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A post-Calumet shoreline along southern Lake Michigan

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Abstract The southern shore of Lake Michigan is the type area for many of ancestral Lake Michigan's late Pleistocene lake phases, but coastal deposits and features of the Algonquin phase of northern Lake Michigan, Lake Huron, and Lake Superior are not recognized in the area. Isostatic rebound models suggest that Algonquin phase deposits should be 100 m or more below modern lake level. A relict shoreline, however, exists along the lakeward margin of the Calumet Beach that was erosional west of Deep River and depositional east of the river. For this post-Calumet shoreline, the elevation of basal foreshore deposits east of Deep River and the base of the scarp west of Deep River indicate a slightly westward dipping water plane that is centered at ~184 m above mean sea level. Basal foreshore elevations also indicate that lake level fell ~2 m during the development of the shoreline. The pooled mean of radiocarbon dates from the surface of the peat below post-Calumet shoreline foreshore deposits indicate that the lake transgressed over the peat at 10,560 ± 70 years B.P. Pollen assemblages from the peat are consistent with this age. The elevation and age of the post-Calumet shoreline are similar to the Main Algonquin phase of Lake Huron. Recent isostatic rebound models do not adequately address a high-elevation Algonquin-age shoreline along the southern shore of Lake Michigan, but the Goldthwait (1908) hinge-line model does.

Keywords Lake Michigan · Lake level · Calumet beach · Calumet phase · Algonquin phase

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Introduction

Three relict shoreline complexes, consisting of mainland-attached beaches, spits, barriers, and beach ridges, occur in northwestern Indiana and northeastern Illinois, arcing subparallel to the modern shoreline of Lake Michigan (Fig. 1). From most landward to lakeward, they are formally known as the Glenwood, Calumet, and Toleston Beaches. They were defined in their current usage by Leverett (1897), who established reference

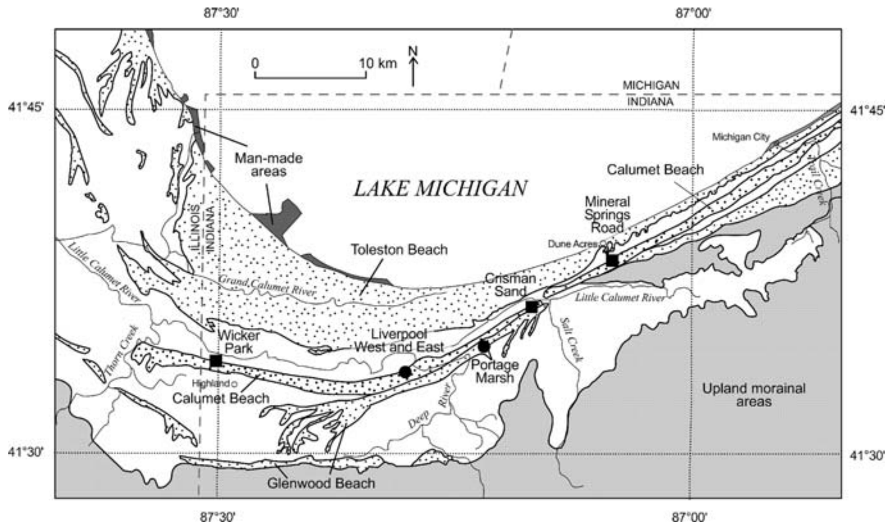

Fig. 1 Map of the southern shore of Lake Michigan showing major relict shorelines and sites referenced in the text. Base map modified from Schneider and Keller (1970)

lake-level elevations of ancestral Lake Michigan for each shoreline at 195, 189, and 184.5 m above mean sea level (AMSL), respectively. More recent workers (Hansel et al. 1985; Hansel and Mickelson 1988; Schneider and Hansel 1990; Thompson 1990, 1992; Thompson and Baedke 1997) added chronological control on the ages of these shorelines using radiocarbon dating, and refined lake-level elevation changes through time.

An Algonquin-phase shoreline, present in the Lake Huron, Lake Superior, and upper Lake Michigan basins, is not generally recognized at the southern end of the Lake Michigan basin. Various theories were proposed concerning the absence of Algonquin coastal features. Goldthwait (1908) favored a hinge-line model where the northern end of the lake was rebounding at progressively higher rates than the southern end, causing inundation and erosion of the Algonquin features in southern Lake Michigan. In this model, a bend, or hinge, occurs in relatively flat isobases that rise abruptly north of Grand Haven, Michigan. This idea was later questioned by Larsen (1987), who proposed an exponential uplift model with a mid-lake outlet to explain the submergence of Algonquin coastal features along the southern margin of the lake. In his model, Algonquin features should be more than 100 m below modern lake level. This model is supported by the geophysical modeling of Clark et al. (1990, 1994).

The absence of Algonquin-phase deposits in southern Lake Michigan is widely accepted by modern Great Lakes researchers (Hansel et al. 1985; Larsen 1987; Hansel and Mickelson 1988; Colman et al. 1994a), although deposits and corresponding radiocarbon dates similar to the timing of the Algonquin phase do occur in southern Lake Michigan (e.g., Schneider and Hansel 1990). In a study of coastal deposits between Dune Acres and Michigan City, Indiana, Thompson (1987, 1990) recovered deposits interpreted as foreshore (swash-zone) sediments at 184.2 m to 185.7 m AMSL along the Calumet Beach at Mineral Springs Road just south of Dune Acres. This elevation is approximately 4 m below the 189 m reference elevation for the Calumet Beach. Additionally, radiocarbon dates of wood and peat taken from within and below the foreshore deposits range in radiocarbon age from 11,500 years to 10,350 years before the present (year B.P.). These dates correspond better with the Main Algonquin phase of Lake Huron, which ranges from 11,200 year to 10,400 year B.P. (Karrow et al. 1975), than with the 11,800- to 11,000-year-B.P. age for the Calumet phase in Lake Michigan (Hansel et al. 1985; Hansel and Mickelson 1988; Schneider and Hansel 1990). Chrzastowski and Thompson (1992, 1994) correlated the 184–185 m foreshore at Mineral Springs Road to a 2.7-m-high erosional scarp (with a basal elevation of 183 m) lakeward of the Calumet

Beach at Wicker Park (Highland, Indiana) near the Illinois-Indiana state line. They suggested that the similar elevation of these two features may represent a former Algonquin water-plane in southern Lake Michigan. Colman et al. (1994a), however, dismissed this interpretation because of inconsistencies in the age control of the shoreline. Regardless of the rebound model and age control, coastal features and deposits lakeward of the Calumet Beach have been only partially addressed in reconstructions of past lake-level change for the basin (e.g., Chrzastowski and Thompson 1992, 1994). The main focus of this study is to examine the geomorphological, sedimentological, paleoecological, and radiocarbon evidence for post-Calumet phase coastal features and deposits along the Indiana shore of southern Lake Michigan and to collect additional data to support or refute their existence.

Methods

U.S. Geological Survey (USGS) 1:24,000-scale topographic maps and 1938 aerial photos along southern Lake Michigan in northwest Indiana were examined to identify geomorphic features associated with former shorelines. Landforms, including beach ridges, terraces, and erosional scarps, were traced. Particular attention was given to the Calumet Beach complex and to proximal lakeward features. Although northwestern Indiana is heavily urbanized and industrialized, relatively undisturbed sites in northwest Indiana are present. In this study, north–south-oriented (roughly onshore–offshore-oriented), transit-surveyed topographic profiles were constructed from the Calumet Beach lakeward at Wicker Park, north of the former site of Crisman Sand Company, Inc., and east of Mineral Springs Road (Fig. 1). Elevations for the profiles were established from U.S. Geological Survey and U.S. National Park Service benchmarks and are reported using the U.S. National Geodetic Vertical Datum of 1929. Fourteen vibracores were collected at strategic points along these profiles, focusing on key geomorphic changes. A ground-penetrating radar (GPR) line using a 250 MHz Sensors and Software Inc. Noggin Smart Cart was taken along the Wicker Park transect to obtain preliminary stratigraphic information on the shallow subsurface. GPR transect lines at the other two sites were unsuccessful in imaging the subsurface because of surface debris and tree roots.

Cores were transported back to the laboratory where they were split, described, sampled, and photographed. Latex peels were created from the cores to preserve them and enhance the visibility of sedimentary structures. Genetic facies, following Thompson and Baedke (1997, their Fig. 2) were defined based on sediment composition, color, texture, and structures. Two different grain-size analysis techniques based on overall grain size were used to process 148 sediment samples. Coarse-grained samples (sand-and gravel-sized) were wet and dry sieved and finer-grained samples (mud-and silt-sized) were analyzed using a hydrometer. Grain-size data were plotted versus depth for each core, and onshore–offshore-oriented cross sections were created and correlated by facies. Peat samples for paleoecological analyses were collected from two cores. Pollen analysis was performed on one sample in each core, macrofossil analysis was performed on two samples in each core, and two samples from each core were scanned for testate amoebae. Processing followed standard procedures (Hendon and Charman 1997; Jackson 1999). One accelerator mass spectrometry (AMS) radiocarbon date and two conventional radiocarbon dates were obtained on the peat. Radiocarbon analyses were performed by Geochron Laboratories, and all ages in this report are radiocarbon years before 1950.

Results

Wicker Park

Wicker Park is at the western end of the Calumet Beach near the Illinois-Indiana state line and north of Ridge Road in northwestern Lake County, Indiana (Fig. 1). West of Wicker Park, the Calumet Beach terminates in a spit but immediately south of the park it is a 10- to 15-m-high

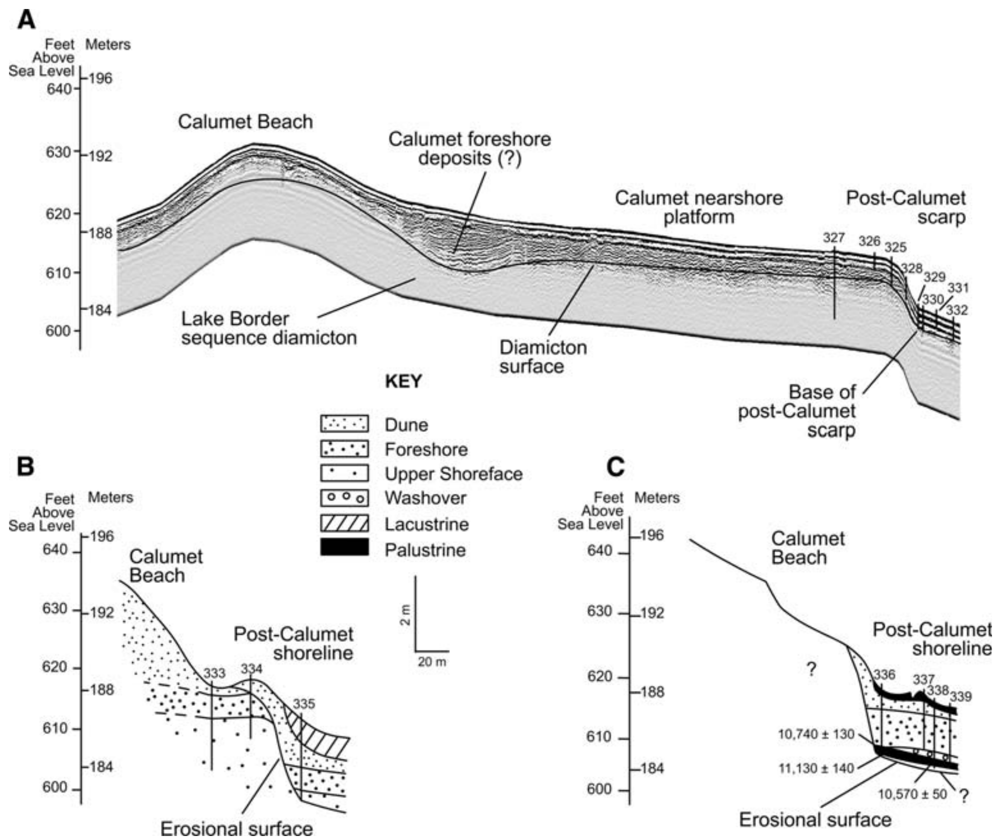

Fig. 2 Schematic cross sections at the Wicker Park (**A**), Crisman Sand (**B**), and Mineral Springs Road (**C**) sites. The Wicker Park cross section is displayed on a ground-penetrating radar profile. Numbered vertical lines are vibracores

dune and beach ridge. A broad and slightly undulating nearshore platform stretches lakeward from the crest of the Calumet Beach for ~280 m and abruptly terminates at a scarp where topographic elevations decrease 2.5 to 3 m to a second flat platform (Fig. 2A). The scarp can be traced eastward of Wicker Park for 15 km where it terminates near the western edge of Deep River (Fig. 1). At Wicker Park, eight cores were collected and a 365-m-long GPR line was run along a lakeward-oriented transect (Fig. 2A).

Cores along the transect at Wicker Park penetrated to a light gray clayey diamicton with quartzite and siltstone pebbles and granules that is interpreted as subglacial till of the Lake Border sequence (Brown and Thompson 1995). The diamicton is clearly identified on the GPR profile where the GPR signal is rapidly dissipated and reflected by the clay-rich nature of the deposit. Landward of the scarp (Cores 325 to 327), the diamicton is overlain by upper shoreface deposits of lakeward-dipping subhorizontal and micro-trough cross-stratified, lower fine- to upper fine-grained sand, sandy gravel, and granular sand. The position of these deposits lakeward of the crest of the Calumet Beach suggests that they are nearshore deposits associated with the Calumet phase of ancestral Lake Michigan. Lakeward of the scarp (Cores 329 to 332) is a mix of poorly sorted and organic-rich muddy sand and sandy gravel. Many of the clasts are locally derived from the diamicton. No recognizable coastal facies occur in these deposits, and they are interpreted to be colluvial. The elevation of the surface of the diamicton (Core 329) beneath the colluvium is 182.8 m AMSL.

The GPR profile shows a bowl-shaped scour at an elevation of ~186 m AMSL beneath the toeslope of the Calumet Beach. The bowl-shaped scour likely represents the location of the Calumet phase foreshore deposits. These probable foreshore deposits were not cored because Ridge Road follows the northern margin of the Calumet Beach; consequently, the Calumet foreshore deposits are inaccessible and probably disturbed at this location. However, we estimate an elevation of 186 m for basal Calumet foreshore deposits at Wicker Park based on the elevation of the base of the scour in the GPR profile.

Crisman Sand

The Crisman Sand site is 0.5 km northeast of the intersection of State Route 249 and Interstate 94 in northwestern Porter County, Indiana (Fig. 1). In this area, a shore-parallel, 2- to 5-m-high, topographic rise occurs 80 to 100 m lakeward of the crest of the 10- to 15-m-high Calumet Beach. Vibracores were collected on the crest and lakeward and landward toeslopes of this post-Calumet beach ridge (Fig. 2B).

The two landward cores (Cores 333 and 334) are capped by dune sediments, consisting of structureless lower to upper fine-grained sand with scattered rootlets throughout. The dune sediments overlie ~1-m-thick foreshore deposits of horizontally to subhorizontally stratified, upper fine- to upper coarse-grained sand. Laminae are defined by alternations in grain size, and the foreshore sequence slightly coarsens downward. Basal foreshore elevations for the Calumet Beach in the two cores range from 186.4 m to 187 m AMSL. Upper shoreface sediments below the foreshore deposits consist primarily of upper fine-grained sand alternating with more coarse-grained sand to granular horizons. Sedimentary structures in the upper shoreface sequence vary from horizontal and subhorizontal parallel laminae to ripple and micro-trough cross-stratification.

Facies within the core-collected lakeward of the post-Calumet ridge (Core 335) are similar to the two landward cores, but the elevation of the basal foreshore deposits is much lower and the dune deposits are overlain by ~2 m of lower to upper fine-grained sand and marly granular sand. The fine-grained sand and marly sand are interpreted as Nipissing-phase lagoonal (back-barrier lacustrine) deposits because of their texture and composition, and occurrence upsection, and therefore, lakeward of the post-Calumet shoreline but landward of the Nipissing-aged Toleston Beach. Thompson (1990) recognized similar deposits in the eastern part of the Indiana Dunes. The elevation of the post-Calumet basal foreshore sediments is 183.2 m. This elevation is 3 m to 4 m below the elevation of the basal Calumet Beach foreshore deposits in the two landward cores.

Mineral Springs Road

The Mineral Springs Road study site is 200 m northeast of the intersection of U.S. Route 12 and Mineral Springs Road in north-central Porter County, Indiana (Fig. 1). The Calumet Beach in this area is a mainland-attached beach that truncates the Glenwood Beach at the western end of the Lake Border Moraine. Reconnaissance in the area suggests that a discontinuous 1- to 1.5-m-high ridge occurs ~100 m north and ~6 m below the crest of the Calumet Beach. This post-Calumet ridge is difficult to trace because of disturbances along U.S. Route 12 and the Chicago Southshore and South Bend Railroad that both follow the lakeward margin of the Calumet Beach. Only south of Dune Acres, Indiana, where U.S. Route 12 shifts southward and correspondingly upward on the Calumet Beach, is this subtle ridge exposed. Three vibracores were collected along a north–south-oriented (onshore to offshore) transect (Fig. 2C), and an additional vibracore was collected lakeward of Core 14 of Thompson (1990).

Because the cores were collected along the landward margin of an area of active peat accumulation, all the cores have 0.3 m to 0.6 m of fibrous peat at the top of the core. The peat overlies 0.25 m to 0.5 m of structureless lower fine- to upper medium-grained dune sand. The dune deposits overlie a thick sequence of foreshore sediments consisting of 1.9 m to 2.1 m of upper fine- to upper coarse-grained sand and sandy gravel. Some sandy gravel beds contain woody plant debris. Some of the cores were disturbed by the vibracoring, but undisturbed cores contain a horizontal to lakeward-dipping subhorizontal stratification in the foreshore deposits. Core 337 contained some ripple cross-stratification in the upper part of the foreshore. Basal foreshore elevations increase landward and range from 185.2 m to 185.9 m AMSL. The foreshore deposits overlie fibrous peat in the landward cores, but in the more lakeward core the foreshore deposits overlie 0.3 m of horizontally stratified, upper fine- to upper medium-grained sand containing disseminated and layered plant debris. We interpret this sand as a possible washover deposit.

Three of the four cores recovered fibrous peat below the foreshore and washover deposits. Core 337 was unable to penetrate the gravelly basal foreshore deposits above the peat. Macrofossil analysis revealed that peat from Cores 336 and 338 was dominated by *Sphagnum* moss remains. A few *Viola* (violet) seeds and *Picea* (spruce) needles were also recovered from the peat in Core 338. In the upper 8 cm of peat in Core 336, there were also achenes of *Carex* and *Scirpus americanus* (sedges), fruits and seeds of *Potamogeton* and *Najas* (submerged aquatics), and needles of *Larix laricina* (tamarack). Seven testate amoebae taxa were encountered in the peat samples from Cores 336 and 338. These included *Arcella artocrea* Leidy type, *Assulina muscorum* Greef, *Assulina seminulum* (Ehrenberg) Leidy, *Bullinularia indica* Penard, *Centropysis cassis* (Wallich) Deflandre type, *Cyclopyxis arcelloides* (Penard) Deflandre type, and *Trigonopyxis arcula* (Leidy) Penard. Testate amoebae were not recovered from the portion of the Core 336 that contained submerged aquatic plants. The percentage of pollen taxa in two 1-cm-thick samples from Cores 336 and 338 are shown in Table 1. Bulk radiocarbon dates taken from the base and top of the peat in Core 336 yielded ages of 11,130 ± 140 and 10,740 ± 130 year B.P., respectively; a sample of *Sphagnum* moss from the middle of the peat in Core 338 yielded an AMS age of 10,570 ± 50 year B.P. (Table 2).

Table 1 Percentage of pollen taxa in peat samples from Cores 336 and 338

	Core 336, 2.83–2.84 m	Core 338, 3.31–3.32 m
Abies (fir)*	2.3	0.5
Acer rubrum (red maple)*	0.6	1.4
Betula (birch)*	5.1	7.8
Carya (hickory)*	0.6	0.5
Cupressaceae (Thuja/Juniperus)	1.1	6.4
Fagus (beech)*	0.6	0.0
Fraxinus americana (american ash)*	1.1	1.4
Fraxinus nigra (black ash)*	1.7	7.4
Larix (tamarack)	0.0	0.9
Ostrya/Carpinus (ironwood)*	0.6	1.4
Picea (spruce)*	56.0	24.3
Pinus Subgenus *Pinus* (jack/red pine)*	4.6	5.0
Pinus Subgenus *Strobus* (white pine)*	0.6	2.8
Pinus undifferentiated*	10.9	15.6
Quercus (oak)*	8.6	8.3
Tilia (basswood)*	0.0	0.5
Tsuga (hemlock)*	0.0	0.5
Ulmus (elm)*	4.0	15.6
Monolete spores (fern)	0.0	1.4
Pteridium (bracken fern)	0.0	0.7
Ambrosia (ragweed)	1.2	2.1
Arceuthobium (mistletoe)	0.2	0.0
Artemisia (sagebrush)	0.7	1.7
Caryophyllaceae	0.0	0.3
Chenopodiaceae/ Amaranthaceae	0.7	1.4
Cyperaceae (sedge)	2.2	0.0
Poaceae (grass)	34.2	10.0
Tubuliflorae	0.7	2.1
Alnus (alder)	17.7	1.7
Ericaceae (heath)	0.0	0.7
Salix (willow)	0.5	2.4

Taxa with asterisks are arboreal taxa that were used for the ordination in Figure 3

Discussion

Topographic profiles, vibracores, and a GPR profile collected in this study supplemented with a survey of aerial photographs indicate that a scarp exists along the lakeward margin of the Calumet Beach from roughly the Illinois-Indiana state line to just west of Deep River. At Wicker Park this scarp is 2.5 m to 3 m high and cut into the lakeward edge of a platform of Calumet upper shoreface deposits and older diamicton. To the east, the scarp is less pronounced, especially where it occurs through numerous housing communities; however, a Calumet nearshore platform is observable that gently slopes from ~188 m to ~186 m AMSL. The platform and scarp end in the Liverpool west site of Schneider and Hansel (1990). East of the mouth of Deep River, the

Table 2 Radiocarbon dates from this study and Thompson (1987, 1990)

Lab number	Core	Material dated	Depth	^{14}C year B.P.	Cal year B.P. 2 sigma
GX-28492	336	Peat	2.80 m	10,740 ± 130	12,381–12,951
GX-28493	336	Peat	2.96 m	11,130 ± 140	12,855–12,256
GX-28491-AMS	338	*Sphagnum* moss	3.22 m	10,570 ± 50	12,550–12,776
ISGS-1355	14	Rounded wood fragments	2.91 m	11,490 ± 130	13,119–13,641
ISGS-1354	14	Wood fragments	3.22 m	10,350 ± 380	11,074–12,996
ISGS-1327	14	Peat	3.26 m	10,440 ± 110	11,995–12,744
Beta-20633	15	Wood	2.43 m	10,610 ± 110	12,340–12,844

Calumet nearshore platform is narrower, and where it is not disturbed, a 1- to 5-m-high beach ridge may be observed. We have been unable to trace the ridge farther than 1.7 km east of Mineral Springs Road because of road and railroad construction. The erosional scarp and beach ridge indicate that a post-Calumet water plane existed in northwestern Indiana and that the shoreline associated with this water plane was primarily depositional east (updrift) of Deep River and primarily erosional west (downdrift) of the river's mouth. Of particular importance is the elevation and age of this post-Calumet water plane with respect to the main Calumet Beach.

Elevation

Thompson (1992), Thompson and Baedke (1997), and Baedke et al. (2004) have shown that the elevation of past lake level can be reconstructed from the elevation of foreshore deposits. Specifically, the elevation of the basal contact of the foreshore deposits is a close approximation of the elevation of the lake when the foreshore sediments accumulated. Foreshore deposits were recovered at the Crisman Sand and Mineral Springs Road sites. The Crisman Sand site has basal foreshore contacts at two separate elevations. Basal foreshore contact elevations for the Calumet Beach range from 186.4 m to 187 m, whereas the basal foreshore contact of the post-Calumet deposits is 183.2 m AMSL. These elevations suggest a 3- to 4-m difference in lake level between the Calumet phase of ancestral Lake Michigan and the post-Calumet shoreline. A similar relationship occurs at the Wicker Park site. At Wicker Park, the interpreted elevation of basal Calumet foreshore deposits is ~186 m AMSL and the base of the post-Calumet scarp is about 3 m lower at 182.8 m AMSL. At the Mineral Springs Road site, basal foreshore elevations for the post-Calumet shoreline range from 185.2 m to 185.9 m AMSL. Thompson (1990, his Fig. 5), however, shows that these foreshore deposits extend ~150 m north of the Mineral Springs Road site. Here, the basal foreshore contact occurs at 184 m AMSL, indicating that lake level fell ~2 m during the development of the post-Calumet shoreline. Unfortunately, no cores have been collected farther landward and higher in elevation at the Mineral Springs Road site; these would recover Calumet Beach foreshore deposits and define Calumet phase water levels.

Thompson (1987) collected 10 cores along the lakeward margin of the Calumet Beach from Dunes Acres to Michigan City, Indiana. These cores recovered foreshore deposits that Thompson (1990) interpreted to have accumulated during the Calumet phase of ancestral Lake Michigan. The cores, however, were collected in the same position relative to the Calumet Beach as the post-Calumet ridge at the Crisman Sand and Mineral Springs Road sites. The foreshore deposits are most likely post-Calumet. Basal foreshore contacts show some variability depending on the onshore-offshore position of the core site relative to the toeslope of the Calumet Beach, but they primarily occur at 184 m AMSL from Dune Acres to Michigan City. No peat was recovered beneath the foreshore deposits east of the Mineral Springs Road site.

Schneider and Hansel (1990) also described and illustrated deposits along the lakeward margin of the Calumet Beach platform at the Liverpool West and East sites. These sites are midway along depositional strike between the Wicker Park and

Crisman Sand study areas. At the Liverpool West site, Calumet and post-Calumet deposits were exposed in a currently flooded borrow pit. A stratigraphic section for the Liverpool West site (Schneider and Hansel, 1990, their fig. 7) shows a basal till (diamicton) of the Lake Border sequence overlain by sand, gravel, clay, and peat. A peat layer less than 1 m above the diamicton surface was dated at 11,815 ± 640 year B.P. This Two Creeks (pre-Calumet) phase peat is overlain by ~6 m of stratified sand, clay, and cross-bedded sand with gravel lenses. Two peat layers ~2 m below the top of the exposure were dated at 9,110 ± 640 year B.P and 10,890 ± 560 year B.P. Although detailed descriptions of the sediments are not available, the lower sand, clay, and cross-bedded sand with gravel lenses that are positioned lakeward of the main crest of the Calumet Beach and on the Calumet Beach platform suggests that they are probable Calumet upper shoreface deposits. Sand and gravel overlying the two upper peats may be post-Calumet foreshore deposits, but these sediments are about 4 m higher than post-Calumet foreshore deposits at the Crisman Sand site. An examination of the stratigraphic section suggests that it is plotted about 3.5 to 4 m too high. The top of the section is shown at 189 m (620 ft) AMSL, but the entire site is enclosed by a 186-m (610-ft) AMSL contour on the USGS Gary, Indiana, quadrangle topographic map (1986). Also, the basal diamicton is shown at 183.4 m AMSL, but Brown (1994) mapped the surface of the Lake Border sequence diamicton from 177 m (580 ft) to 180 m (590 ft) throughout the area. Clearly, the section is illustrated at the wrong elevation. It would be more in line with the Wicker Park and Crisman Sand sites if the plotted section was ~3.7 m lower. The Liverpool East site also exposes an organic horizon between two ~2-m-thick sands. The lower sand with gravel may be Calumet upper shoreface deposits; the upper sand is interpreted by Schneider and Hansel (1990) as eolian. Unfortunately, no elevations are reported for these deposits, but the peat and associated organic materials were radiocarbon dated five times resulting in ages ranging from ~11,300 year to 9,100 year B.P. A reexamination of these sites is needed to clarify elevations of coastal deposits, better describe sediment characteristics and stratigraphic relationships, and evaluate the paleoecology of the organic horizons.

For the post-Calumet shoreline, combining all the Calumet and post-Calumet sites together indicates a slightly westward-dipping water plane that is ~3 m below a similarly westward-dipping Calumet Beach water plane. More cores of Calumet Beach foreshore deposits are needed to better define the elevation and long-term behavior of Calumet phase lake level. Obtaining undisturbed Calumet Beach nearshore sediments will be difficult in this heavily urbanized and industrialized area.

Age

At the Mineral Springs Road site, foreshore deposits overlie peat lakeward of the Calumet Beach. This stratigraphic and spatial relationship indicates that lake level fell from the Calumet phase, a wetland developed lakeward of the Calumet Beach, and the wetland was inundated by a landward-transgressing post-Calumet shoreline. Age determinations on the base and surface peat, therefore, provide a minimum age for the abandonment of the Calumet Beach and a maximum age for the development of the post-Calumet shoreline, respectively. The base of the peat in Core 336 was bulk radiocarbon dated at 11,130 ± 140 year B.P. Hansel et al. (1985), Hansel and Mickelson (1988), and Schneider and Hansel (1990) place the end of the Calumet Phase at roughly 11,000 year to 11,200 year B.P. The basal age on the peat at Minerals Springs Road indicates that the wetland formed and began accumulating organic material at the end of the Calumet phase. The bulk radiocarbon age determination from the top of the peat in Core 336 is 10,740 ± 130 year B.P., suggesting that washover and foreshore deposits from the landward-translating post-Calumet shoreline covered or partially covered the peatland by ~10,700 year B.P.

The AMS age determination for *Sphagnum* moss from the upper few centimeters of the Core 338 peat is slightly younger at 10,570 ± 50 year. B.P. than the bulk age from the top of the peat in Core 336. Most *Sphagnum* species are intolerant of strong ground-water influence (Andrus 1986; Crum 1988), therefore, the AMS radiocarbon date on *Sphagnum* remains should not be influenced by any radiocarbon-dead carbonates present in the ground water. Testate amoebae, amoeboid protozoans that produce a decay-resistant shell, provide additional support for only limited ground-water influence at the surface of the peatland. The distribution of testate amoebae in *Sphagnum*-dominated peatlands is primarily controlled by moisture conditions, and secondarily by pH, trophic status, and other aspects of water chemistry (Woodland et al. 1998; Mitchell et al. 2000; Booth 2001, 2002; Charman 2001). The species of testate amoebae recovered from the peat all have optimum abundance today in relatively dry and low pH habitats (Booth 2001, 2002). Together, the macrofossil and testate amoeba data suggest that the peatland lakeward of the Calumet Beach at Minerals Springs Road was a *Sphagnum*-dominated poor fen or bog, with little standing water except for upper portions of Core 336. Upper portions of Core 336 were probably deposited under fluctuating hydrologic conditions that may possibly have been caused by the landward-translating post-Calumet shoreline.

Pollen data collected from the peat in Cores 338 and 336 are consistent with the ^{14}C age determinations. Pollen assemblages prior to ~11,500 to 10,000 year B.P. in northern Indiana and southern Michigan are characterized by high *Picea*, *Pinus*, and *Cyperaceae* percentages (e.g., Williams 1974; Futyma 1988; Singer et al. 1996), probably reflecting the dominance of open *Picea* woodlands at this time (Webb et al. 1983). Between 11,000 year and 10,000 year B.P., a mixed forest dominated by *Picea*, *Betula*, *Fraxinus*, and *Ulmus* developed, and by 10,000 year B.P. forests dominated by *Pinus* and *Quercus* became established (Webb et al. 1983; Singer et al. 1996). The peat sample from Core 336 contains relatively high percentages of *Picea*, *Fraxinus*, and *Ulmus* (Table 1) and is characteristic of the mixed forest that developed in the region between 11,000 year and 10,000 year B.P. The sample from Core 338 contains very high percentages of *Picea* and *Poaceae* pollen, as well as moderately high *Ulmus* pollen (Table 1). The much larger *Picea* percentages in the sample from Core 338 suggest that the sample may be several hundred years older than the sample from Core 336. These interpretations are also supported by a quantitative comparison between the arboreal pollen assemblages in the Mineral Springs Road peat and the pollen record of nearby AMS-dated Portage Marsh (Singer et al. 1996) (Fig. 1). Detrended correspondence analysis reveals that pollen assemblages from the Mineral Springs Road peat are most similar to samples at Portage Marsh that are between 10,000-years and 11,000-years old (Fig. 3).

Additional bulk radiocarbon age determinations on the peat at Mineral Springs Road are available from Core 14 of Thompson (1990). This core is similar to Cores 336 to 338 with dune deposits over foreshore, washover, and paludal deposits. The top of the peat was dated at 10,440 ± 140 year B.P., and wood fragments from the base of overlying washover deposits were dated at 10,350 ± 380 year B.P. Upsection, rounded wood fragments were dated at 11,490 ± 130 year B.P. at the contact between the washover and overlying foreshore deposits. The wood fragments were obviously transported because they are rounded. Consequently, the age determination is not meaningful because the provenance of the wood cannot be determined, and its position within the transgressive sequence means that the radiocarbon date has no stratigraphic significance. Thompson (1987, his Core 15) also collected a large wood fragment of *Pinus* cf. *banksiana* between post-Calumet dune and foreshore deposits 250 m west of Mineral Springs Road. This piece of probable driftwood radiocarbon dates at 10,610 ± 110 year B.P.; similar to the rounded wood fragments in Core 14, the radiocarbon date has limited stratigraphic significance. Radiocarbon dates on the probable post-Calumet organic deposits at the Liverpool East and West sites are similar to age determinations at Minerals Springs Road, but no stratigraphic correlation of palustrine deposits can be established between the sites. The large error on the Liverpool West samples and the lack of a stratigraphic context for the Liverpool East site makes these ages difficult to evaluate. We infer, however, that the palustrine deposits at the Liverpool

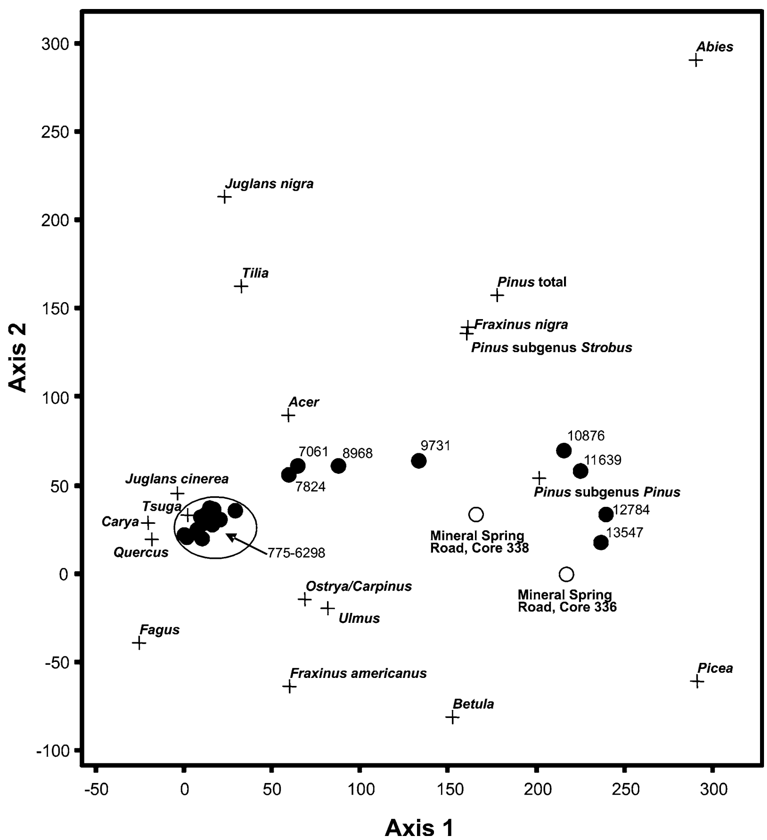

Fig. 3 Detrended correspondence analysis for arboreal pollen taxa from the Mineral Springs Road peat (open circles) and Portage Marsh (closed circles) (Singer et al. 1996), with radiocarbon ages (year B.P.) for the samples from Portage Marsh indicated. Centroids for pollen taxa are also shown. Axis 1 explains 96 percent of the variance, and generally represents a gradient from older samples on the right to younger samples on the left. The position of Mineral Springs Road peat samples along axis 1 suggests that they are between 10,000 and 11,000 years old, consistent with the ^{14}C age determinations

sites and Mineral Springs Road are most likely time-equivalent.

Radiocarbon dates collected from the surface of the peat at Mineral Springs Road from this study and Thompson (1990) were compared using the techniques of Ward and Wilson (1978) to determine if they represented the same time period. Using a χ^2-probability of 0.05, the dates and their error were accepted as a homogenous population. The pooled mean age with error is calculated at 10,560 ± 70 year B.P. Although only one basal peat date is available, the age determinations at Mineral Springs Road suggest that the wetland formed at about 11,100 years ago and existed for about 500 years before being transgressed by washover and foreshore deposits about 10,600 years ago. The pooled mean age is a maximum age for the creation of the post-Calumet shoreline. Basal foreshore elevations and the age of the post-Calumet shoreline indicate the existence of a high-elevation shoreline in southern Lake Michigan that is similar in elevation and age to the Main Algonquin phase of Lake Huron (cf. Eshman and Karrow 1985; Karrow et al. 1975, 1995).

Shoreline development

Four scenarios are possible for the development of the post-Calumet shoreline along southern Lake Michigan (Fig. 4).

Scenario 1

Chrzastowski and Thompson (1992, 1994) proposed that the post-Calumet shoreline formed after the Lake Michigan ice lobe retreated from the Lake Michigan basin, permitting the water in the Lake Michigan and Huron basins to join. When the lakes joined, the elevation of ancestral Lake Huron was lower than that of Lake Michigan, and Lake Michigan rapidly fell to an elevation of 180 m AMSL. A subsequent rise in the elevation of the water in the Lake Michigan basin occurred as Lake Huron rose to the Main Algonquin level.

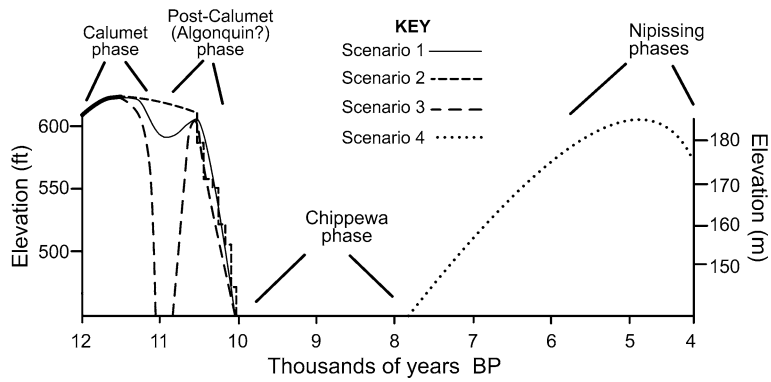

Fig. 4 Schematic lake-level hydrograph illustrating possible lake-level behavior to create the post-Calumet shoreline

Scenario 2

The retreat of the Lake Michigan ice lobe joined Lake Michigan and Lake Huron at the Main Algonquin level or one of the post-Algonquin phase levels. Combined with Lake Huron, Lake Michigan underwent similar stair-step lowerings of lake level throughout the post-Algonquin as glacial ice margin retreated from northern Lake Huron (cf. Eshman and Karrow 1985). The post-Calumet shoreline is time-equivalent to one of the post-Algonquin phase levels.

Scenario 3

The post-Calumet shoreline formed during the Moorhead phase influx from glacial Lake Agassiz around 10,900 year to 9,900 year B.P. (Clayton 1983; Teller 1985, 1987) that raised lake level in the Lake Michigan basin high enough to reach the post-Calumet level. Colman et al. (1994a, 1994b) correlated the gray Wilmette Bed of Lake Michigan to the Moorhead discharge, establishing glacial Lake Agassiz influence in the Lake Michigan basin at the time that the post-Calumet shoreline formed. Kehew (1993) suggested that the influx of this glacial Lake Agassiz water was also instrumental in eroding the Chicago outlet from the Calumet to the Nipissing I level.

Scenario 4

The post-Calumet shoreline formed along the southern margin of a lagoon between the Calumet and Toleston Beaches sometime during the Nipissing I phase of ancestral Lake Michigan. Thompson (1990) showed that basal foreshore deposits in the landward (Nipissing) part of the Toleston Beach occur at an elevation of 182.8 m AMSL. Water level in the lagoonal area landward of the Toleston Beach would have been at the same elevation as the base of the scarp at Wicker Park.

Scenario 2 is the least likely of shoreline development mechanisms, because it is not possible for palustrine sediments to accumulate beneath nearshore deposits during the post-Algonquin lake-level fall. A lake-level rise is needed to transgress the wetlands at the Mineral Springs Road and Liverpool sites. The eroding outlet model of Kehew (1993) suggests that lake-level is at the elevation of the Calumet phase when outburst water discharged from glacial lake Agassiz. It is possible that the Morehead influx downcut the Chicago outlet, but the palustrine sediments beneath nearshore deposits for the post-Calumet shoreline indicate that lake level was already below the post-Calumet level prior to being transgressed. Scenario 4 is also unlikely because the ages of the palustrine deposits at Mineral Springs Road and Liverpool are more than 4,000 years older than the Nipissing I phase. It is possible, however, that the peat was eroded and that younger palustrine sediments were removed, leaving only deposits that are 10,600 years old and older. In Scenario 4, the Calumet Beach nearshore and underlying diamicton would be eroded and 3 m of dune and nearshore sediments deposited along the southern margin of a shallow-water lagoon. It is not likely that wave activity was sufficient to erode the Calumet nearshore and till, and a source of littoral sediment would not be available landward of the Toleston Beach to build the post-Calumet beach ridge. Scenarios 1 and 3 both involve rising water-levels in the basin at the appropriate time that could scarp the Calumet nearshore and transgress palustrine sediments. It is not possible at this time to distinguish between the two possible scenarios, but we favor Scenario 1 because Scenario 3 may have been too short-lived to have significant impact on shoreline behavior along the southern shore of Lake Michigan.

Rebound

A high-elevation Algonquin-aged shoreline along the southern shore of Lake Michigan is inconsistent with the rebound model of Larsen (1987) and favors the longstanding model of Goldthwait (1908). The Larsen (1987) model is theoretically sound and adequately represents Algonquin-aged shorelines north of the Goldthwait (1908) hinge line. Some other behavior besides uniform exponential uplift must be working within the basin to permit the development of the post-Calumet shoreline in Indiana.

A recent study of differential ground movement between lake-level gages was conducted by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data [Coordinating Committee] (2001) (Fig. 5). These data, referenced to the Port Huron outlet for Lakes Michigan and Huron, show that isostatic rebound does not uniformly increase from the southern tip of Lake Michigan northeastward. An area of decreased rate of rebound extends across the lake from Milwaukee, Wisconsin, to Ludington,

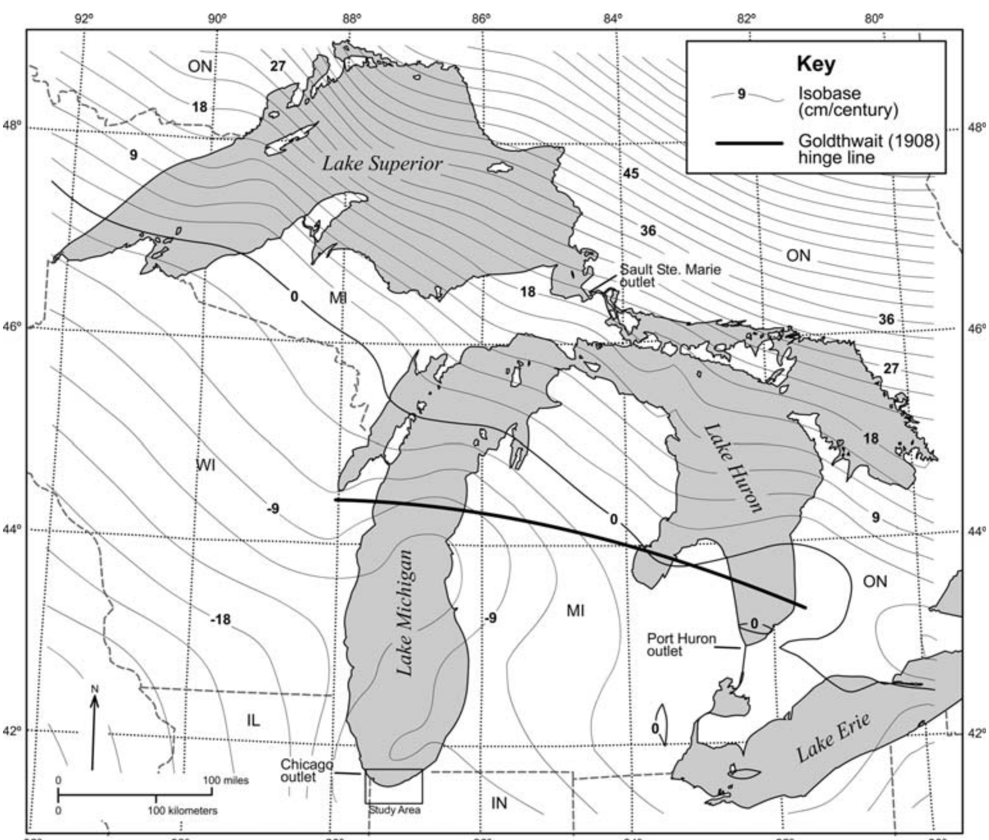

Fig. 5 Map of the upper Great Lakes, showing rates of vertical ground movement from historical lake-level gage records and the position of the Goldthwait (1908) hinge line for the Main Algonquin phase. Modified from Coordinating Committee (2001) and Goldthwait (1908)

Michigan. Rates of rebound increase northward and slightly southward from this area. In effect, the modern gage data illustrate vertical ground movement that is somewhat similar to the Goldthwait (1908) hinge model (Fig. 5). This new interpretation of historical gage data is based on longer data sets and additional gaging sites that were not available to Larsen (1987) or Clark et al. (1994) who used Coordinating Committee (1977) data.

The post-Calumet shoreline of southern Lake Michigan is elevation-and time-equivalent to the Main Algonquin of southern Lake Huron. The gage data of the Coordinating Committee (2001) show that the southern shore of Lake Huron is relatively rising 9 to 12 cm/century more rapidly than the southern tip of Lake Michigan (Fig. 5). Following the Coordinating Committee (2001) data and projecting modern rates into the past, the post-Calumet shoreline of southern Lake Michigan should be 9.5 m to 13 m lower than coastal features and deposits of similar age along southern Lake Huron. Baedke and Thompson (2000), however, have shown that during the late Holocene the southern shore of Lake Michigan was rising more rapidly (19 cm/century) than the Port Huron outlet before 1,400 cal year B.P. and less rapidly (–7 cm/century) than the Port Huron outlet after 1,400 cal year B.P. The pattern observed by the Coordinating Committee (2001), therefore, may hold for only the past 14 centuries, yielding an elevation difference between southern Lake Michigan and southern Lake Huron of no more than –1.2 m to –1.7 m. Such a slight difference in the elevation of coastal features and deposits between locales that are 450 km apart is probably not recognizable.

Conclusions

Geomorphological, sedimentological, paleoecological, and radiocarbon data indicate that deposits and features of a relict shoreline are present along the lakeward margin of the Calumet Beach in northwestern Indiana. This post-Calumet shoreline was primarily erosional west of Deep River but primarily depositional east of the river. The elevations of basal foreshore deposits east of Deep River and the base of the scarp west of Deep River indicate a slightly westward-dipping water plane for the shoreline that is centered at ~184 m AMSL. Basal foreshore elevations also indicate that lake level fell ~2 m during the development of the shoreline. Post-Calumet foreshore deposits overlie peat at Mineral Springs Road, and the pooled mean of radiocarbon dates from the surface of the peat indicates that the lake transgressed over the peat at 10,560 ± 70 year B.P. Pollen assemblages from the peat are consistent with this age. The elevation and age of the post-Calumet shoreline is similar to the Main Algonquin phase of Lake Huron. Recent isostatic rebound models do not adequately address a high-elevation Algonquin-age shoreline along the southern shore of Lake Michigan. The long-standing hinge-line model of Goldthwait (1908) is consistent with a high-elevation shoreline, and this model, or a model very similar to it, may best fit reconstructions of ground deformation in the upper Great Lakes from historical gage records.

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