields resultant SAR ages for modern littoral sands of 260 ± 140 yr (UIC863), 90 ± 70 yr (UIC 869), 120 ± 90 yr (UIC861), and 130 ± 110 yr (UIC864) for modern dune sands (Table 2). An additional assessment of modern beach sediments at Batchawana Bay, Ontario, Canada shows significantly less analytical scatter (Fig. 3B) and yields SAR ages of 30 ± 10 yr (UIC995) and 50 ± 10 yr (UIC996) for dune and swash zone sediments, respectively (Table 2). These results indicate that quartz sand grains from foreshore and dune environments are nearly, if not completely solar reset, with an inheritance OSL emission <100 yr (Table 2), well within 1-σ errors for ages of late Holocene littoral and eolian sediments.

SAR dating of strandplain sequences

Manistique–Thompson bay embayment, Lake Michigan

The Manistique and Thompson embayments were initially joined during the Nipissing I phase high stand, ca. 4500 cal yr B.P., but separated into two distinct standplains with lake-level fall and continued development of beach ridges (Thompson and Baedke, 1997). Combined, the embayments contain ~90 beach ridges that vary in height from 0.5 to >10 m (Thompson and Baedke, 1997). The chronology of strandplain development is constrained by conventional ^{14}C ages on 29 bulk peat samples collected in swales landward of 250 m (Thompson and Baedke, 1997) (Table 1). Sampling for SAR analyses follows the transect of Thompson and Baedke (1997), focusing on eight ridges to evaluate the general concordance with ^{14}C ages (Fig. 4). In several cases, extensive eolian deposition (>2 m) precludes sampling of waterlain sediments, specifically for ridges between 975 and 2000 m from the modern shoreline.

Littoral sediments collected from ridges 86 and 57 yield SAR ages of 3070 ± 290 yr (UIC1028) and 3550 ± 360 yr (UIC1027), respectively (Table 3; Fig. 5). Ridge 86 has a thick dune cap and thus, the SAR age is a minimum estimate for subjacent littoral sediments. Corresponding bulk peat samples for ridges 86 to 54 yield ^{14}C ages ranging from ca. 5370 to 1460 cal yr B.P. (Table 1; Fig. 5). SAR ages of 2110 ± 210 (UIC1024), 1520 ± 190 (UIC1056), and 2060 ± 220 yr (UIC1155) for ridges 32, 28, and 25, respectively, are ca. 1000 yr less than corresponding ^{14}C ages of 3683–3413 (GX-18162) and 2813–2773 (GX-18160) cal yr B.P. generated from bulk peat (Table 1).

There is a disparity of ~1000 yr between ^{14}C ages corresponding to ridges 24 and 21 (Table 1). Based on this age offset and the extensive relief of ridge 24, ~13 m higher than the crest of ridge 21, Thompson and Baedke (1997) suggest that a hiatus occurred in ridge development or that ridges were eroded contributing to vertical aggradation of the shoreline. The SAR age of 1320 ± 110 yr (UIC 1154) for ridge 13 on littoral sands is concordant with ^{14}C ages of ca. 1000 to 1500 cal yr B.P. for ridges 8 to 11 (Table 1).

SAR dating yields ages on the youngest ridges for which there are no corresponding ^{14}C ages. Ridge 5, which yields the SAR age of 660 ± 80 yr (UIC1025), contains a soil that exhibits a Bs-horizon, >40 cm in depth, similar to pedons

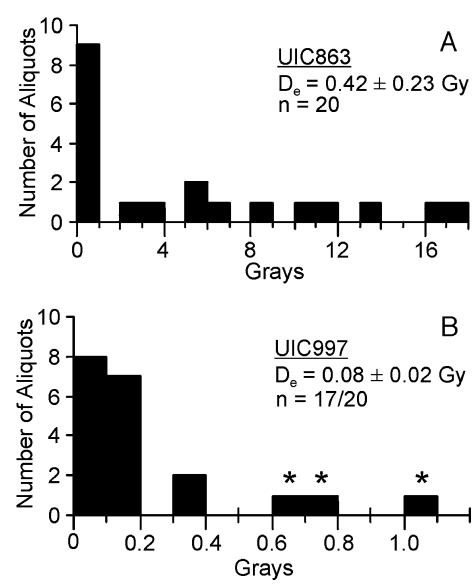

Figure 3. Distribution of the equivalent dose (D_e) for individual aliquots from SAR sample UIC863 from the swash zone of the modern beach at Grand Traverse Bay (A), and UIC997 from the swash zone of the modern beach at Batchawana Bay, Ontario, Canada (B). Asterisks designate aliquots removed prior to analysis of the weighted mean of the distribution and the final SAR age. Weighted D_e's with 1-σ error and the number of aliquots (n) used to calculate SAR ages are shown.

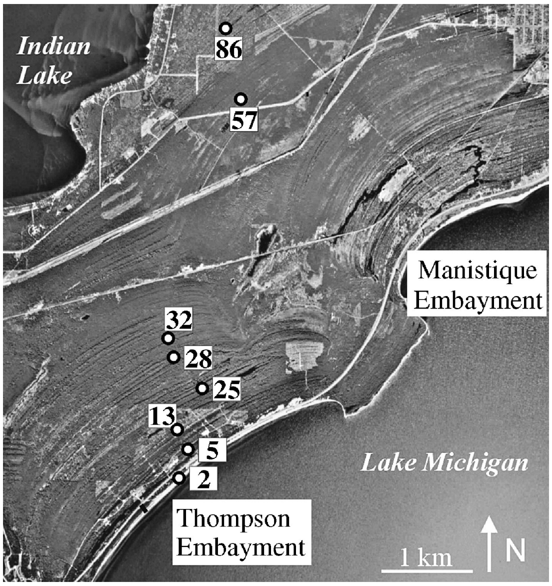

Figure 4. Aerial photograph of Manistique–Thompson embayment, upper peninsula, Michigan. Ridges sampled for OSL dating are identified by white circle and corresponding ridge number.

that are 200 to 1000 yr in age (Barrett, 2001). Ridge 2 occurs ~10–20 m behind the modern beach and is associated with the 1973–1974 high stand for Lake Michigan (T.A. Thompson, personal communication, 2003). The uppermost littoral and eolian sand in ridge 2 exhibits little to no podzolization, suggesting an age of several decades (Barrett, 2001). Ridge 2 yields a SAR age of 40 ± 10 yr (UIC1026), consistent with tree-ring data (Thompson and Baedke, 1997) and observed soil characteristics. Without correction for the apparent missing ridges, the average ridge formation rate at Manistique/Thompson Bay, Michigan, is 83 ± 4 yr during the past ~1500 yr, with ridges prior to that time forming every 50 ± 4 yr (Fig. 5).

Grand traverse bay embayment, Lake Superior

This strandplain consists of ~70 beach ridges with a slough ~400 m inland in the northern portion of the strandplain (Fig. 6). The difference between ridge crest-to-swale elevation decreases from about 1.0 m at the modern shoreline to ~0.5 m at the slough and increases landward of the slough. Beach ridges between 0.5 and 1.2 km (ridges 16–49) from the modern shore are ~0.5 to 1.0 m in relief, are heavily vegetated, and contain an ortstein-like layer, requiring the use of percussion coring to collect unaltered sediments from below the water table.

Littoral sands from ridges 62 and 58 yield SAR ages of 2400 ± 240 yr (UIC927) and 2040 ± 190 yr (UIC928), respectively. Corresponding ^{14}C ages for bulk peat are highly variable, ranging from 1607–1362 (GX-25948) to 4473–4042 (GX-25950) cal yr B.P. (Table 1). Seeds from ridges 60 and 63 yield AMS ^{14}C ages of 4138–3978 (NSRL-10539) and 4196–3952 (NSRL-10540) cal yr B.P., which are significantly older than SAR ages on nearby beach ridges (Tables 1 and 3; Fig. 7). Duplicate analyses of quartz grains from ridge 51 yield SAR ages of 2390 ± 230 (UIC926A) and 2470 ± 240 (UIC926B) yr, agreeing within 1-σ (Table 3), and overlaping within 2-σ of ^{14}C ages of 3295–3020 (GX-25945) and 2976–2792 (GX-25946) cal yr B.P. on bulk peat from ridges 52 and 53, respectively (Table 1).

Littoral sediments from ridges 41, 35, and 27 yield SAR ages of ca. 1800 yr (Table 3; Fig. 7). Duplicate analyses of quartz grains from ridge 27 yield SAR ages of 1590 ± 140 and 1520 ± 240 yr that agree within 1-σ. In contrast to the SAR results, ^{14}C ages are highly variable. Bulk organics from ridges 43 to 26 produce ^{14}C ages from 3522 to 1620 cal yr B.P. (Table 1). AMS ^{14}C ages on in situ plant needles are significantly younger than those produced by conventional dating of bulk peat and SAR methods (Table 1; Fig. 7). Ridge 44 produces a ^{14}C age of 1350–1320 cal

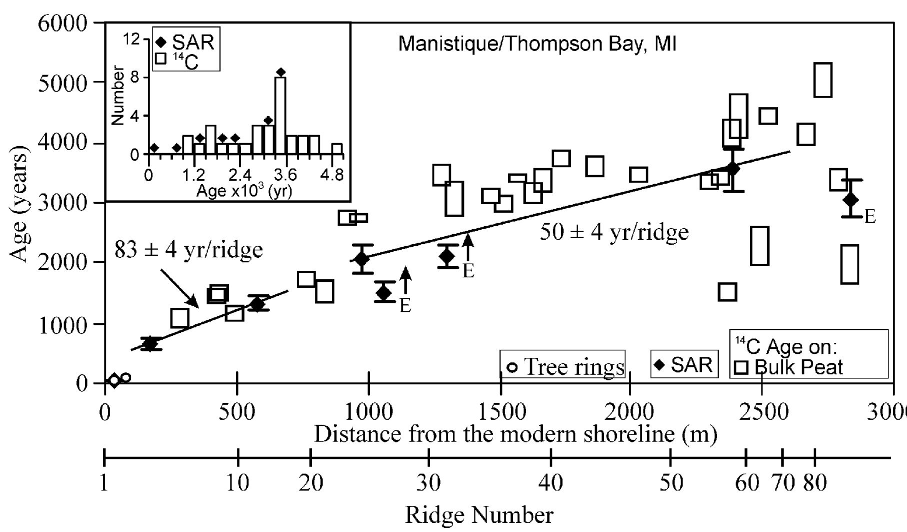

Figure 5. Age results from beach ridges sampled at the Manistique–Thompson strandplain, Michigan, USA-Lake Michigan. SAR ages (black diamonds) are presented with 1-σ error bars. Conventional ^{14}C ages on bulk peat (open rectangles) represent the 1-σ age range. Average rates of ridge formation are based upon unweighted, linear regressions of littoral sediments only. Histogram illustrates the distribution of all ^{14}C (open bars) and SAR (black diamond) ages. Ages generated for dune facies are denoted by a subscript (E).

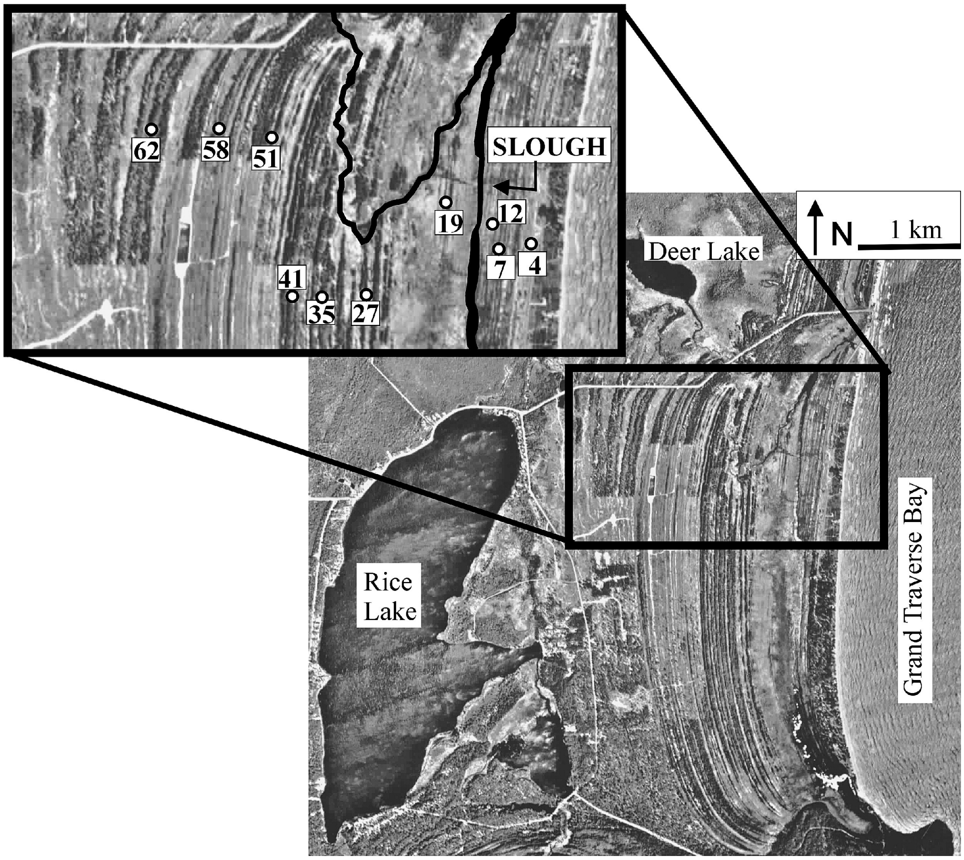

Figure 6. Aerial photograph of Grand Traverse Bay embayment. Ridges sampled for OSL dating are identified by white circle and corresponding ridge number.

yr B.P. (NSRL-10537), whereas two samples from ridge 42 yield ages of 566–390 (NSRL-10534) and 704–586 (NSRL-10533) cal yr B.P. (Table 1; Fig. 7). Similarly, charcoal samples corresponding to ridges 46, 45, 43, and 36 also yield highly variable ^{14}C ages of 3880–3632 (NSRL-10536), 1859–1682 (NSRL-10535), 3404–3137 (NSRL-10644), and 2045–1949 (NSRL-10533) cal yr B.P., respectively.

In the lakeward portion of the strandplain, ridges 19, 12, and 7 yield SAR ages of 1140 ± 110 (UIC925), 1020 ± 100 (UIC924), and 790 ± 80 (UIC923) yr (Table 1; Fig. 7). These results are consistent with ^{14}C ages of ca. 1500 to

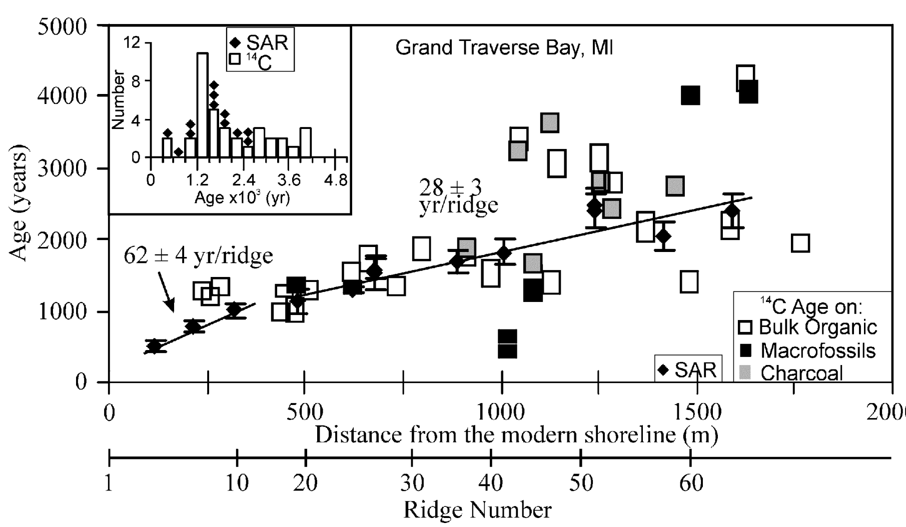

Figure 7. Age results from beach ridges sampled at the Grand Traverse strandplain, Michigan, USA-Lake Superior. SAR ages (black diamonds) are presented with 1-σ error bars. Conventional ^{14}C ages for bulk peat (open rectangles), and AMS ^{14}C ages for charcoal (grey rectangles) and plant macrofossils (black rectangles) represent the 1-σ age range. Average rates of ridge formation are based upon unweighted, linear regressions of littoral sediments only. Histogram illustrates the distribution of all ^{14}C (open bars) and SAR (black diamond) ages. Ages generated for dune facies are denoted by a subscript (E).

1000 cal yr B.P. on bulk peat for ridges 9 to 24 and AMS ages of ca. 1300 cal yr B.P. for plant macrofossils from ridges 19 and 24 (Table 1; Fig. 7). Ridge 4 is the youngest ridge sampled and produces a SAR age of 510 ± 70 yr (UIC922). Soil development on this youngest ridge with an incipient B horizon is consistent with a strandplain pedon of 200–1000 yr old (Barrett, 2001). Preserved beach ridges at Grand Traverse Bay, Michigan form on average every 62 ± 4 yr during the past ~1500 yr and at a rate of 28 ± 3 yr prior to 2000 yr (Fig. 7).

Tahquamenon bay, Michigan

Tahquamenon Bay is a northward-opening embayment along the southern shore of Lake Superior (Fig. 1). A primary source of sediment supply is the Tahquamenon River located ~9 km north of the embayment. The Tahquamenon Bay strandplain extends ~2.5 km inland from the modern beach and contains ~80 beach ridges (Fig. 8) (Johnston, 2004; Johnston et al., 2001). Ridge deposition occurs lakeward of a bluff associated with high water levels during the Nipissing phase (Johnston, 2004; Johnston et al., 2001). Field studies concentrate on examining every fifth ridge between the modern shoreline and ridge 77.

A SAR age of 4280 ± 390 yr (UIC913) on ridge 77 at Tahquamenon Bay shows clear concordance with regression from the high lake level of the Nippising II phase dated to ca. 4500 cal yr B.P. (Baedke and Thomspon, 2000) (Table 3; Fig. 9). Ridges 72, 61, and 56 yield SAR ages of ca. 3000–4000 yr (Table 3) consistent with ^{14}C ages ranging from 4015 to 2939 cal yr B.P. for bulk peat from ridges 61, 59, and 56 (Table 1; Fig. 9). The AMS ^{14}C age of 4400–4206 cal yr B.P. (NSRL-11561) on plant macrofossils for ridge 61 is older than the corresponding ^{14}C age of 3015–3698 cal yr B.P. (GX-25973) on basal peat from the same swale.

Foreshore sediments collected between ridges 50 and 27 yield SAR ages of ca. 2000 to 3000 yr (Table 3). Corresponding ^{14}C ages for bulk peat from ridges 55 to 29 range from ca. 4280 to 2819 cal yr B.P. and are generally within 2-σ of SAR ages (Table 1; Fig. 9). Charcoal collected from ridges 51 and 43 produce older ages of ca. 4000 cal yr B.P. (Table 1). However, a ^{14}C age of 3296–3132 (NSRL-11680) cal yr B.P. on plant macrofossils from ridge 42 is consistent with SAR results. Two plant macrofossils from ridge 37 produce significantly different ages of 2803–2675 (NSRL-11558) and 1356–1329 cal yr B.P. (CURL-6007) (Table 1). Littoral sediments from ridge 27 sampled at depths of 0.85 m and 1.7 m, representing the dune and foreshore facies, yield corresponding SAR ages of 1670 ± 170 yr (UIC850) and 3020 ± 410 yr (UIC833) (Table 3; Fig. 9). The age disparity suggests that considerable time may elapse between deposition of littoral sediments and stabilization of the overlying dune facies.

Ridges 23 and 18 within the youngest (lakeward) portion of the strandplain yield SAR ages of ca 2000 yr (Table 3) that are generally consistent with ^{14}C ages between 3490 and 1875 cal yr B.P. for ridges 24 to 14 (Table 1; Fig. 9). Two plant macrofossil ages of 3427–3321 (NSRL-11557)

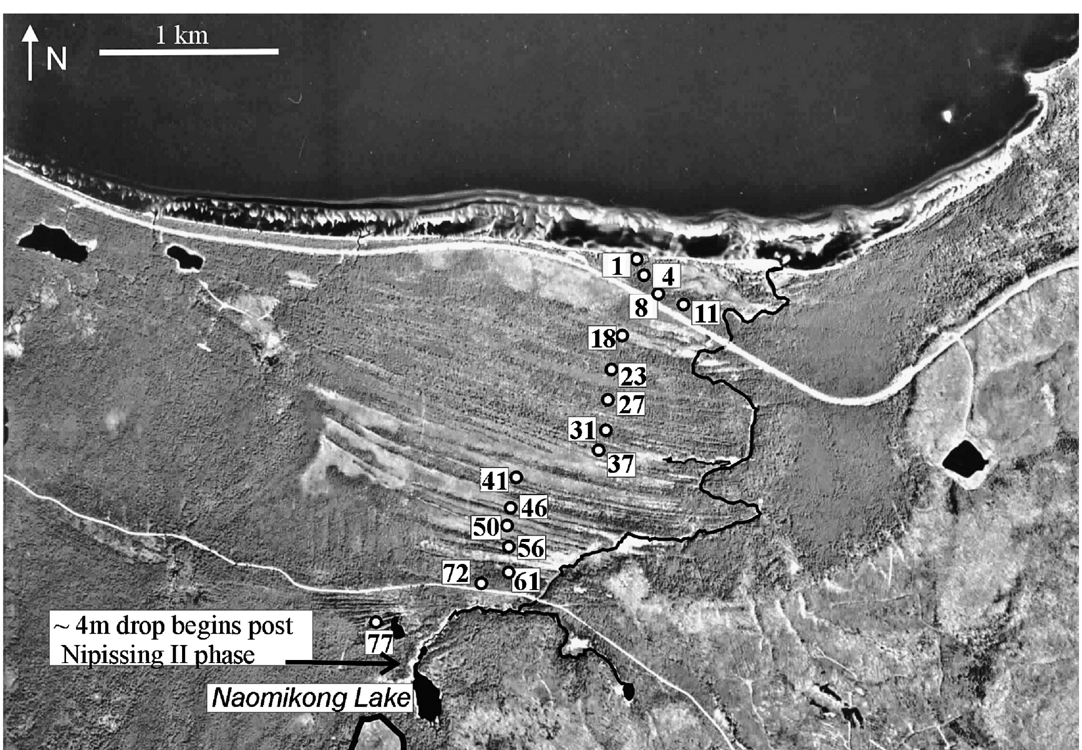

Figure 8. Aerial photograph of Tahquamenon Bay embayment, Michigan, USA-Lake Superior. Ridges sampled for OSL dating are identified by white circle and corresponding ridge number.

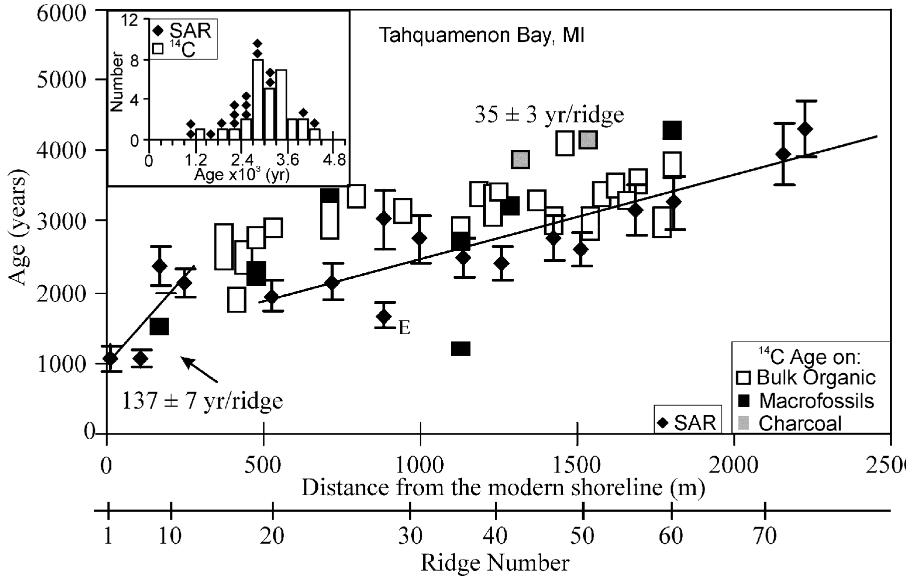

Figure 9. Age results from beach ridges sampled at the Tahquamenon Bay strandplain, Michigan, USA-Lake Superior. SAR ages (black diamonds) are presented with 1-σ error bars. Conventional ^{14}C ages for bulk peat (open rectangles), and AMS ^{14}C ages for charcoal (grey rectangles) and plant macrofossils (black rectangles) represent the 1-σ age range. Average rates of ridge formation are based upon unweighted, linear regressions of littoral sediments. Histogram illustrates the distribution of all ^{14}C (open bars) and SAR (black diamond) ages.

and 2355–2175 (NSRL-11556) cal yr B.P. are determined for ridges 23 and 17; the former is ~1000 yr older than the corresponding SAR age for ridge 24 (Table 1; Fig. 9).

Ridges 11 and 8 generate SAR ages of 2120 ± 210 yr (UIC907) and 2360 ± 290 yr (UIC1107), respectively (Table 3). An AMS ^{14}C age of 1577–1465 cal yr B.P. (NSRL-11678) for plant macrofossils from ridge 8 is ~700 yr younger than corresponding SAR ages. Ridges 4 and 1 are the youngest ridges and yield SAR ages of 1050 ± 115 yr (UIC834) and 1050 ± 230 yr (UIC880), respectively (Table 3). Based on preserved ridges at Tahquamenon Bay the average beach ridge formation rate is 137 ± 7 yr during the past ~2000 yr, decreasing from a rate of 35 ± 3 yr for the preceding 2000 yr (Fig. 9).

Discussion

Assessing the accuracy and precision of SAR ages

Modern beach and dune sediments yield SAR ages typically <100 yr, indicating full or nearly so, solar resetting of previously acquired luminescence prior to deposition. Beach ridges yielding SAR ages of <1000 yr at Manistique and Grand Traverse Bays, Michigan have levels of podzolization that are consistent with pedons 200–1000 yr old studied in a nearby Michigan strandplain (Barrett, 2001). SAR ages for Manistique and Grand Traverse Bays usually overlap at 1-ó with corresponding ^{14}C ages for the past 2000 yr (Figs. 5 and 7). The dating results from Tahquamenon Bay are more variable. SAR ages indicate that the lowest preserved ridge formed ~1000 yr. ago (Table 3). Ridges 8 and 11 give SAR ages of ~2300 yr and appear to be ~500 yr older than adjacent ridges (Fig. 8). The reason for this discrepancy is unclear.

It is difficult to forward a robust comparison between SAR and ^{14}C ages for foreshore sediments >2000 yr old because of the large range of ^{14}C ages on swale organic matter, often >500 yr, from 1 or more proximal ridges (Table 1; Figs. 5, 7 and 9). The dispersion in ^{14}C ages increases to >2000 yr for organics from ridges landward from ridge 36 at Grand Traverse Bay and ridge 57 at the Manistique–Thompson embayment (Figs. 5 and 7). Radiocarbon ages cluster between ca. 2800 and 3500 cal yr B.P. for ridges 23 to 61 at Tahquamenon Bay, possibly reflecting hydrologic conditions in swales or reworking of older organic matter caused by shoreline erosion with lake-level rise to the Algoma phase. However, SAR and ^{14}C ages associated with ridges 61, 50, 46, and 37 at Tahquamenon Bay overlap at 1-σ. In turn, the uppermost SAR ages of 3780 ± 410 (UIC1110) and 4280 ± 390 yr (UIC913) on ridges 72 and 77, respectively, at Tahquamenon Bay are consistent with a correlation to prominent regressional shorelines that formed following the Nipissing II high stand at ca. 4500 yr (Johnston, 2004). In general, SAR ages consistently increase in age with distance from the modern shoreline.

Understanding rates of ridge formation during the late Holocene

Quasi-periodic lake-level fluctuations of ~30 and 150 yr are inferred from the average rate of beach-ridge formation for Lake Michigan, determined by cross-strandplain regression analysis of radiocarbon ages and ridge number at five coastal embayments (Baedke and Thompson, 2000; Thompson and Baedke, 1997). In Lake Superior, calculations of average rates of ridge formation are complicated by inflections in long-term patterns of foreshore elevations. Foreshore elevations decrease moving lakeward from the oldest ridges but increase within ~400 and 500 m of the modern shoreline at Grand Traverse and Tahquamenon Bays, respectively.

We determine average rates of ridge formation by unweighted, least-squares regressions between ridge number and SAR age, honoring geologic breaks in the strandplain records determined from sedimentological data (Johnston, 2004; Thompson and Baedke, 1997). The calculated ridge formation rates reflect maximum estimates given that gaps in the sedimentary record likely exist due to hiatuses in ridge formation and erosion of existing ridges by subsequent lake-level high stands. Note that SAR ages at all sites show a decrease in the rate of ridge formation ~2000–1500 yr ago (Figs. 5, 7 and 9). Consistent rates of ridge formation are not expected over the past ~4500 yr because of shifts in sediment supply or in the rate and magnitude of water-level fluctuation induced by the separation of Lake Superior from lakes Huron and Michigan, estimated by Larsen (1994) to have occurred ~2100 cal yr B.P. This study indicates that the average formation rate of preserved beach ridges prior to ~1500 yr is relatively consistent, with Manistique, Grand Traverse, and Tahquamenon Bays forming a beach ridge every 50 ± 4, 28 ± 3, and 35 ± 3 yr, respectively. For the past 2000 to 1500 yr the average ridge formation rate is quite variable, with Manistique, Grand Traverse, and Tahquamenon Bays forming a beach-ridge every 83 ± 4, 62 ± 4, and 137 ± 7 yr, respectively. This inconsistent rate of beach ridge formation in different localities indicates that local factors such as isostasy, sediment supply, and storm seiche may have been more significant in beach-ridge preservation and the development of individual strandplains, rather than solely regional climate, once Lake Superior separated from lakes Michigan and Huron.

Implications for dating Holocene strandplains

This study illustrates that SAR dating provides a credible method for dating littoral and eolian sediments from Great Lakes strandplains that span the past ca. 4500 yr. These results also underscore the complexities of employing ^{14}C dating of swale organic matter to constrain the chronology of strandplain development and to verify SAR dating of associated foreshore sediments. Age control for Great Lakes strandplains has principally relied on ^{14}C dating of peats between beach ridges with the inherent assumption that organic matter accumulation is penecontemporaneous with beach-ridge formation (e.g., Johnston, 2004; Larsen, 1994; Thompson and Baedke, 1997). However, bulk organic matter, charcoal, and plant macrofossils from swales at strandplains at Manistique–Thompson, Grand Traverse, and Tahquamenon bays show an unclear relation between ^{14}C age and ridge distance from the modern shoreline that is most apparent in ages >2000 cal yr B.P. Chronologies at Grand Traverse and Tahquamenon Bays are not uniformly improved through AMS ^{14}C dating of macrofossils from basal peat deposits, primarily due to a lack of organic matter accumulation across the strandplain. The uncertainty in the source of carbon for swale organic deposits is reflected in the low precision of ^{14}C ages, spanning ca. 300 to >1000 yr, for the same or proximal ridges (Larsen, 1994; Thompson and Baedke, 1997), a considerable range given a lake-level record that spans the past ca. 4500 yr.

SAR dating of littoral sediments provides a viable alternative to ^{14}C dating of interswale organics of questionable origin for constructing lake level age models for at least the past 2000 yr. The SAR method provides direct ages with at least centennial-scale resolution on beach ridges by dating wave-rounded quartz grains from the foreshore facies, which is the most reliable sedimentological indicator of paleo-lake level (Thompson, 1992). In turn, the use of SAR dating allows for selection of strandplains that provide the longest continuous record of lake level variability, rather than restricting analyses to ridge sequences with wetlands that may be amenable for ^{14}C dating. Currently, there exists a paucity of dated beach ridge sequences spanning the past 1000 yr, an interval of poor resolution for ^{14}C dating (Stuiver et al., 1998). SAR dating is an appropriate method for resolving lake-level variations and effectively bridging the gap between late Holocene and historical instrumental lake-level records.

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