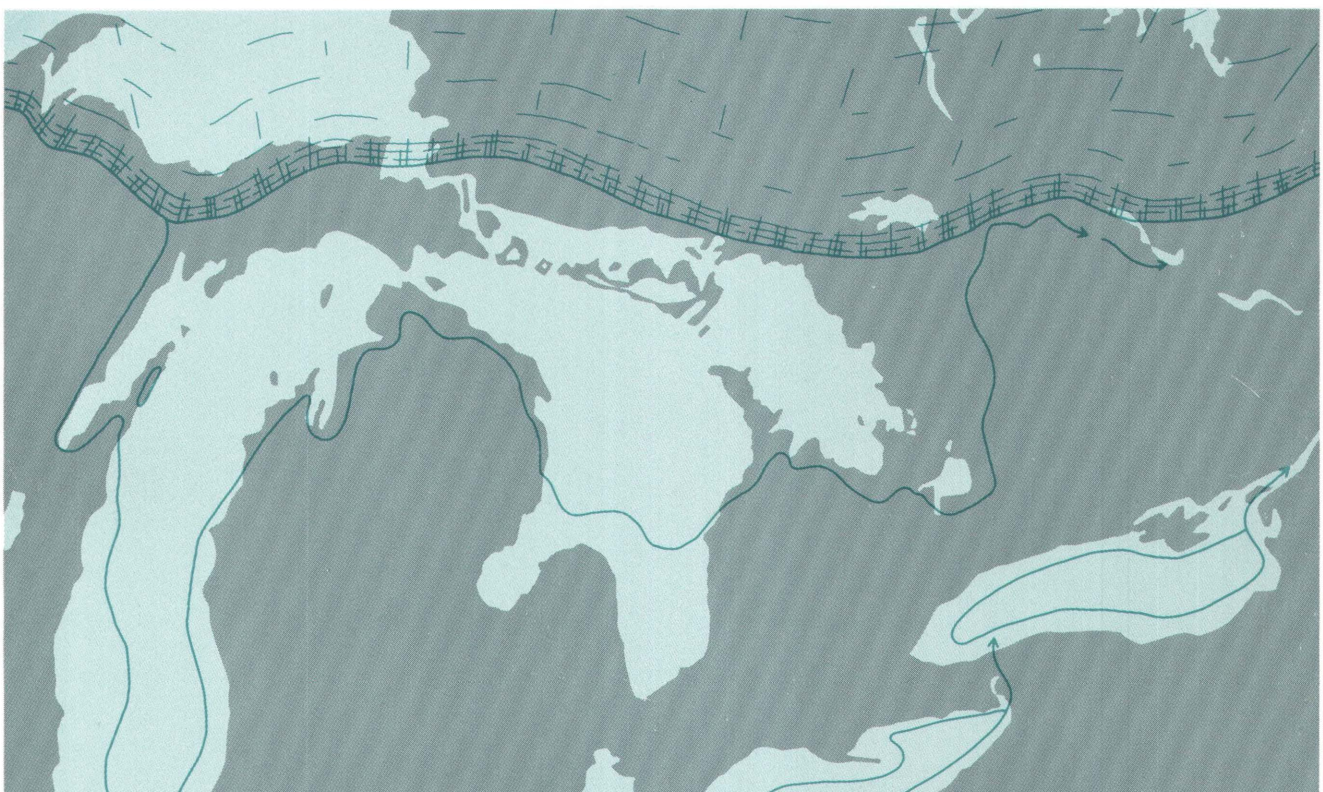
Geological History of Glacial Lake Algonquin and the Upper Great Lakes



U.S. GEOLOGICAL SURVEY BULLETIN 1801

Cover. Main Algonquin level of Lake Michigan confluent with the Orillia (?) level of the Lake Huron basin (11,200 to 11,000 yr B.P.).

Geological History of Glacial Lake Algonquin and the Upper Great Lakes

By CURTIS E. LARSEN

U.S. GEOLOGICAL SURVEY BULLETIN 1801

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By Curtis E. Larsen

Abstract

Lake-level gauge records show modern tilting of the entire Great Lakes basin at rates ranging from 0.53 m/century in the north to 0.08 m/century in the south. This pattern of historic deformation is used in this study as a control to describe the upper or Main Algonquin shoreline. Regression analyses calculated on the uplifted Algonquin beach features show them to descend exponentially with distance to the south. The projected Main Algonquin–Fort Brady shorelines (about 11,200 to 10,500 B.P.) plunge below the level of Lake Michigan at the "hinge line" of former models and intersect the southern lake bottom between altitudes 60 and 95 m.

Red glaciolacustrine clays, contained in the Sheboygan Member of the Lake Michigan Formation and transported by meltwater from the Lake Superior basin, are contemporary with the Main Algonquin–Fort Brady shorelines. The descending altitude of these red clays to the south points to continuous deformation of the lake basin as low-level lakes drained northward through lower outlets near North Bay, Ontario.

Comparative regression analyses of the Main Algonquin shoreline data between lake basins show the Main Algonquin of Huron (MAH) to lie altitudinally above the Main Algonquin of Michigan (MAM). The MAH was a separate low-level proglacial lake with an outlet control at Fenelon Falls, Ontario. Its level fell when the isostatically lower Kirkfield outlet system was deglaciated about 11,500 B.P. The MAM, on the other hand, reflects a confluent low-level lake in the Michigan and Huron basins that formed upon deglaciation of the Mackinac Straits about 11,200 B.P. The MAM drained northward through the Fossmill outlet system south of North Bay, Ontario.

INTRODUCTION

Lake Algonquin is currently thought to be the largest and latest proglacial lake to occupy the three upper Great Lakes (fig. 1). It is currently considered to have drained southward through the St. Clair River at Port Huron, Mich., and through the Des Plaines and Illinois River valleys near Chicago, Ill.

The Algonquin shoreline was first described along the eastern shore of Lake Huron by Spencer (1888, 1891), who named it and noted that it had been differentially uplifted. Subsequent work by Taylor (1894), Goldthwait (1906, 1907, 1908, 1910a,b), and Leverett and Taylor (1915) defined the highest or upper Algonquin shoreline in the Lake Michigan basin. The shoreline features of this former lake had been deformed from an area of minimum displacement in the south to progressively higher altitudes in the north. The zone at which steeply sloping northern terraces blended with a relatively horizontal terrace in the south was identified as a hinge line (fig. 2). This explanation, which has varied little since the first decade of this century, reflects the rigid-earth models favored by the early researchers in the region (Chamberlin and Salisbury, 1904; Chamberlin, 1909, 1926; Taylor, 1910).

The Algonquin shoreline, as defined, has subsequently been used to establish postglacial lake-level chronologies in the upper Great Lakes region (most recently Drexler and others, 1983; Farrand and Drexler, 1985). More important, however, is that the deformation of the Algonquin shoreline has been used to model the glacio-isostatic recovery of the Great Lakes basin (Broecker, 1966, 1970; Walcott, 1970, 1972; Brotchie and Silvester, 1969). Thus, ironically, the geomorphic interpretations of the rigid-earth era are used to examine the responses of a visco-elastic crust to ice loading.

This paper investigates the nature of the deformed Main Algonquin shoreline in the Lake Michigan basin and the concept of the hinge line. In an earlier paper (Larsen, 1985b), the rates of measured vertical crustal movements, as determined from lake-level gauge records (Clark and Persoage, 1970; Coordinating Committee on Basic Hydraulic and Hydrologic Data, 1977), were shown to increase exponentially with distance northward from the southern shore of Lake Michigan. Following Gilbert's (1898) suggestion that measured vertical crustal movements were central to understanding the uplift history of the Great Lakes, the middle Holocene Nipissing and Algoma shorelines were also shown to conform to an exponential model (Andrews, 1970a,b).

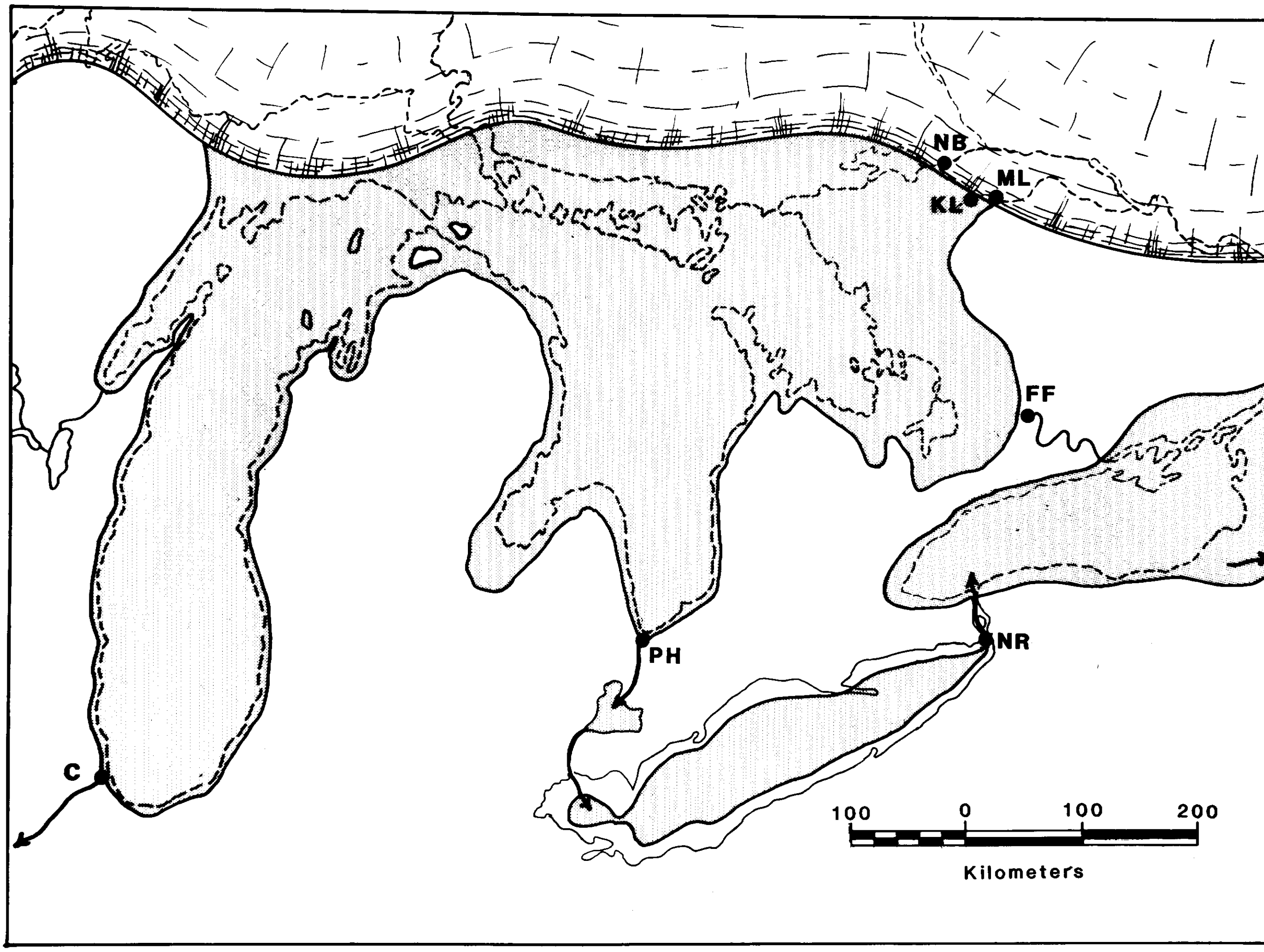


Figure 1. Main Lake Algonquin draining southward through the Chicago (C) and Port Huron (PH) outlets. The Fenelon Falls (FF) spillway to the Kirkfield outlet has been abandoned. The northern outlets remain ice covered. KL and ML are the Kilrush Lake and Mink Lake sills that controlled overflow through the Fossmill outlet. NB is the threshold to the North Bay outlet. Early Lake Erie drains eastward through the Niagara River (NR) to Lake Iroquois in the Lake Ontario basin. (Based on Hough, 1958, 1963; Eschman and Karrow, 1985.)

Comparison among the historic, middle Holocene, and late Wisconsinan deformation of the former shorelines suggests that (1) uplift was a continuous glacio-isostatic response to deglaciation of the region, (2) the hinge line of former usage is an invalid concept, (3) the Main Algonquin water plane of Lake Michigan reflected a low-level phase of the upper lakes, and (4) Main Lake Algonquin did not overflow to the south. Instead, the Main Algonquin shorelines of Lake Michigan and Lake Huron appear to be of dissimilar age and to have discharged first through the Kirkfield outlet to the Lake Ontario basin (Main Algonquin of Huron) and then through the Fossmill outlet network to the Ottawa River valley (Main Algonquin of Michigan).

Acknowledgments

Several working drafts of this paper were commented on by colleagues whose insights have helped me better understand the Great Lakes. Peter Sly deserves special thanks for patiently reading each draft and providing thoughtful comments. Both he and Christine Kaszycki shared data with me and increased my awareness of the Lake Huron basin. Paul F. Karrow and C.F.M. Lewis provided perspectives on their own Great Lakes research. L. Harvey Thorleifson commented on uplift models and the complexities of drainage from Lake Agassiz, a topic not yet fully explored in the upper Great Lakes. Ardith Hansel provided an ongoing appraisal of her research and has shared important data. David Rea made available unpublished Lake Michigan cores, and Lee Clayton gave many important suggestions. James A. Clark and I are pursuing similar research goals concerning Great Lakes uplift but from different perspectives. We have profited from discussions and an exchange of manuscripts. Byron Stone, Juergen Reinhardt, and William Farrand provided helpful reviews of this paper.

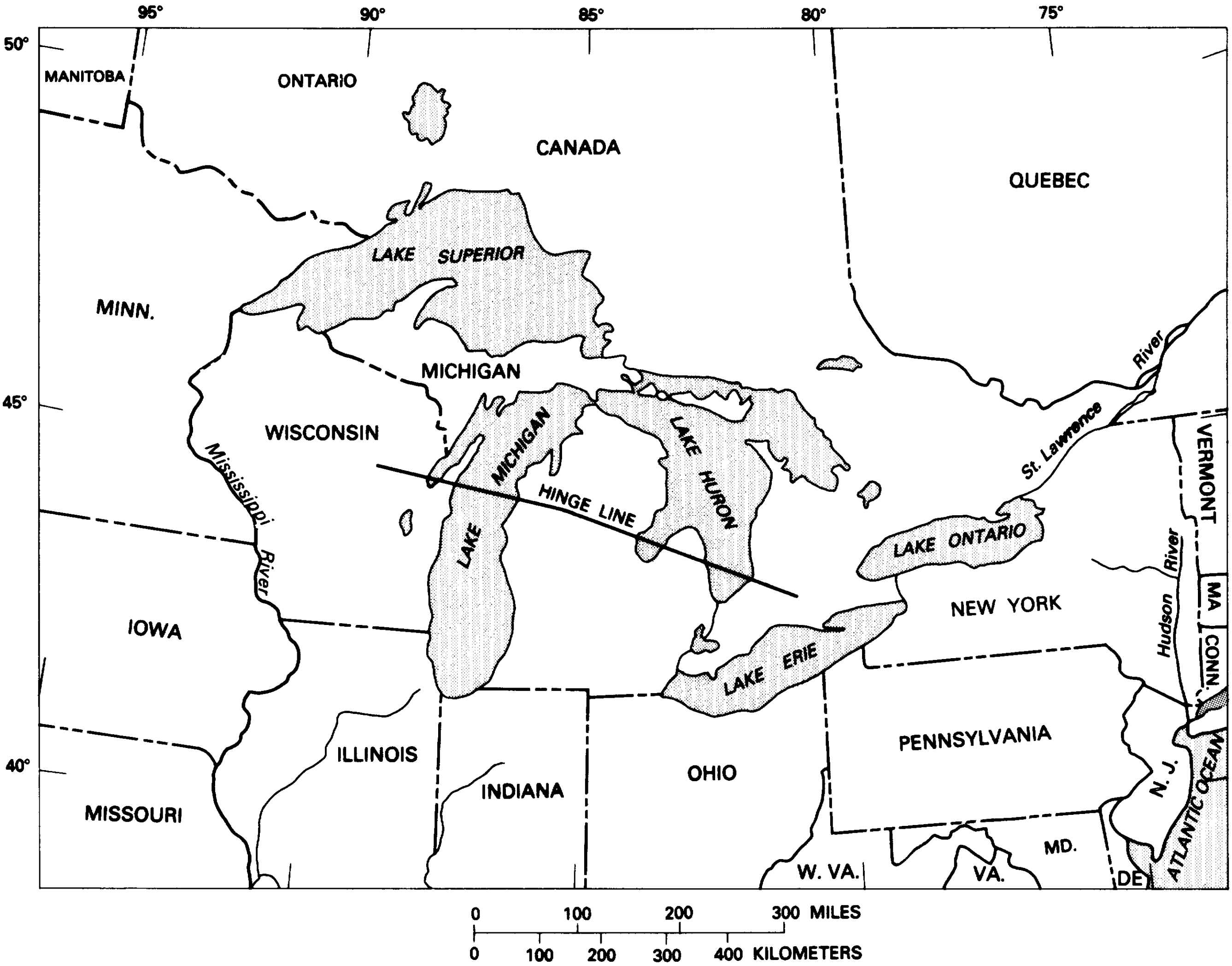


Figure 2. Position of the Algonquin hinge line. North of this line postglacial lake shorelines were thought to diverge in a fan-like array. South of this line, shorelines were considered to be subhorizontal (modified from Goldthwait, 1908).

PREVIOUS RESEARCH

Lake Algonquin and its Outlets

Spencer (1888, 1891) identified Lake Algonquin as the earliest and highest lake to simultaneously occupy the Lake Huron, Lake Michigan, and Lake Superior basins. The lake was defined on the basis of raised terrace remnants marked by conspicuous cobble and boulder pavements and located along the eastern shores of Georgian Bay in Lake Huron. The Algonquin shoreline, recognized as the uppermost set of coastal landforms in the northern lake basins, was found at progressively lower altitudes to the south until it apparently plunged beneath the modern surface of Lake Michigan and Lake Huron. Spencer recognized an early temporary outlet channel to the Ontario basin, the Kirkfield outlet, but he considered the major drainage to be through the Mattawa/Ottawa river system at North Bay, Ontario. Significantly, Spencer did not recognize the proglacial origin of Lake Algonquin (Taylor, 1927a,b).

Taylor (1894), Goldthwait (1906, 1908, 1910a,b), and Leverett and Taylor (1915) also described Algonquin and post-Algonquin shoreline features along the northern shores of Lake Michigan and Lake Huron, reconstructing the former water planes associated with these features as concave-upward surfaces rising to the north. In addition, they interpreted Lake Algonquin as a proglacial lake bounded on the north by glacial ice. Each of these writers began his research along the *southern* shores of the lakes, where raised coastal terraces seemed horizontal. The undeformed terraces of the south were thought to extend northward to Green Bay, Wis., and Grand Traverse Bay, Mich., on Lake Michigan, and Saginaw Bay, Mich., on Lake Huron. Here, the horizontal shorelines apparently diverged to correlate with the deformed Algonquin and post-Algonquin terraces of the north. The zone of transition, where Spencer had earlier projected the Algonquin shoreline beneath modern lake level, was identified as a hinge line (Goldthwait, 1908).

Leverett (1897, 1899) and Taylor (1895, 1908), concentrating on the southern outlets to Lake Michigan and Lake Huron, respectively, found that altitudes of shoreline features and terraces were about 184.5 m (605 ft) in both regions. Leverett identified this shoreline as the Toleston level, the lowest level associated with glacial Lake Chicago. In sequence from oldest to youngest, the three levels that Leverett named were the Glenwood level, 195.2 m (640 ft), the Calumet level, 189.1 m (620 ft), and the Toleston level. Taylor (1895) considered a 184.5-m terrace around the southern shores of Lake Huron to represent a second Lake Algonquin level. The 184.5-m terraces were clearly related to the southern outlets of both lakes; therefore, they were later associated by Leverett and Taylor (1915) with the southern shores and outlets of Lake Algonquin. The southern drainage at Port Huron was, in fact, a prerequisite to Taylor's model for the lake-level chronology (Leverett and Taylor, 1915). Their synthesis of lake-level chronology is summarized in table 1.

With the exception of the postglacial chronology, which has been revised through radiocarbon age control (table 2), Leverett and Taylor's basic outline for Lake Algonquin events continues to be accepted with only slight modification. Stanley (1936, 1937), for example, considered the Lower Algonquin, Battlefield, and Fort Brady shorelines of Leverett and Taylor (1915) to represent separate, falling, post-Algonquin lake systems draining at North Bay, Ontario. He assigned the new names Wyebridge, Penetang, and Cedar Point to the correlated shorelines of northern Lake Huron.

Until recently, the major debates involving Lake Algonquin have revolved about the role of the Kirkfield outlet, its related period of lower lake level, and a subsequent rise to a high Main Algonquin level. Deane (1950) suggested that blockage of the Kirkfield outlet by an ice advance caused the rise to the Main Algonquin level. Stanley (1938), Hough (1958, 1963), Prest (1970), Harrison (1970, 1972), and Eschman and Karrow (1985) supported an uplift theory. Radiocarbon age control was added by Karrow and others (1975), who inferred an age greater than 11,500 yr B.P. for Early Lake Algonquin. A fall in level related to drainage through the Kirkfield outlet is placed between 11,500 and 11,200 yr B.P., followed by a rise to the Main Algonquin level. Karrow and his coworkers concluded that by 10,600 yr B.P. Lake Algonquin was drained, probably related to deglaciation of the North Bay region. They, too, remained uncertain whether the Kirkfield outlet opened briefly about 12,000 yr B.P., possibly related to an ice-margin fluctuation, or whether the outlet had been continuously open since that date. In any event, opening of the outlet preceded deglaciation of the Mackinac Straits, which took place about 11,200 to 11,000 yr B.P. (Hansel and others, 1985a,b) and formation of the Main Algonquin shoreline there.

Kaszycki (1985) suggested that the Kirkfield outlet was deglaciated before 11,500 yr B.P. and continued in use as an outlet until 10,800 yr B.P., when drainage was shifted to the Fossmill outlet system (Harrison, 1970, 1972; Fullerton, 1980), the southernmost channel in the North Bay region (fig. 2). In addition, she presented evidence that the Main Algonquin level of Lake Huron drained eastward through the altitudinally lower Kirkfield outlet, leaving the Port Huron outlet subaerially exposed. In effect, this interpretation resembles that developed by Spencer (1888, 1891) for the Algonquin water plane.

Evolution of the Hinge Line Model

The upper Great Lakes basin became a testing ground for opposing theories of crustal movement in the late 19th century. The tilted Algonquin shoreline piqued G.K. Gilbert's interest in isostasy. Gilbert felt that unloading of the crust, such as he proposed to have followed evaporation of Lake Bonneville (Gilbert, 1890), resulted in its return to an original preloaded condition. Tilted or deformed shorelines provided a means to monitor the processes of isostatic adjustment. Shaler (1874), Jamieson (1865, 1882), and De Geer (1892) pointed out that tilting of marine and lacustrine terraces in northern Europe and North America had followed deglaciation. This suggested depression of an elastic crust by glacial ice and subsequent rebound upon unloading. Gilbert proposed that a network of lake-level gauges at critical localities around the lakes would record differential movement of the crust in relation to a common water plane, and he demonstrated historic rates of tilting for the Lake Michigan and Huron basins relative to Chicago.

During the 1890's, glacial mapping of this region by the U.S. Geological Survey was begun under the aegis of T.C. Chamberlin. Chamberlin, a proponent of episodic tectonic movements and diastrophism as the key to geologic correlation (Chamberlin and Salisbury, 1904; Chamberlin, 1909, 1926), discounted glacio-isostasy in favor of a rigid, permanent earth; isostasy necessitated a fluid or viscous mantle. Chamberlin's group of cooperating glacial geologists (Leverett, Taylor, and Alden) was joined in 1904 by J.W. Goldthwait, who continued the mapping of abandoned shorelines along the shores of Lake Michigan (White, 1949). Using precise measuring techniques, Goldthwait extended his mapping of lake shorelines and terraces northward where he defined six successively lower shorelines present in both the Lake Michigan and Huron basins (Goldthwait, 1906, 1907, 1908, 1910a,b). These shorelines, beginning with the highest Algonquin

Table 1. Summary of Leverett and Taylor's Great Lakes chronology (adapted from Leverett and Taylor, 1915, p. 469)

OUTLETS	LAKE MICHIGAN	LAKE HURON	OUTLETS
	Modern Lakes → Algoma Beach	Modern Lakes → Algoma Beach	→ Port Huron
	Nipissing Great Lakes →	Nipissing Great Lakes →	→ North Bay and Port Huron
	Ottawa Low Stage	Ottawa Low Stage	→ North Bay
Chicago ←	Fort Brady Battlefield Lower Algonquin Main Algonquin	Fort Brady Battlefield Lower Algonquin Main Algonquin	→ Port Huron
	Kirkfield Low Stage	Kirkfield Low Stage	→ Kirkfield
Chicago ←	Lake Chicago: Toleston Level	Early Lake Algonquin	→ Port Huron
Chicago ←	Lake Chicago: Calumet Level	Lake Lundy	→ Syracuse
Chicago ←	Lake Chicago: Calumet Level ← Grand River	Lake Warren	
Chicago ←	Lake Chicago: Glenwood Level	Lake Wayne	→ Syracuse
Chicago ←	Lake Chicago: Glenwood Level ← Grand River	Lake Whittlesey	
Chicago ←	Lake Chicago: Glenwood Level ← Grand River	Lake Arkona	
Chicago ←	Lake Chicago: Glenwood Level ← Grand River	Lake Maumee	→ Fort Wayne

of Taylor (1892) and continuing to the lowermost Nipissing and Algoma shorelines, were incorporated into Leverett and Taylor's (1915) work. The four upper shorelines descended in altitude to the south where they appeared to converge at a point south of Traverse City, Mich. (fig. 3).

The Main (or upper) Algonquin water plane was defined by a series of isobases that became more closely spaced from south to north. The true gradient of the plane, drawn along a N. 15° E. trend, showed a concave-upward surface. North of the Mackinac Straits, the

Table 2. Comparison of Leverett and Taylor's (1915) Great Lakes chronology with current interpretations controlled by ^{14}C dating

AGE YEARS B.P.	LAKE MICHIGAN (Inferred from Leverett and Taylor, 1915)	LAKE HURON (Inferred from Leverett and Taylor, 1915)	LAKE MICHIGAN (Bretz, 1955, Hough, 1958, Larsen, 1985a & b, Hansel et al., 1985a & b)	LAKE HURON (Bretz, 1955, Hough, 1958, Lewis, 1969, 1970, Eschman and Karrow, 1985)	OUTLET (Michigan / Huron)
1000–2000	Modern Lakes (Port Huron Outlet)		Modern Lakes →		Port Huron
3000	-Algoma Beach-		Algoma Great Lakes →		Port Huron
4000–6000	Nipissing Great Lakes (Draining at North Bay and Port Huron)		Nipissing Great Lakes (Confluent with Lake Superior) →		Port Huron and Chicago
6000–10,000	Nipissing Great Lakes (Draining at North Bay)		Chippewa Low Phase →	Stanley Low Phase	North Bay
10,000	Ottawa Low Stage		Post-Algonquin Lakes		
11,000	Main Lake Algonquin		Kirkfield Low Phase	Main Lake Algonquin	→ Port Huron
	Kirkfield Low Stage		Lake Chicago: Calumet Level	Kirkfield Low Phase	→ Kirkfield
12,000	Lake Chicago: Toleston Level	Early Lake Algonquin		Early Lake Algonquin	→ Port Huron
	Lake Chicago: Calumet Level	Lake Lundy, Lake Warren, Lake Wayne, Lake Whittlesey, Lake Arkona, Lake Maumee	Lake Chicago: Two Creeks Low	Lake Lundy, Lake Warren, Lake Wayne, Lake Whittlesey, Lake Arkona, Lake Maumee	To New York and Lake Chicago
13,000	Lake Chicago: Glenwood Level		Lake Chicago: Glenwood II, Intra Glenwood Low, Glenwood I		

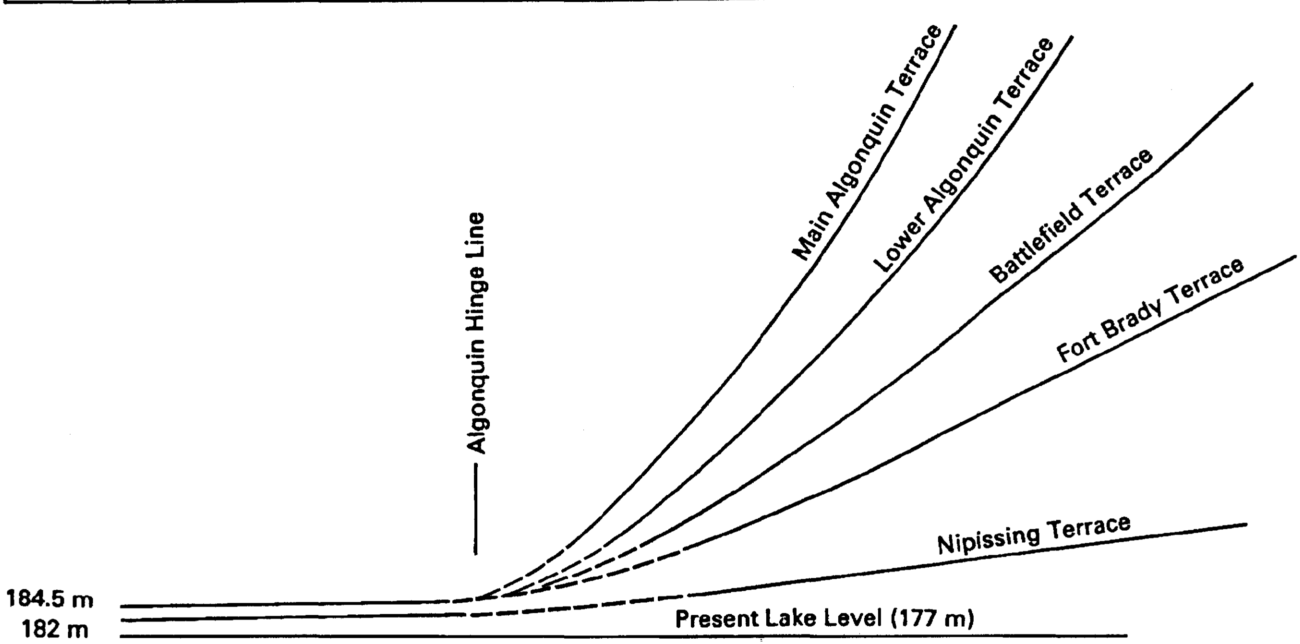


Figure 3. Relationship of the Main Algonquin and post-Algonquin shorelines of the northern Lake Michigan and Lake Huron basins interpreted on the basis of Goldthwait's (1908) hinge-line model. (Adapted from Hough, 1958.)

gradient was 0.7 m/km (3.73 ft/mi), but it became less steep to the south. Between Mackinac Island and Traverse City it decreased to 0.63 m/km (3.3 ft/mi), and south of Traverse City it was only 0.19 m/km (1 ft/mi) (Goldthwait, 1908). The gradients of each of the converging shorelines were less steep in each successively lower position. This indicated progressive deformation of the northern lake region.

To explain this, Goldthwait (1908) adopted a framework of multiple working hypotheses (Chamberlin, 1897). To explain the concave-upward water planes he examined an ice attraction model (Woodward, 1888), which provided for contemporaneous curved water surfaces rising to the edge of an adjacent ice front. Next he examined Spencer's interpretation that the Lake Algonquin surface projected beneath Lake Michigan at a point south of Green Bay, Wis., and Traverse City, Mich. Spencer's Lake Algonquin was a low-level lake draining northward at North Bay but unaffected by glacial ice; its level rose in the south as the northern outlet was uplifted.

Goldthwait considered the logic of Spencer's hypothesis. It was possible that the point of shoreline convergence that he had observed represented a zone where Lake Algonquin and subsequent levels plunged beneath modern lake level as Spencer had suggested. For this to have occurred, an outlet was needed at the point of convergence south of Traverse City, or along an isobase of equal uplift passing through that point. This condition allowed the controlling outlet to rise relative to the southern shore of the basin.

Detailed mapping by Goldthwait (1908) showed four possible outlets to Lake Algonquin. Chicago and Port Huron represented the southernmost. An intermediate channel to the east was located at Kirkfield, Ontario, while in the north the North Bay outlet remained ice covered. Spencer's hypothesis required an isobase joining the point of terrace convergence with one of these outlets. Goldthwait's synthesis of the shoreline altitudes showed the Algonquin shorelines converging between the isobases of the Port Huron and Kirkfield outlets. Therefore, neither could have controlled the mapped shoreline configuration.

Goldthwait favored episodic crustal movements. In his view, the northern terraces converged at a *hinge line* that separated a tectonically active northern crust from a stable region in the south (fig. 4). The horizontal terrace at 184.5 m showed stability and continuous drainage to the south. Each lower and less deformed shoreline represented an episode of tilting at an axis while the lake was controlled by a stable southern spillway.

Goldthwait's (1908) concepts of terrace deformation are illustrated simplistically in figure 5. Case 1 shows a southward-draining basin with a level controlled by the altitude of its spillway. Case 2 (a shoreline-convergence concept) shows a basin with an intermediate outlet control. Here, the sequence of tilted shorelines converges on a central axis of the basin. North of the axis the shorelines descend from oldest to youngest, but to the south the evidence is submerged with the oldest shoreline at the bottom of the sequence. Case 3 is an example of a tilting lake basin with northern outlet control. Here successively less deformed but younger shorelines rise to the uplifting outlet.

Goldthwait's explanation was a variation on case 2. With inflow balanced by outlet flow in Lake Algonquin, an outlet was required at the axis of the basin. He did not, however, consider successively lower northern outlets. Were such outlets deepened, either by erosion into unconsolidated glacial sediments or by deglaciation of successively lower outlet thresholds, as we now recognize (Harrison, 1970, 1972), a series of shorelines similar to those illustrated in case 2 would appear. Each shoreline would rise to its own successively lower spillway in the north. This mechanism is shown graphically in figure 6. An outlet at the point of terrace convergence is clearly not required. Therefore, Goldthwait's model was incomplete.

Nonetheless, Goldthwait's analysis had a profound effect on subsequent research. On the one hand, it supported Chamberlin's (1909) earth model. On the other, it demonstrated that detailed mapping of shoreline features could be used to understand processes of crustal deformation. Taylor (1927a) used the hinge-line model to discount Gilbert's observations on glacio-isostasy and to downplay lake-level gauge records in favor of detailed geomorphic mapping for recording earth movement. This bolstered the rigid-earth models of Suess (1883–1904) and Chamberlin (1898, 1909, 1926), which were required by his own early hypothesis of continental drift (Taylor, 1910) and his subsequent interpretations of Great Lakes shorelines (Leverett and Taylor, 1915; Taylor, 1927b).

RELATIVE VERTICAL MOVEMENT BEYOND THE HINGE LINE

Differential vertical movement south of the Algonquin hinge line was suggested by Eschman and Farrand (1970) and Evenson (1973) on the basis of anomalously high altitudes of the Glenwood and Calumet shorelines on the Allendale delta near Grand Rapids, Mich. More recent studies (Taylor, 1985) proposed that these same shorelines farther to the north are uplifted and deformed in the manner of the Algonquin shoreline. Difficulties in interpreting the Nipissing hinge line of Holocene age (see differing interpretations of Leverett and Taylor, 1915, and Hough, 1953) have been indicated on the basis of differing altitudes of dated Nipissing and Algoma terraces and deposits between Chicago and Port Huron (Larsen, 1985a,b). Thus, the Algonquin and

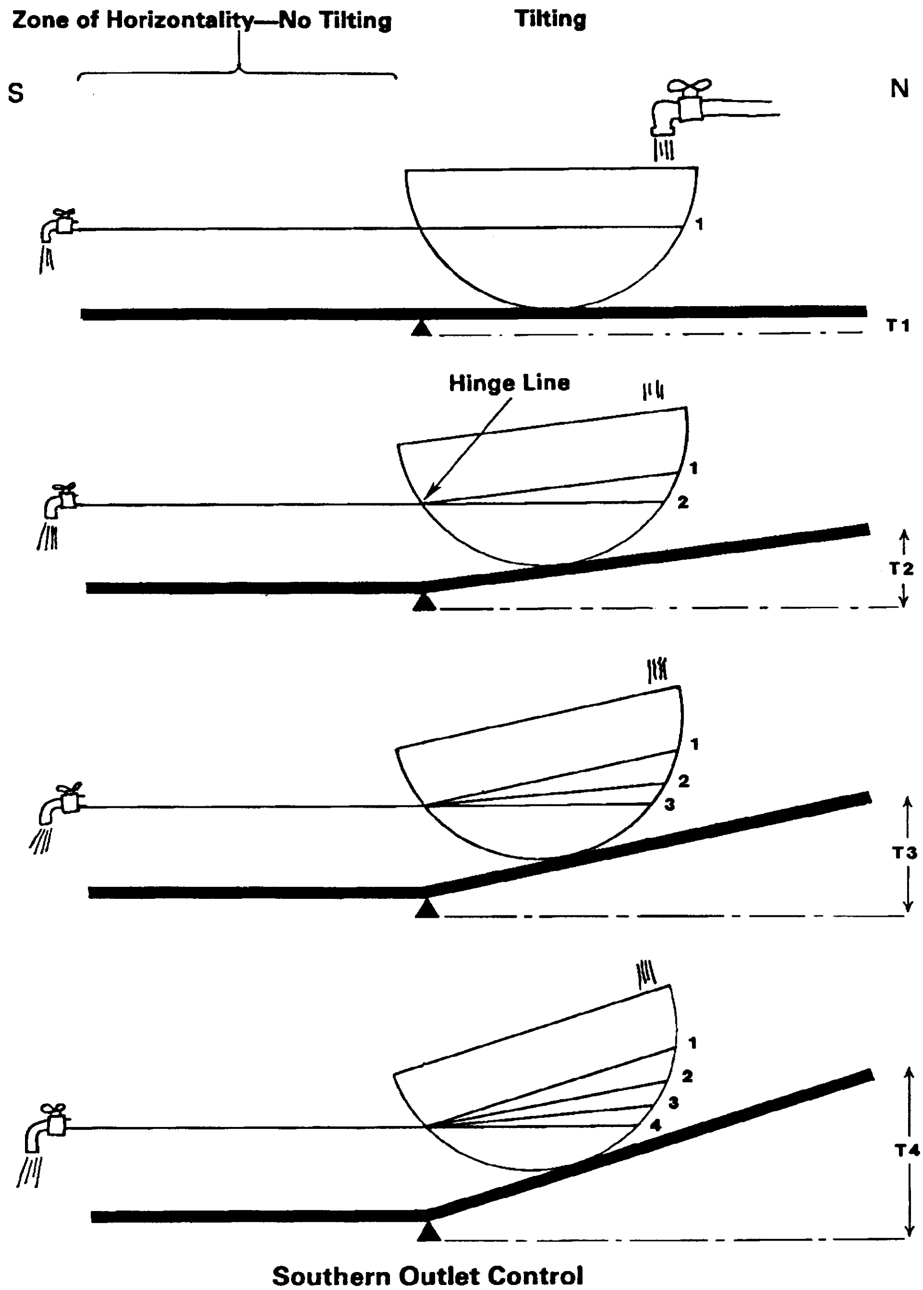


Figure 4. Goldthwait's (1908) hinge-line concept for a southward-draining basin. Goldthwait could find no intermediate outlet located on the point of convergence; therefore, he adopted southern outlet control. In order to match the model to the geomorphic record, he added a zone of no tilting and concluded that shorelines 1, 2, 3, and 4 were identical south of the hinge line. This implied crustal stability in the south.

Nipissing hinge lines are not limits of differential vertical crustal movement. Postglacial vertical movement south of the hinge lines can be documented from the historic perspective proposed by Gilbert (1898) and compared with the geomorphic data. Each synthesis of lake-level gauge records since Gilbert's time has measured differential movement south of the hinge lines (Moore, 1922, 1948; Gutenberg, 1933, 1941, 1954; Clark and Persoage, 1970; Walcott, 1972; Coordinating Committee, 1977). The most recent appraisal (Coordinating Committee, 1977) suggested uplift of the Port Huron outlet region relative to the south shore of Lake Michigan. Clark and Persoage's (1970) synthesis of historic movement is contoured in figure 7.

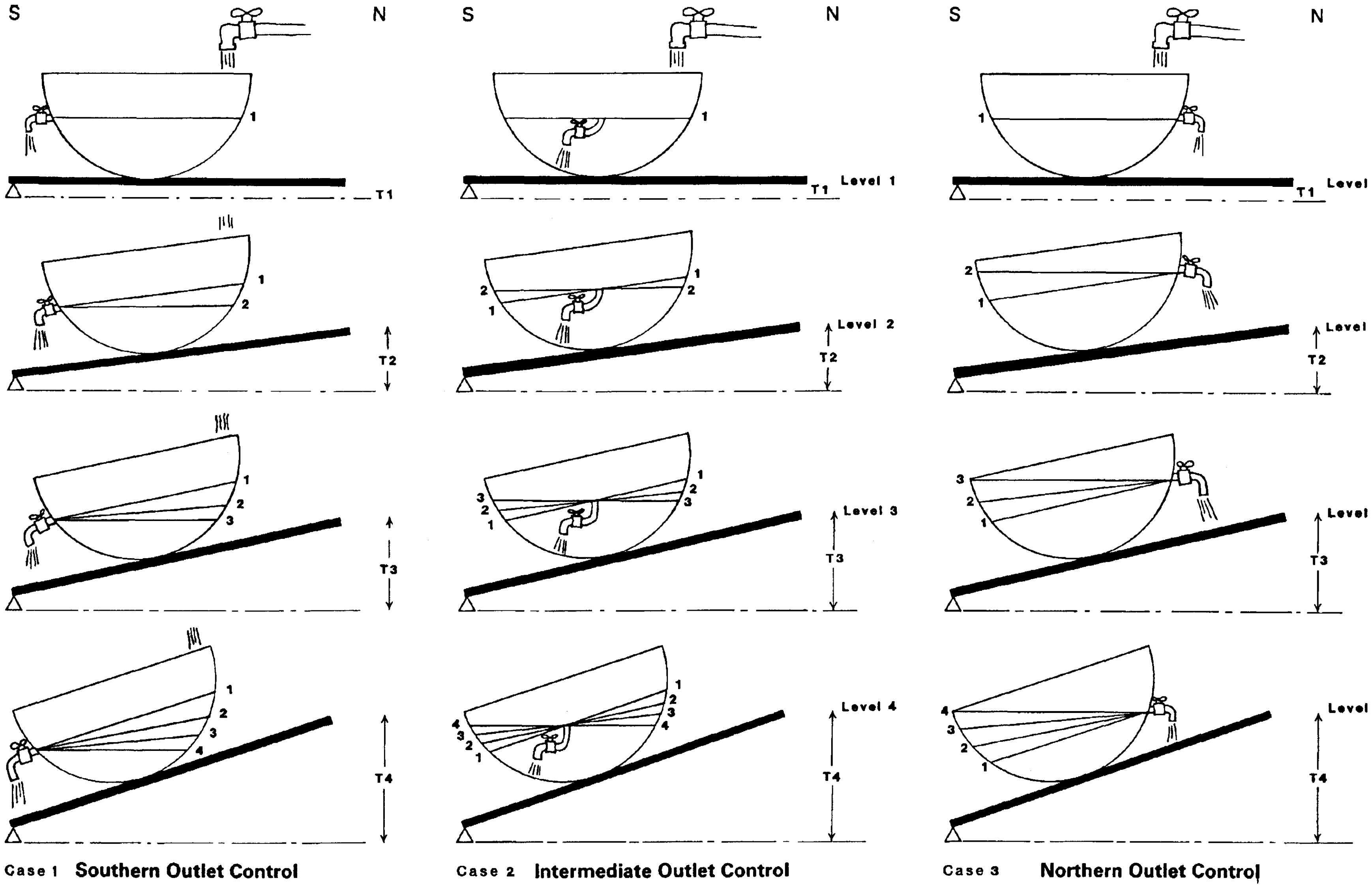


Figure 5. Schematic model of shoreline positions in an uplifting basin. Goldthwait (1908) considered only case 1 and case 2. Each concept involved a lake having a positive hydrologic budget (evaporation less than inflow) and being tilted to the north. Only southern and intermediate outlet control produced a shoreline sequence from 1 down to 2, 3, and 4. He was unwilling to accept that 1, 2, and 3 plunged beneath 4, so he adopted an intermediate outlet control (fig. 4). Case 3 shows northern outlet control and illustrates transgressing levels controlled by an uplifting spillway.

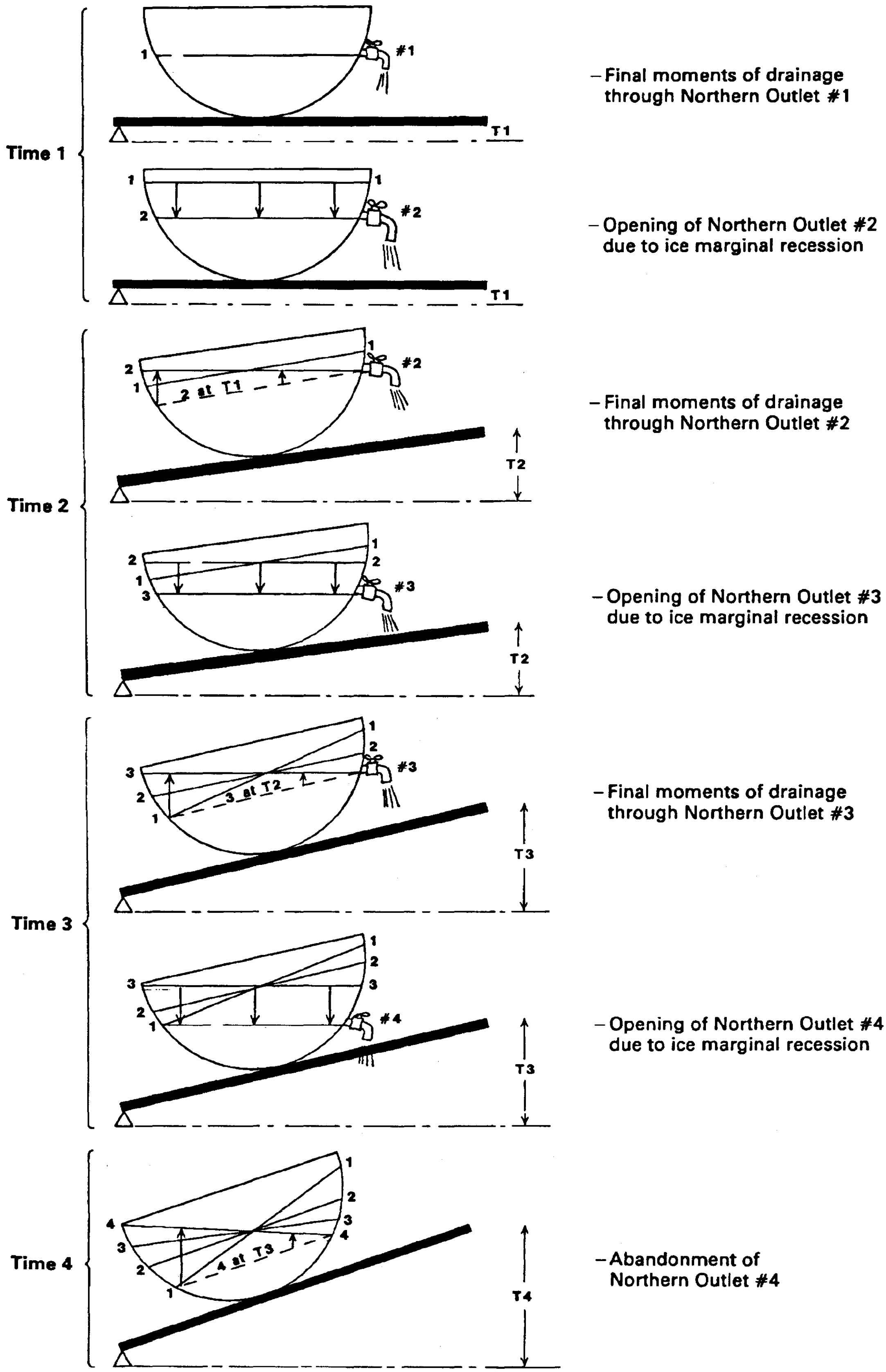


Figure 6. The scenario advocated in this paper, which Goldthwait (1908) failed to consider—a case of multiple northern outlets. A single crossover point is a result of the right combination of vertical intervals between outlets, uplift rate, and rate of ice retreat.

Figure 7. Measured historic vertical movement, contoured as uplift in feet per century, on the basis of lake-level gauge records. Line of profile is normal to isobases along the east shore of Lake Michigan (adapted from Clark and Persoage, 1970; Larsen, 1985b).

The historic data are at odds with the traditional interpretations of the deformed shorelines. The measured historic uplift appears to represent contemporary uplift associated with the former Laurentide ice center near Hudson Bay (Farrand, 1962; Walcott, 1970, 1972; Andrews, 1970b). The observed vertical movement south of the hinges points to glacio-isostatic loading and post-glacial rebound beyond the limits of the shoreline records.

EXPONENTIAL UPLIFT FUNCTIONS AND AN UPLIFT MODEL FOR HOLOCENE EVENTS IN THE UPPER GREAT LAKES

Andrews' (1970a,b) method of plotting terrace slopes, decreasing exponentially with both time and distance, allows reexamination of the deformed terraces and former water planes. This relationship is discernible both from the present altitudes of dated former shorelines and from their gradients measured over several kilometers. The gradient of a given terrace and the uplift rate, which increase exponentially toward the former ice centers, show a relation between the altitudes of former shorelines and time and distance from the center of ice loading.

Figure 8 is a least-squares regression of historic uplift rates calculated from Clark and Persoage's (1970) isobases at their points of intersection with the eastern shore of Lake Michigan shown in figure 7. The rates of uplift relative to the south shore of the lake are defined by an exponential function that demonstrates the predicted increase in uplift rate toward the former ice center and verifies the applicability of Andrews' geomorphic work to the Great Lakes basin. Although the rate of uplift is small in the southern Lake Michigan and Lake Huron basins (0.05 and 0.07 m/century, respectively), the movement illustrates that the observed uplift is related to greater ongoing movement in the north.

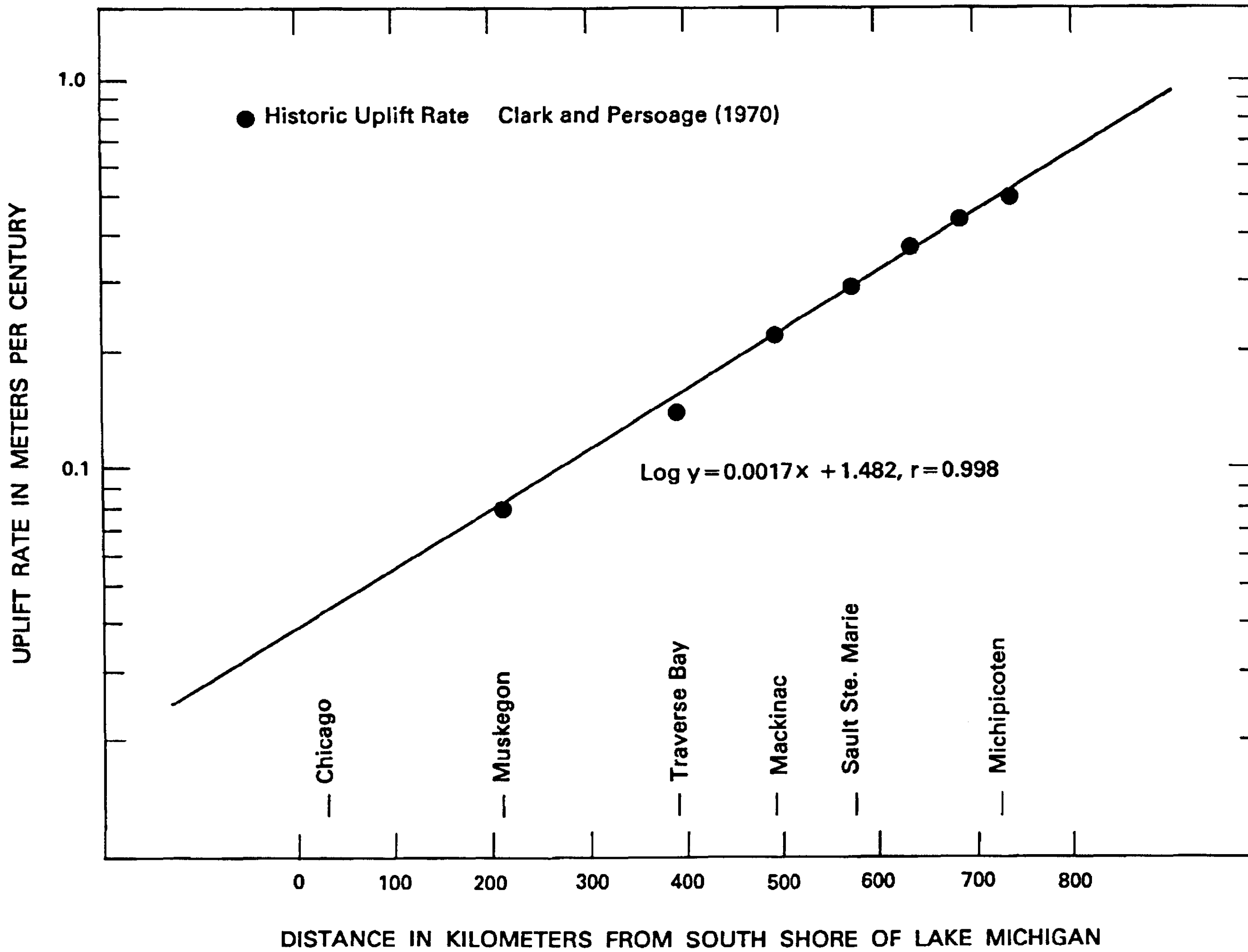


Figure 8. Historic uplift rates plotted along the east shore of Lake Michigan (Larsen, 1985b).

Terrace altitudes measured at various stations along the eastern shore of Lake Michigan or projected from Lake Huron are compiled in table 3 relative to their distance from the southern shore of Lake Michigan and the former Chicago outlet. From these data, least-squares regressions were calculated for Leverett and Taylor's four principal Lake Algonquin terraces. Data points were scaled directly from their original profiles, but their data points south of Traverse City were deleted because of the uncertain differentiation of individual coastal terraces in the hinge-line area. Table 3 includes data for the Nipissing and Algoma terraces (Larsen, 1985b) and for the past century derived from the historic uplift rates.

The four upper terraces related to Lake Algonquin by Goldthwait and by Leverett and Taylor are defined by separate exponential curves decreasing in gradient from north to south (fig. 9). The Nipissing and Algoma terraces (Larsen, 1985b) are shown for comparison. The extrapolated curves of the Main Algonquin through Fort Brady shorelines project below the modern level of Lake Michigan and extend southward to the Chicago area where they intersect the lake bottom at altitudes between 75 m (246 ft) for the former and 120 m (393 ft) for the latter (see also Larsen, 1985c). J.A. Clark proposed a similar projection for the Main Algonquin shoreline on the basis of independent geophysical modeling (Clark and others, 1984, 1985).

The Main Algonquin and post-Algonquin curves intersect and project below the Nipissing and Algoma terraces and modern lake level south of Traverse City, where they converge on the hinge. The Holocene Nipissing and Algoma shorelines, once thought to be horizontal, are themselves deformed. Like the historic uplifted shorelines, these Holocene shorelines are gently sloping surfaces that approach the southern outlet regions asymptotically (Larsen, 1985b). They conform to exponential curves and are not affected by hinge lines. The projected lake levels shown in figure 9 appear to track the continuous change in differential tilting of the upper Great Lakes basin since the formation of the upper Algonquin

Table 3. Altitudes, in meters, of raised shoreline features of the Lake Michigan and Lake Huron basins

[Theoretical altitude of 100-yr B.P. terrace calculated from data in figures 7 and 8. --, no data]

Isobase	Distance from south shore Lake Michigan (km)	Altitude Main Algonquin terrace	Altitude Lower Algonquin terrace	Altitude Battlefield terrace	Altitude Fort Brady terrace	Altitude Nipissing I terrace	Altitude Nipissing II terrace	Altitude Algoma terrace	Theoretical Altitude 100-yr B.P. terrace	Source
Michipicoten	730	--	--	--	--	--	--	--	176.60	Clark and Persoage (1970).
Michipicoten Island	600	--	--	--	--	--	--	--	176.52	Clark and Persoage (1970).
North Bay	630	--	--	--	--	212	207	--	176.44	Lewis and Taylor (1915), Lewis (1969), Clark and Persoage (1970).
Killarney Bay	590	--	--	--	--	--	199.6	--	--	Lewis (1970).
Sault Ste. Marie	570	300	269.9	239.1	--	--	197	--	176.38	Leverett and Taylor (1915), Clark and Persoage (1970).
Algoma Mills	570	--	--	--	223.9	--	--	189.1	--	Leverett and Taylor (1915).
Manitoulin Island	530	287	--	--	--	--	195.1	--	--	Lewis (1970).
Mackinac Island	510	247	231	219.3	208.1	--	192.5	--	--	Leverett and Taylor (1915).
Mackinac City	490	242.5	227.5	--	--	--	--	--	176.30	Leverett and Taylor (1915), Clark and Persoage (1970).
Carp Lake	496	--	--	214.1	--	--	--	--	--	Leverett and Taylor (1915).
Cross Village	480	--	--	--	201.3	--	--	--	--	Leverett and Taylor (1915).
Petosky	450	214.7	205.6	200.7	--	--	--	--	--	Leverett and Taylor (1915).
Burt Lake	450	--	--	--	--	--	--	184.5	--	W. Lovis (personal commun.).
Charlevoix	440	211.10	202	190.6	--	--	--	--	--	Leverett and Taylor (1915).
North Manitou Island	420	--	--	--	187.9	--	--	--	--	Leverett and Taylor (1915).
Traverse City	385	--	--	--	--	--	--	--	176.22	Clark and Persoage (1970).
Saginaw Bay	210	--	--	--	--	--	--	181	176.12	Larsen and Demeter (1979), Clark and Persoage (1970).
Port Huron/Sarnia	190	--	--	--	--	--	183.6	180.5	--	Lewis (1969, 1970), Papworth (1967), Karrow (1980).
Kenosha	100	--	--	--	--	183	181	179	--	Larsen (1974, 1985a).
Michigan City	10	--	--	--	--	182.5	--	--	--	Gutschick and Gonsiewki (1976), Larsen (1985a).

shoreline. This model suggests revision of some aspects of the lake history and indicates sites of confirming evidence beneath Lake Michigan.

EVIDENCE FOR LOW LAKE MICHIGAN AND LAKE HURON LEVELS

Stratigraphic research on Great Lakes level changes has been obscured by the concepts of hinge-line and fixed southern outlet channels for Lake Algonquin and the later Nipissing Great Lakes levels. Although periods of lower lake level have been proposed (for example, the Kirkfield and Ottawa stages of Leverett and Taylor [1915] and the Chippewa and Stanley low stages of Hough [1955, 1958, 1962] and Stanley [1937]), the control to their levels has been difficult to explain. In the Lake Michigan and Lake Huron basins, control of the low levels has been attributed to the Kirkfield and North Bay outlets and that of the high Main Algonquin and Nipissing levels to the altitudes of the southern outlets.

The Chippewa and Stanley Low Levels

Submerged evidence for lower-than-present lake levels in both the Lake Michigan and Lake Huron basins has generally been attributed to the Chippewa and Stanley low levels between about 10,000 and 7,500 yr B.P. For Lake Michigan, the earliest dated submerged evidence (see Appendix for explanations of analysis numbers) is found at the Mackinac Straits, where a fluvially eroded channel joins the lake basins. The 112-km-long channel was incised into a surface at altitude 160 m (Stanley, 1937). The spillway to the channel is at about 140 m, and downstream in Lake Huron, the channel is cut as low as 117 m into red glaciolacustrine clay (Hough, 1962). Spruce stumps near the channel and in growth position at about 140 m range in age from 9,780 yr B.P. (M–1996) to 8,150 yr B.P. (M–2337). Thus, the level of both lakes was below 140 m during this time. The date of a stump at 167 m near the western approach to the Straits, 6,788 yr B.P. (M–1888), suggests that a rising level had rejoined the basins after this time. Confirming evidence from a similar altitude in Lake Huron is reported from St. Joseph Island (6,500 yr B.P., GSC–2245). By 6,270 yr B.P. (M–1282), the rising lake had inundated wood, now at 179 m, near Cheboygan, Mich.

A similar submerged record for a falling water level is preserved in Georgian Bay near Manitoulin Island, Ontario, where plant detritus, peat, and tree stumps have been found at altitudes between 145 and 160 m. Sly and Lewis (1972) reported a date of 10,305±78 yr B.P. on stumps found at a 145-m altitude off the tip of the Bruce Peninsula. Peat near this locality and depth is dated at 9,440 yr B.P. (GSC–1397). Lag gravels (associated with low lake levels) have been reported at 122 m in this general area (Sly and Sandilands, 1988). These authors also suggested that glaciolacustrine clays were exposed to erosion to an altitude of 87 m, and echo trace data indicate that the erosion surface may extend as low as 77 m. Tovell and others (1972) noted plant detritus at an altitude of 81 m in a nearby core as well as shallow-water sands and gravels as low as 62 m. Thus, the drop of Georgian Bay to its Hough low level prior to 10,300 yr B.P. caused related drops in the upstream lakes in the main Huron and Michigan basins.

In the main Lake Huron basin, shallow-water organic layers from the bottom sediments of South Bay, Manitoulin Island, found at 162 and 161 m, were dated at 8,310 (GSC–1979) and 9,260 yr B.P. (GSC–1971), respectively. Gyttja dated at 10,150 yr B.P. (GSC–1108) from nearby Tehkummah Lake (surface altitude 191.7 m; Lewis, 1970) shows that this small lake was separated from the main Huron basin by a falling level before this time.

The fall in level was in response to the opening of a relatively lower outlet at North Bay (Harrison, 1970, 1972). Lake Huron drained northward to a still lower level of Georgian Bay. Lewis and Anderson (1985) suggested that the Stanley level drained through a connecting channel at the Mississagi Strait near the northwestern shore of Manitoulin Island (sediment-water interface at 125 m). A still lower channel (sediment-water interface at 107 m) crosses the Niagaran escarpment at the eastern end of the island. In any event, the main Lake Huron basin drained to Georgian Bay controlled by sills on the Niagaran escarpment, while water in the Lake Michigan basin was controlled by the head of the Mackinac River channel with a threshold at about 140 m. The Michigan and Huron basins were separated by this river between 10,300 and 9,800 yr B.P. and were not rejoined until rising water in the Lake Huron basin inundated the Mackinac Straits after 8,150 yr B.P.

In the southern Lake Huron basin, Anderson and Lewis (1974) described subaerial exposure of the lake bottom north of Saginaw Bay where marsh peat (9,370 yr B.P., GSC–1935) overlies glaciolacustrine sediments at an altitude of 126 m. Reflooding of the basin is indicated by algal gyttja found at nearly the same altitude and dated to 8,460 yr B.P. (GSC–1966). This transgression reached an altitude of 172 m after 7,250 yr B.P. (M–1012), when trees near Thompsons Harbor, Mich., were inundated.

The radiocarbon record for the Stanley level is consistent with dated organic remains from the St. Clair delta south of Port Huron. Subaerial exposure of this outlet channel is indicated at least as early as 9,310±210 yr B.P. (Mandelbaum, 1969) by wood near the base of the deltaic sediments. Gyttja dated at 7,300±80 yr B.P. by Wightman (1961) at 172 m overly-

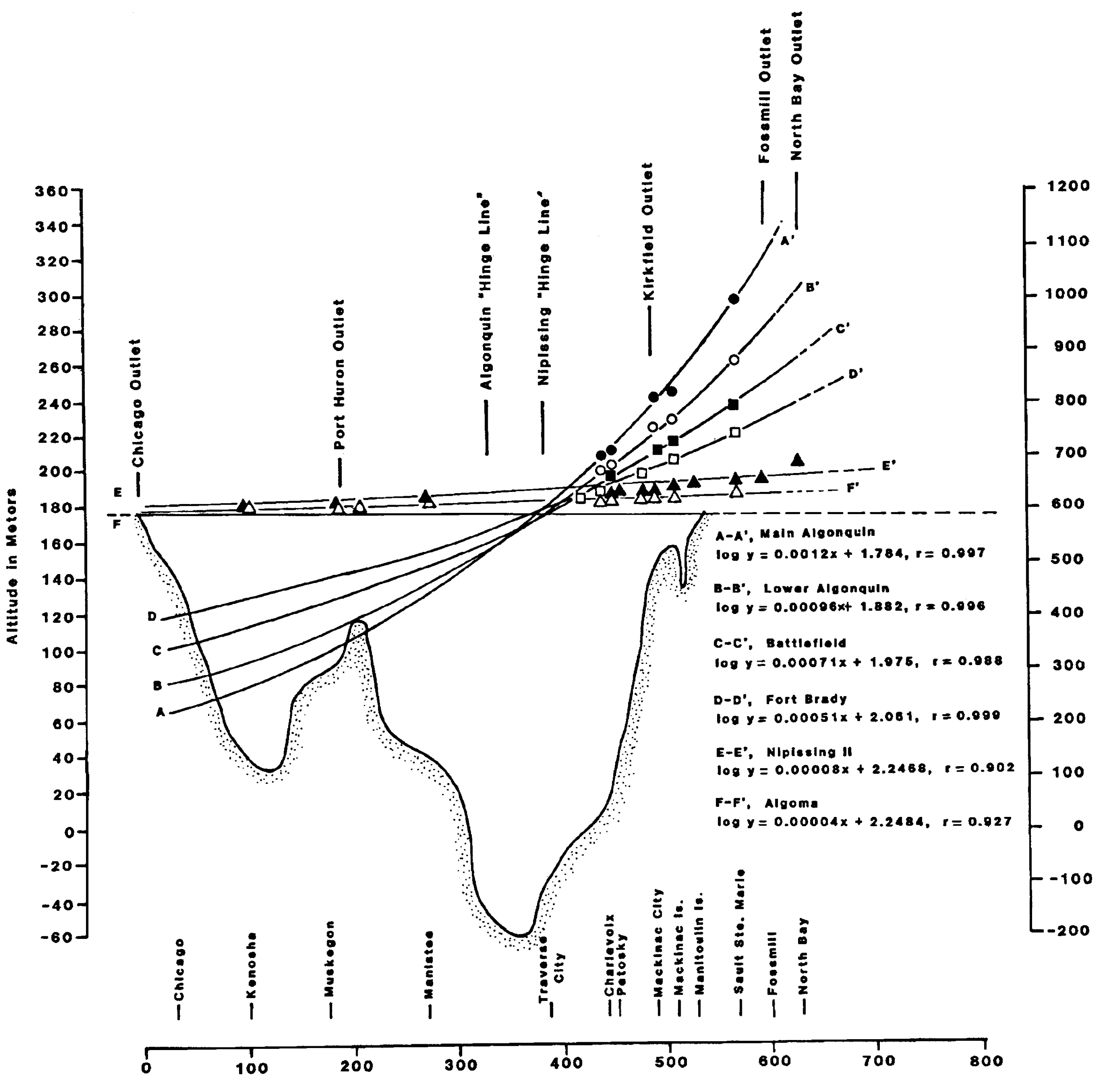


Figure 9. Calculated Main Algonquin and post-Algonquin water planes plotted normal to isobases of historic uplift along the east shore of Lake Michigan.

ing peat beneath the delta indicates rising water levels. Deltaic sedimentation, dated from wood fragments to 6,100±80 yr B.P., covered the gyttja and marsh deposits. Thus, Lake Huron drainage to the south through the St. Clair River began after this date.

The Chippewa low level in the Lake Michigan basin is poorly recorded. Apart from the Mackinac Straits dates, which also apply to northern Lake Huron, evidence for subaerial exposure and marsh development is recorded at Grand Traverse Bay where plant detritus at 153 m is dated at 7,850 yr B.P. (M–834). This deposit indicates a rising level that followed inundation of the Straits at about 8,150 yr B.P. and was caused by a rising North Bay outlet. In the north, the level had risen to 167 m by 6,788 yr B.P. (M–1888), while in the south the transgression surpassed 177 m after 6,350 yr B.P. (ISGS–185) and 6,340 yr B.P. (W–1017) near Kenosha, Wis. (Larsen, 1985a,b).

Dates on peat from the Chicago outlet, 8,690 yr B.P. (ISGS–1241) and 6,280 yr B.P. (ISGS–960), show that the outlet channel was subaerially exposed during these periods. Southward drainage began after 6,300 yr B.P., as indicated by clayey silt deposition that covered these marshes. Active drainage to the south ended by 3,390 yr B.P. (ISGS–1240) when peat accumulation was renewed.

Hough (1955, 1958) defined the Chippewa low level on the basis of bottom cores from southern Lake Michigan. An unconformity at altitude 79 m truncated red glaciolacustrine clays of the Sheboygan Member of the Lake Michigan Formation (fig. 10), dated between 11,200 and 9,800 yr B.P. (Lineback and others, 1970; Drexler and others, 1983; Farrand and Drexler, 1985). A thin zone of sand containing mollusk shells characterized the unconformity. Shells found offshore Muskegon and Manistee, Mich., provided dates of 7,400 yr B.P. (M–1571) at 73 m, 7,580 yr B.P. (M–1736) at 80 m, and 7,570 yr B.P. (M–1972) at 69 m. Gray lacustrine sediments of the Winnetka Member overlie and, in some places, truncate the red clays (Lineback and others, 1970). Hough's dates (Crane and Griffin, 1965, 1968, 1970) mark the base of the Winnetka Member.

The stratigraphic record indicates low postglacial Lake Michigan levels controlled by the threshold altitude of the Mackinac River channel at about 140 m. An apparent fall in level from the 208-m Fort Brady terrace on Mackinac Island to the 140-m spillway took place when the North Bay outlet opened between 10,300 and 10,100 yr B.P. The Stanley level of Lake Huron fell at least as low as 117 m at the Niagaran escarpment before draining into Georgian Bay. The Hough level in Georgian Bay dropped to between 62 and 90 m and drained to the North Bay outlet (Sly and Lewis, 1972; Sly, written commun., 1985). The rising water that inundated the Mackinac Straits after 8,150 yr B.P. shows progressive uplift of the controlling outlet at North Bay. The level rose to within 10 m of the present lake surface between 6,788 and 6,500 yr B.P. and above it by 6,270 yr B.P.

The Main Algonquin Low Level

The truncated glaciolacustrine Sheboygan Member overlain by the lacustrine Winnetka Member in Lake Michigan bottom sediments is a significant marker highlighted by the change from red to gray clay. Lineback and others (1974) related the deposition of red clay to the retreat of Greatlakean glacier ice from the Lake Michigan basin. The red clay originated in ice in the Lake Superior basin (Lineback and others, 1979). Drexler and others (1983) associated red clays of the upper and lower parts of the Sheboygan Member with separate discharges of meltwater from ice fronts lying in the Upper Peninsula of Michigan. The Sheboygan Member postdates the retreat of ice from the Lake Michigan basin at about 11,200 yr B.P. The upper part of the member corresponds to the Marquette glacier advance into Lake Superior at about 9,900 yr B.P. (Drexler and others, 1983; Farrand and Drexler, 1985). This sequence marks the final flow of meltwater and red clay from the north. The subsequent gray lacustrine clays of the Lake Michigan Formation were derived from erosion of the surrounding glacial deposits and postdate retreat of Marquette ice at about 9,800 yr B.P. Definitive dates on the red clay–gray clay interface in Lake Michigan are not available, but in Georgian Bay, near Manitoulin Island, the change from glaciolacustrine sedimentation predates 9,770 yr B.P. (GSC–1830, Sly and Sandilands, 1988) and predates peat formation at 9,370 yr B.P. (GSC–1935) near Saginaw Bay (Anderson and Lewis, 1974).

The Main Algonquin through Wyebridge terraces near Sault Ste. Marie that postdate deglaciation of the Mackinac Straits at about 11,200 yr B.P. were truncated by the Grand Marais Moraine of the Marquette advance at about 9,900 yr B.P. (Drexler and others, 1983; Farrand and Drexler, 1985) and possibly as late as 9,600 yr B.P. (Clayton, 1983). The altitude of the Wyebridge terrace as identified by Drexler and others (1983) coincides with the Battlefield shoreline of Leverett and Taylor (1915). Marquette ice remained at this terminal position until about 9,800 yr B.P. Therefore, the Main Algonquin through Fort Brady terraces of Leverett and Taylor range in age from about 11,200 to about 10,000 yr B.P. and are broadly contemporaneous with the red clays of the Sheboygan Member. Retreat of the Marquette ice front marked the end of red-clay deposition but apparently postdated opening of the North Bay outlet (Farrand and Drexler, 1985). The red clays of the Sheboygan Member are stratigraphic markers in the bottom sediments of Lake Michigan.

In the southern Lake Michigan basin, the red clays of the Sheboygan Member are found present below an altitude of 95 m (Lineback and others, 1972). On the southern slope to the Lake Michigan basin, they are onlapped by the Winnetka Member at an altitude of 92 m (Lineback and others, 1972). East of Waukegan, Ill., the upper limit to the red clay is also 92 m, but, east of Milwaukee, the Sheboygan is found as high as 100 m (Lineback and others, 1972, Core 861). Farther to the north near the Straits, the Sheboygan Member has been reported at an altitude of 152 m (Illinois State Geological Survey, Core 1132, A. Hansel, written commun., 1984). D. Rea (written commun., 1985) also reported the presence of the Winnetka-Sheboygan unconformity between altitudes 120 and 130 m at Little Traverse Bay near Charlevoix. Cahill (1981) reported red glaciolacustrine clays at about 172 m in Green Bay. Finally, Kelly (*in* Crane and Griffin, 1961) described varved red clays overlain by gray Holocene lacustrine clays above the level of the lake (178

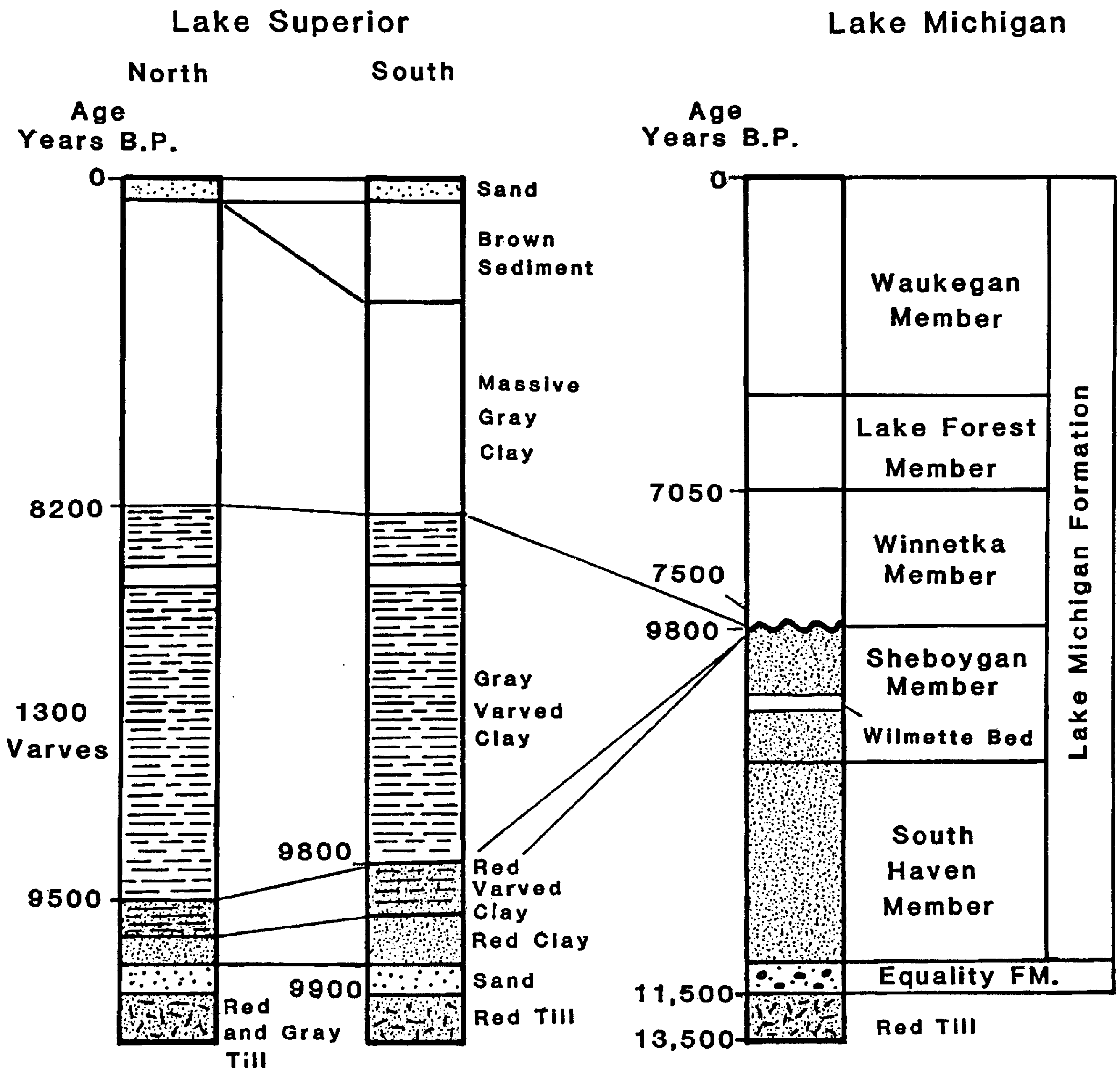


Figure 10. Dating of the Lake Michigan Formation (Lineback and others, 1979) on the basis of the revised glacial geology of the Lake Superior basin (Drexler and others, 1983; Clayton, 1983; Farrand and Drexler, 1985).

m) at the Mackinac Straits. This progression suggests that the upper limit to the red clay rises to the north.

In all reports, the red clays occur below the projected Battlefield water plane (fig. 11) that immediately predates the Marquette advance. Farrand and Drexler (1985) pointed out that final overflow to the Michigan basin from the Superior basin, including that from the Marquette advance, was through the Whitefish–Au Train channels near northern Green Bay. Because the gradient of these channels, with a threshold at 234 m (Lineback and others, 1979; Farrand and Drexler, 1985), coincides with the Battlefield shoreline (figs. 9, 11), a relationship between that former water plane and the early Sheboygan Member is likely. Although Lake Huron had fallen below the threshold of the Mackinac Straits before the final contribution of red clays from Marquette ice, the Battlefield and Fort Brady water planes in the south approximate a nearly contemporaneous upper limit to the occurrence of the Sheboygan Member. The successively younger Winnetka and Lake Forest members tend to pinch out at progressively higher altitudes, 132 m (Buckley, 1974) and 147 m (Lineback and others, 1970), respectively. This

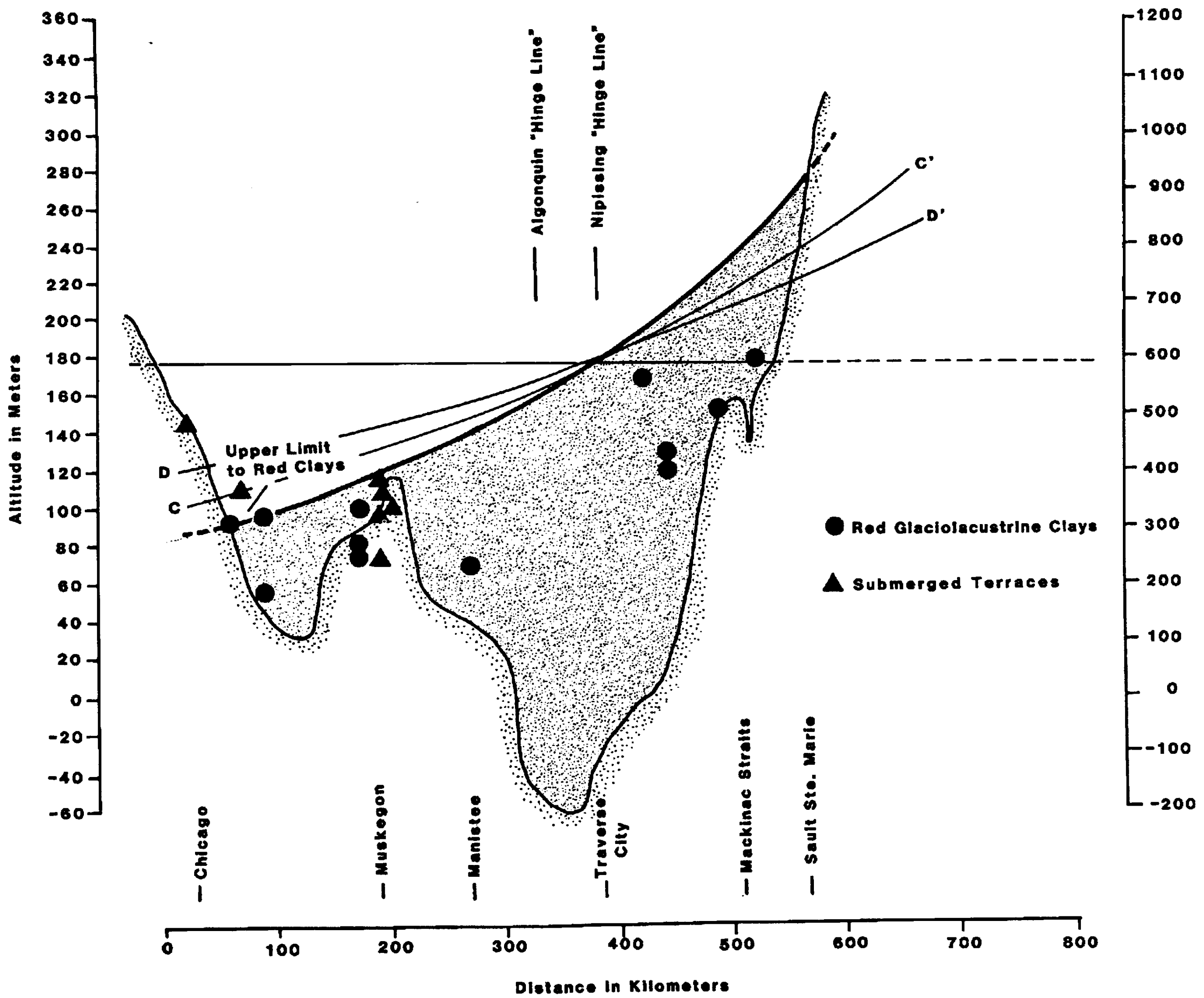


Figure 11. Probable attitude of late-glacial red glaciolacustrine clays of the Lake Michigan basin. Circles represent present altitudes of red clays from bottom cores. Triangles show altitudes of submerged terraces. C-C' and D-D' are the calculated Battlefield and Fort Brady shorelines of figure 9.

suggests that the red glaciolacustrine clay was originally deposited in a horizontal attitude and was differentially raised to the north by postglacial isostatic uplift.

Terraces eroded into glacial till and covered by the Waukegan or Lake Forest Members of the Lake Michigan Formation (7,000 yr B.P. or younger) have been identified in high-resolution seismic profiles along the eastern edge of the Lake Michigan basin (Lineback and others, 1972). Apparent erosional surfaces are found offshore Muskegon at altitudes 70.3 m, 95 m, 98 m, 104 m, and 113 m (fig. 11). Dating of these features is hampered by the thickness of the overlying late Holocene Waukegan Member. The cores used by Lineback and others (1972) rarely reached into the Winnetka Member in these areas. The oldest age determined for the Lake Forest Member, 7,050 yr B.P. (ISGS–36), provides the younger limit for terrace formation. These submerged terraces, which lie below the projected Algonquin-age shorelines, may be related to early low levels, but, because of our lack of knowledge of the Winnetka Member, we cannot rule out a Chippewa age.

Higher erosional terraces are present on the lake bottom offshore Benton Harbor, Mich., and Michigan City, Ind., at altitudes 107 m and 142.4 m, respectively (Lineback and others, 1972). These terraces are covered by the Waukegan and Lake Forest Members and are related to the post-Chippewa rise in lake level. Unconformities in the Lake Michigan Formation are present offshore Benton Harbor at 100 and 110 m, where conspicuous breaks in sedimentation predate the Waukegan Member (3,460 yr B.P., ISGS–68) but postdate the Carmi Member of the underlying Equality Formation (11,500 yr

B.P., Lineback and others, 1979). It is impossible to differentiate low Chippewa from low Algonquin events here, although these terraces are also found below the projected Battlefield water plane.

OVERFLOW FROM GLACIAL LAKE AGASSIZ

Lake Superior played a key role in dispersal of glacial Lake Agassiz water during the late glacial period. During most of its postglacial history, Lake Superior drained directly into the Lake Huron basin through the St. Marys River at Sault Ste. Marie. However, large continuous volumes of overflow from Lake Agassiz occurred during its Moorhead (11,000 to 10,500 yr B.P.) and Nipigon (9,500 to 8,500 yr B.P.) phases when ice retreat exposed outlets to the Lake Superior basin. Overflow was apparently punctuated by periodic bursts of catastrophic discharge that entered Lake Superior and passed eastward into Lake Huron (Teller and Thorleifson, 1983; Teller, 1985; Clayton, 1983).

Direct overflow into the Lake Michigan basin took place briefly during the Moorhead phase. This overflow entered the basin through the Whitefish–Au Train channels and spilled into a post-Main Algonquin lake that drained eastward through the Mackinac Straits. Teller (1985) suggested that the Wilmette Bed within the Sheboygan Member of Lake Michigan Formation (fig. 10) may reflect this diversion of Lake Agassiz water, but the major portion of Moorhead-phase water flowed directly into the Lake Huron basin. On the basis of Teller and Thorleifson's (1983) research, Farrand and Drexler (1985) postulated that catastrophic diversions of as much as 4,000 km^3 of water into Lake Superior over short periods might have resulted in brief rises of 50 m in that lake. Similarly, they consider that if Lake Superior was broadly connected with the Lake Michigan and Lake Huron basins during the Algonquin-phase Great Lakes, then all three lakes may have experienced brief surges of as much as 20 m of Lake Agassiz water. No evidence for such surges has been discovered as yet.

The advance of Marquette ice into Lake Superior closed drainage from Lake Agassiz until ice retreated once again after 9,900 yrs. B.P. Ice retreat from the Lake Nipigon region reopened drainage to Lake Superior. Increased water flow and catastrophic flooding once again affected the upper Great Lakes during the Nipigon phase. This water was directed to the Lake Huron basin, which had already fallen to its Stanley low level. Overflow of Lake Agassiz water from the Lake Huron basin was through the North Bay outlet to the Ottawa River. Catastrophic floods may have had a significant impact on both Lake Superior and Lake Huron. Teller (1985) pointed out that, during the Nipigon phase, flood events with volumes as great as 3,000 km^3 took place. Had there been no overflow from Lake Superior, this volume would have raised that lake by 36 m. Clearly, then, significant short-lived bursts of Lake Agassiz water must have raised Lake Huron waters during the Stanley low phase. Because Lake Huron was at its low phase, subaerial evidence for these events can only be anticipated at the outlet region near North Bay. Submerged evidence from the Lake Huron basin, at this juncture, seems to reflect a slow rise governed by uplift of the controlling outlet.

THE NORTH BAY OUTLETS

A complex system of outlets controlled the levels in the Lake Huron basin. Harrison (1970, 1972) showed that a series of interconnected channels along a retreating ice front provided the drainage link between the Great Lakes and the Champlain Sea to the east. Harrison noted that drainage shifted initially from the Kirkfield outlet and the Lake Ontario basin to the Ottawa River drainage through an intermediate outlet at South River, but this shift is poorly documented. The earliest northern drainage for which we have evidence was through the Fossmill outlet system, which directed overflow along the retreating ice front and into the upper Petawawa River drainage. Harrison (1972) suggested that overflow through this system took place in four distinct phases as ice retreat uncovered successively lower outlets to the Petawawa valley.

The earliest of these, the Genesee phase, left evidence of a water plane as high as 365 m, overflowing a sill at 348 m at Kilrush Lake before draining to the eastern lowlands. A lower Fossmill-phase level at 357 m followed. The lake had fallen below a 348-m sill at Kilrush Lake before gyttja deposition dated at 9,860 yr B.P. (GSC–1246), but drainage may have begun as early as 11,800 (GSC–1363) and 11,400 yr B.P. (GSC–1429) as indicated by gyttja from Boulter Lake 6.5 km farther north. Fullerton (1980) and Kaszycki (1985) suggested that the shift to the Petawawa did not occur until 10,800 yr B.P. Lower phases at 343 and 328 m were termed the Sobie-Guilmette and Mink Lake. Before 8,670 yr B.P. (GSC–1097) and 9,820 yr B.P. (GSC–638), the outlet shifted northward to the Mattawa valley through the Amable du Fond valley. The relative water level fell below an altitude of 290 m at this time.

Shortly before 10,100 yr B.P. (GSC–1275), the deglaciation of North Bay allowed direct drainage through Trout Lake into the Mattawa River system. The water level there was about 212 m (Harrison, 1972). Gyttja deposits from lakes in the North Bay area at altitudes 211.8 and 213.5 m have been dated at 8,320 (GSC–821) and 8,200 yr B.P. (GSC–815), respectively (Lewis, 1969). Anderson and Lewis (1987) recently suggested that shoreline features at about the 212-m altitude relate to catastrophic overflow from Nipigon-phase Lake Agassiz. If this is the case, then a brief surge may have interrupted the steady rise in level caused by outlet uplift.

Gyttja from successively lower lakes, including Trout Lake at the North Bay sill (207 m), provided younger dates. These included samples at 204.2 m (4,650 yr B.P., GSC–843), 206.8 m (4,580 yr B.P., GSC–828), 202.3 m (4,490 yr B.P., GSC–850), and 204.6 m (4,430 yr B.P., GSC–808). These dates limit the final drainage through the North Bay channel. Uplift is generally considered to have raised the North Bay sill above the altitudes of the southern outlets at this time.

RECONSTRUCTING FORMER WATER PLANES

The present altitudes of the northern outlets, together with the exponential-uplift model investigated here, provide a framework for examining the complex of deformed shorelines in the upper Great Lakes basin. One of the current problems is the correlation of the Main Algonquin water planes of the Lake Michigan and Lake Huron basins. Karrow and others (1975) pointed out a lack of consistency between the basins, indicating that the Algonquin level of Lake Michigan is considered younger than that of Lake Huron.

This is highlighted in figure 9, where the calculated Main Algonquin of Goldthwait, Leverett, and Taylor passes below the controlling sill to the Kirkfield outlet at Fenelon Falls (257 m). Similarly, the Main Algonquin terrace on Manitoulin Island at 289 m lies above the Main Algonquin shoreline of Lake Michigan (MAM), while lower terraces tend to match the altitudes shown in figure 8 (Sly and Lewis, 1972; Sly, written commun., 1984). Clearly, if Goldthwait's concept of outlet control or the model discussed here have validity, then contemporaneous water planes, though deformed, must pass through their controlling outlet as well as any connecting channels.

Figure 12 shows the position of the Chippewa unconformity in the Lake Michigan basin. Once the isostatically depressed channel at North Bay was deglaciated, three interconnected lakes were formed, each with levels controlled by a downstream sill. As the outlet at North Bay was uplifted, lake levels rose accordingly until each successively higher connecting channel was inundated. When this occurred at the Mackinac Straits, a single water plane briefly joined the Mackinac River sill (140 m), the North Bay sill (207 m), and the Chippewa unconformity in the bottom sediments of Lake Michigan. The few data points available suggest that the late Chippewa water plane is described by an exponential function passing through four critical altitudes. Data from the southern basin do not plot on this curve because that basin contained a separate lake controlled by a channel with a sill at 74 m (Hough, 1958, p. 240).

Figure 12 also identifies the locations and present altitudes of the northern outlets and their controlling sills. If deglaciation is taken as the primary explanation for drainage of the Michigan and Huron basin lakes, then it is clear that the Fenelon Falls spillway was the first outlet exposed. This was followed by successive exposures of the Fossmill (Kilrush Lake) and the North Bay systems. Concomitantly, least-squares regressions calculated on contemporaneous shoreline features must intersect outlets of similar age.

Shoreline data from the eastern Lake Huron shore are shown in figure 13 superimposed on the calculated Lake Michigan shorelines, as projected along isobases of historic uplift (fig. 9). Main Algonquin and Orillia shoreline data were those assembled by Kaszycki (1985) and Finamore (1985) on the basis of their own and earlier work (Deane, 1950; Chapman, 1954). The Main Algonquin of Huron (MAH) shows a best-fit relationship through the Fenelon Falls sill and the Algonquin terrace of Manitoulin Island. The slope of MAH ($m = 0.0014$) is greater than that of the Main Algonquin of Michigan (MAM) ($m = 0.0012$), which implies a greater age and greater continuous differential uplift. A still lower shoreline, identified by Kaszycki as the Ardtrea, is based upon a correlation with "lower Algonquin" shorelines to the north and is not shown here. Its position, however, is below the MAH and its apparent spillway control is at Fenelon Falls. Thus, it predates the MAM. Her Orillia data, and other surfaces she considered to be Ardtrea (1985, her fig. 9), tend to plot on the MAM curve and below the Fenelon Falls sill. A least-squares regression calculated on Kaszycki's three recognized Orillia terraces and plotted on figure 13 shows a slope ($m = 0.0012$) and y intercept ($b = 1.7802$) nearly identical with those of the MAM in figure 9. In each example, these curves project beneath the level of Lake Huron. As a comparison, the MAH projects to a lower altitude than the MAM, pointing to its earlier place in the sequence.

The calculated MAH level rises northward to the vicinity of Maple Lake, Ontario. It is extrapolated to an altitude of 361 m near the mouth of the Fossmill outlet system, which is nearly coincident with the Genesee level proposed by Harrison (1970, 1972) as the first overflow channel to the east. The MAM curve intersects the Mink Lake sill, and the Lower Algonquin curve intersects the lower threshold to the Amable du Fond River valley that, when deglaciated, shifted overflow northward from the Petawawa River drainage. No lower outlets correspond to the Battlefield and Fort Brady curves, although deglaciation of the North Bay region probably exposed lower channels. The North Bay sill (207 m) probably functioned as early as 10,300 yr B.P., as indicated by submerged stumps in Georgian Bay. A late-Chippewa low-phase (8,000 yr B.P.) curve passing through the controlling North Bay sill is shown for comparison, as are

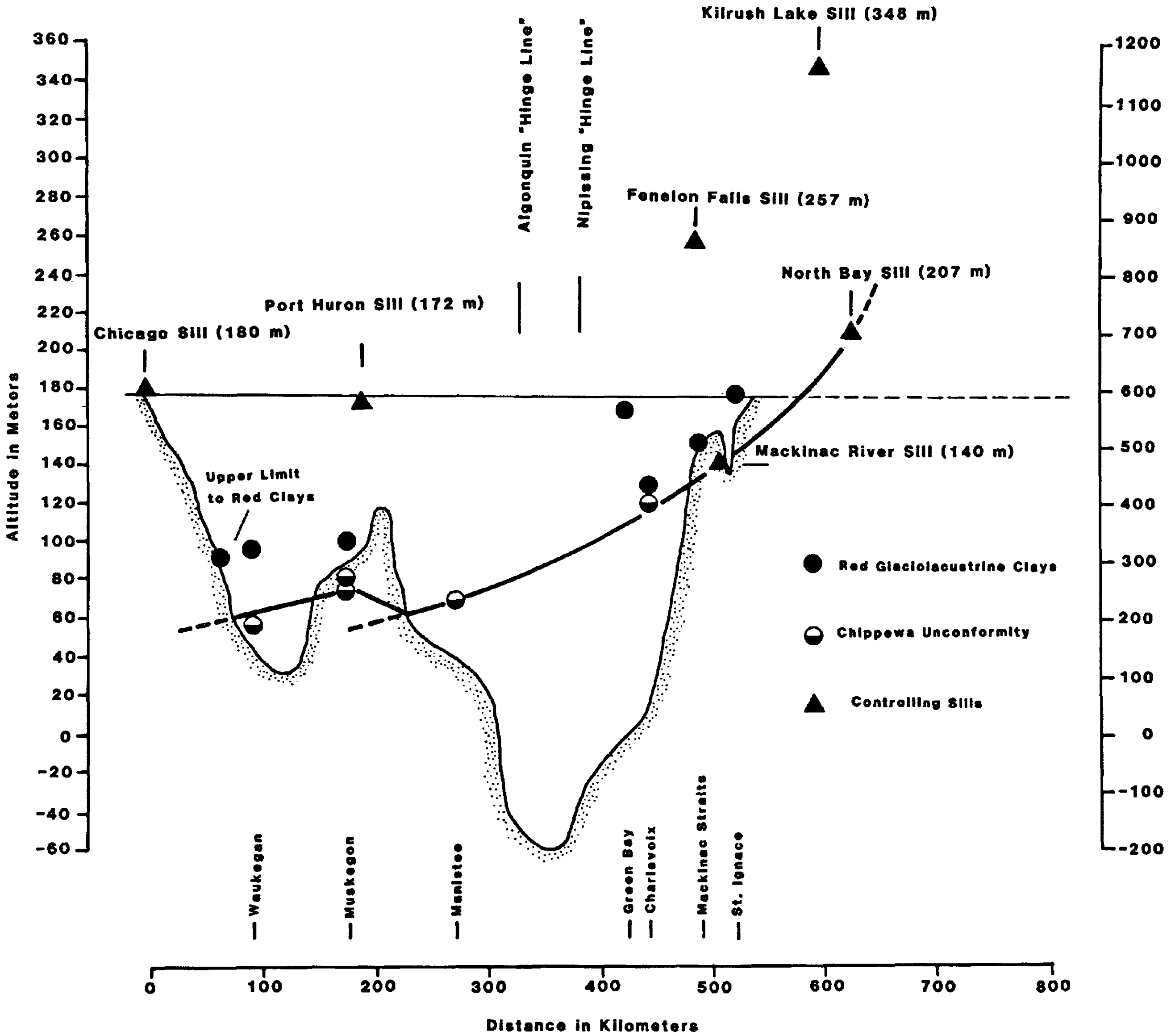


Figure 12. Calculated late Chippewa water plane at about 8,000 yr B.P. Overflow of the Lake Michigan basin is to the northeast at the Mackinac Straits and is ultimately controlled by the North Bay outlet.

curves for the Hough low level of Georgian Bay (10,300 yr B.P.) and the mid-Stanley level (9,000 yr B.P.) linking Georgian Bay with the main Huron basin. Because all the calculated shorelines project below the lake surface, an outlet control is indicated to the north and east rather than at Port Huron to the south.

The complete array of late Wisconsinan and early Holocene shoreline curves assembled along isobases of historic uplift suggests that outlet controls to the post-MAH lakes were to the northeast through the Fossmill and then the North Bay drainage systems. This alternative, not considered by Goldthwait (1908) in his derivation of the hinge-line model, provides an explanation for terrace convergence.

In addition to demonstrating outlet control, figure 13 places the uplifted shorelines of Lake Michigan and Lake Huron in chronological sequence by slope value until the basins drained through North Bay at about 10,300 yr B.P. The MAH and Ardtrea shorelines of eastern Lake Huron predate the MAM and lower shorelines of northern Lake Michigan, and the MAM may correlate with the Orillia shoreline of Ontario.

At the same time, figure 13 demonstrates anomalously steep curves for the low-level lakes draining through North Bay. The current concept of shoreline deformation interprets each shoreline as an increment in an uplifting lake basin. The earliest and highest shoreline therefore records the cumulative uplift since deglaciation and shows

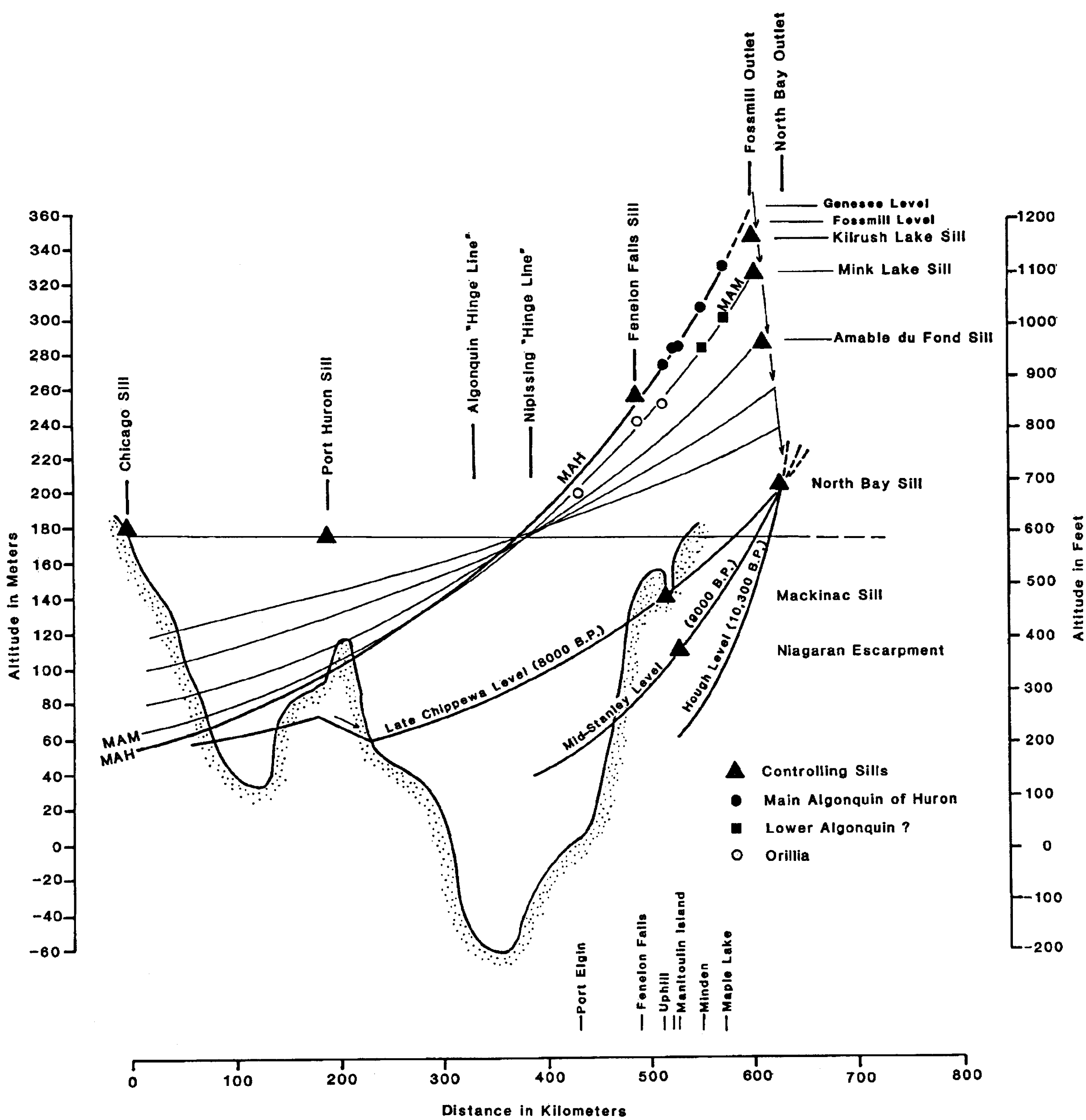


Figure 13. Algonquin shoreline data of Lake Huron projected onto the Lake Michigan normal plane (fig. 9). The Chippewa-Stanley-Hough low levels are also shown. The Main Algonquin of Huron (MAH) is altitudinally higher than the Main Algonquin of Michigan (MAM). The Main Algonquin and post-Algonquin lakes drain northward as progressively lower outlets are deglaciated. The Lower Algonquin shoreline of Lake Michigan apparently drained across the Amable du Fond sill.

the steepest gradient. Each successively younger shoreline should be lower in the sequence and display decreasing gradients through time. The calculated water planes for the lakes draining at North Bay show slope coefficients of 0.005, 0.0024, and 0.0012, indicating gradients as great as or greater than those of the MAH and MAM. Figure 14, on the other hand, demonstrates that the slopes of the low-level lakes are consistent with those of the Nipissing II (4,000 yr B.P.) and Algoma (3,200 yr B.P.) shorelines (fig. 9) and a historic shoreline (100 yr B.P.) calculated from the lake-level gauge data (table 3). The slopes of the MAH and MAM are shown for comparison. This anom-

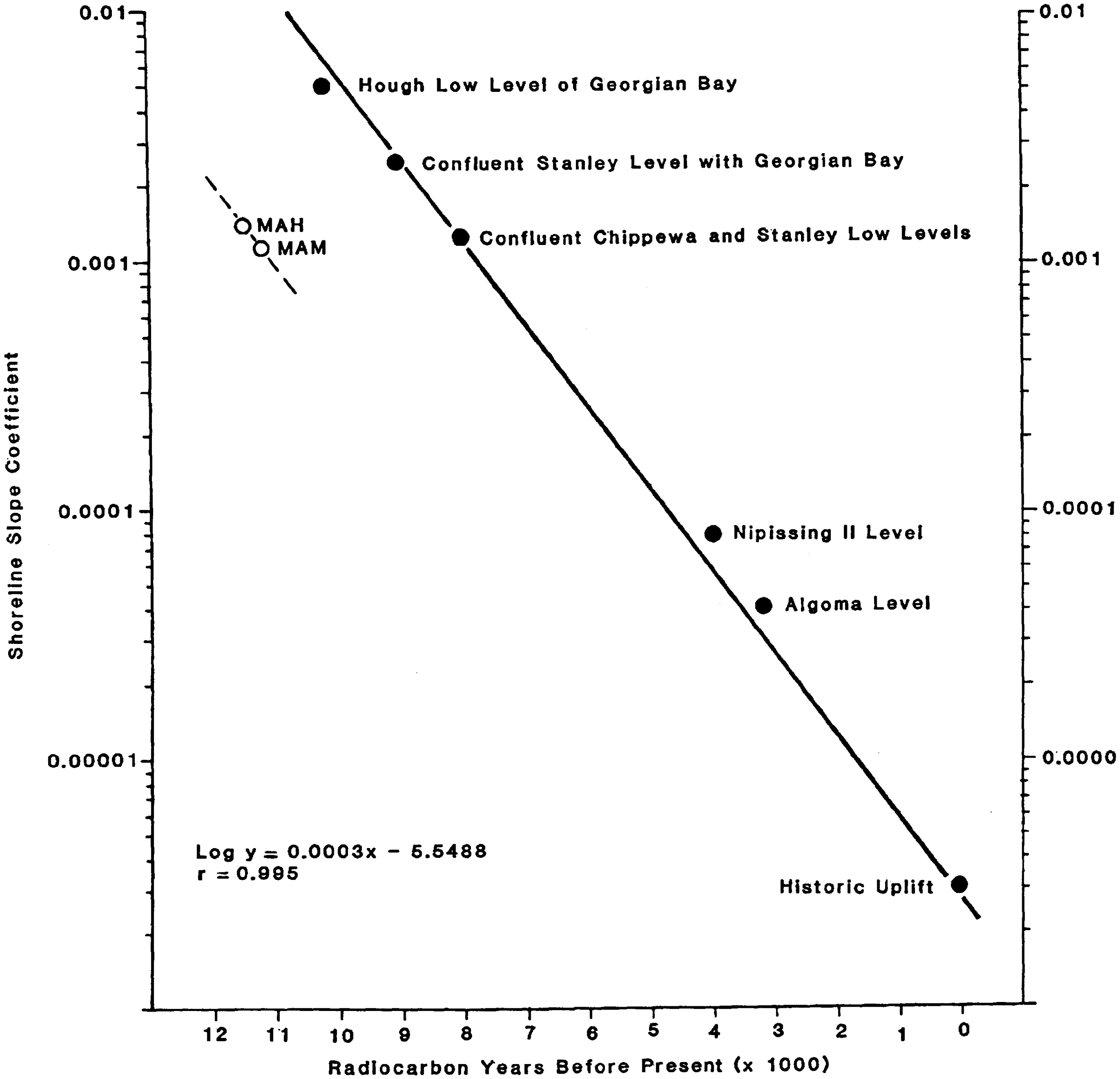


Figure 14. Decreasing slope coefficients of postglacial water planes following the establishment of the North Bay outlet. The slopes of the MAH and MAM are shown for comparison.

aly underscores the value of the exponential model for reconstructing post-10,300 yr B.P. water planes but points out potential problems with the earlier shoreline data.

Several factors may influence the low gradients of the Algonquin shorelines. Figure 13 shows the control of a single, rising spillway between 10,300 and 4,000 yr B.P. The Algonquin water planes, on the other hand, were governed by a shift from the Kirkfield to the Fossmill systems, each spillway rebounding at a different rate upon deglaciation. In addition, the Fossmill spillways were occupied only briefly as successively lower channels were deglaciated. These changes, coupled with the dissimilar deglaciation histories of the two lake basins, the effect of the Marquette advance into the Lake Superior basin, and overflow from Lake Agassiz, may account for the discrepancies noted.

A CHRONOLOGY OF LAKE MICHIGAN AND LAKE HURON LEVELS

A preliminary chronology for the Lake Michigan and Lake Huron basins is shown in table 4 using 11,500 yr

B.P. as the youngest probable deglaciation of the Kirkfield outlet (Karrow and others, 1975). In the few hundred years before 11,500 yr B.P., separate proglacial lakes draining southward through the Chicago and Port Huron outlets occupied the Michigan and Huron basins, respectively. Lake Chicago stood at its Calumet level of 189 m while Early Lake Algonquin filled the southern Huron basin, possibly at a 184.5-m level (fig. 15). Ice retreat into a progressively deepening isostatic depression caused deglaciation of successively lower northern outlets, which in turn caused the lakes to fall.

Main Algonquin of Huron (MAH)

Deglaciation of the Fenelon Falls sill before 11,500 yr B.P. opened a low outlet to the Ontario basin near Kirkfield, Ontario. This event caused a drop in Lake Huron to a low level identified as the Kirkfield Stage (table 1) by Leverett and Taylor (1915) but correlated in table 4 with the MAH shoreline, which passes through the Fenelon Falls sill. Continued rapid ice retreat into the North Bay region opened lower overflow channels to the headwaters of the Petawawa River drainage and allowed the lake to fall and to abandon the Kirkfield outlet (fig. 16).

Main Algonquin of Michigan (MAM)

Deglaciation of the Lake Michigan basin was accompanied by northward expansion of Calumet-level Lake Chicago until drainage channels to the Huron basin were uncovered north of Traverse City, Mich. Drainage through the Indian River lowland possibly linked the two lake basins briefly, joining the Calumet level of Lake Chicago with the MAH (fig. 17).

Deglaciation of the Mackinac Straits at about 11,200 yr B.P. joined the basins at depth. The MAM dates from this period and represents a single water plane draining to the north through the Fossmill system and probably controlled by the Mink Lake sill at 328 m. This isostatically depressed outlet channel caused the level of Lake Michigan to fall to a low of about 61 m in the southern basin. The best altitudinal correlative with the MAM is the Orillia shoreline of northeastern Lake Huron.

The Post-Algonquin Lakes

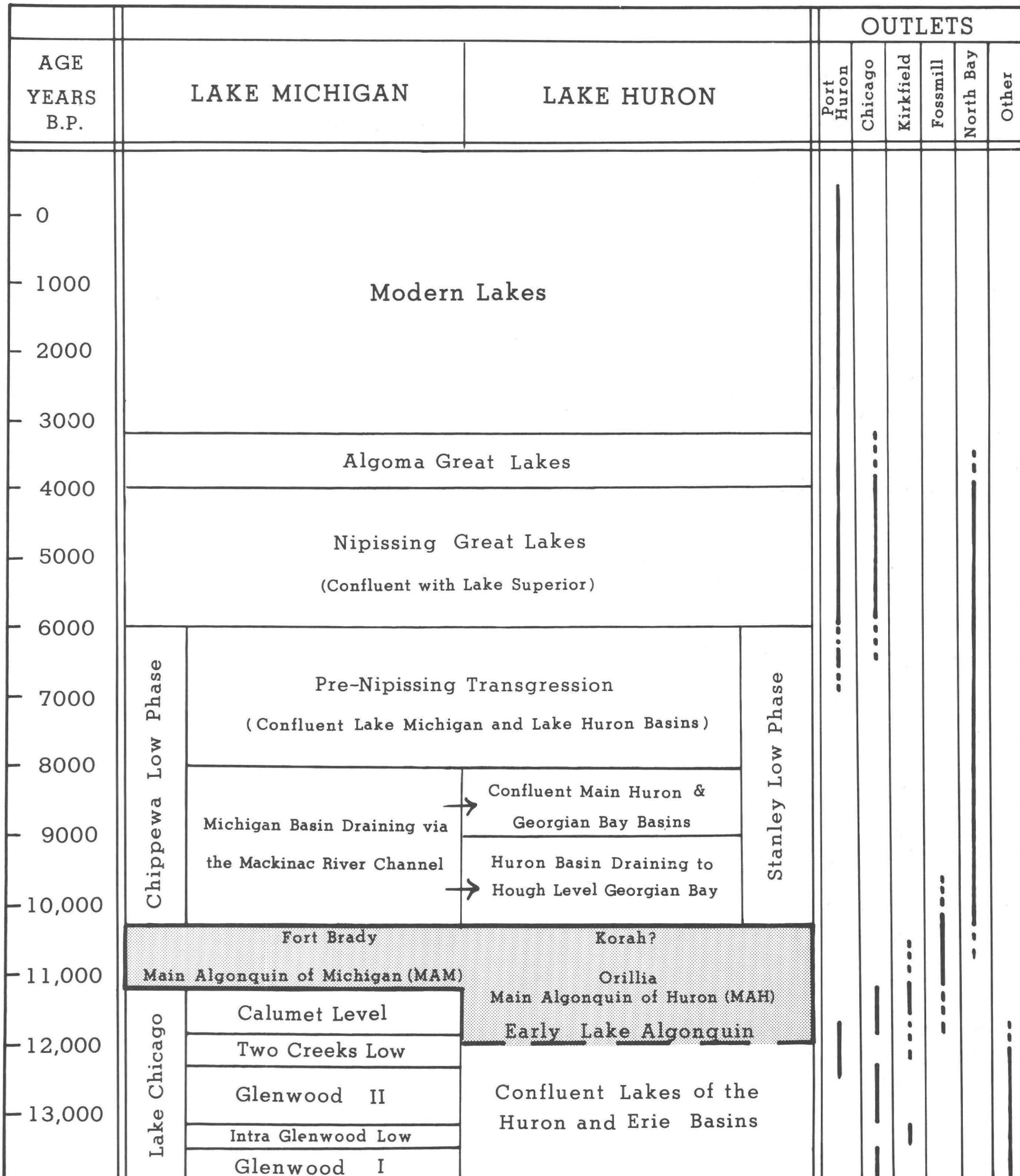
The Lower Algonquin, Battlefield, and Fort Brady shorelines of Leverett and Taylor (1915)—subsequently renamed by Stanley (1937) as the Wyebridge, Penetang, and Cedar Point—as well as the altitudinally lower Payette, Sheguiandah, and Korah shorelines of Lake Huron, postdate the MAM (11,200 yr B.P.) and predate drainage across the North Bay sill (10,300 yr B.P.). Each shoreline relates to northern overflow via successively lower outlet thresholds. The Lower Algonquin shoreline, as originally described for Lake Michigan, appears to coincide with overflow to the Mattawa valley through the Amable du Fond valley as well as a shift away from the Petawawa headwaters. The outlet controls to the subsequent levels are not documented. As Harrison (1970, 1972) proposed, overflow may have paralleled the receding ice edge and allowed the lakes to fall until the final channel at North Bay was uncovered. A progressive fall in outlet altitude, in concert with a rapidly rebounding crust, resulted in a transgression in the southern lake basins in the manner shown in figure 5, until North Bay was deglaciated.

The Chippewa and Stanley Low Levels

The lakes underwent their final fall when ice receded from North Bay (fig. 18). The level of Georgian Bay dropped to as low as 62 m. The Stanley level of the main Huron basin, controlled by sills along the Niagaran escarpment separating it from Georgian Bay, fell to as low as 107 m. The Lake Michigan level, in turn, fell to a plateau near 160 m at the Mackinac Straits and subsequently eroded the Mackinac River channel to a controlling threshold now at about 140 m. This spillway governed a lowered level of the lake, creating a separate lake in the south at an altitude of about 55 m that overflowed northward through a channel near Muskegon (Hough, 1958, p. 241). The slow rise from the early Chippewa low level in the southern basin was controlled by uplift of the Mackinac Straits. In contrast, southern Lake Huron was drained when the waters of the Stanley level fell below a 113-m threshold along an escarpment separating the northern and southern basins.

The low-level phases of Lake Michigan and Lake Huron (table 4) were progressively ended by uplift of the controlling spillway at North Bay. First, the uplifting outlet caused the Hough level of Georgian Bay to rise until it attained the altitude of the connecting channels to the main Huron basin about 9,000 yr B.P. The confluent level of both basins then rose to the 113-m threshold to reflood the southern Huron basin after 8,460 yr B.P. Some portion of this rise to reflood the southern Huron basin may have been caused by Nipigon-phase flooding from Lake Agassiz, but the evidence is unclear. A transgression, led by the expanding lake in the Huron basin and caused by the steadily rising North Bay outlet, rejoined the Michigan and Huron basins at the Mackinac Straits after 8,150 yr B.P. The episode marked the end of separate low-level phases in the lakes and initiated the pre-Nipissing transgression.

Table 4. Preliminary chronology for the Lake Michigan and Lake Huron basins



Pre-Nipissing Transgression

Reflooding of the Mackinac Straits began a tandem transgression in the Lake Michigan and Lake Huron basins related to overflow at North Bay (fig. 19). This transgression continued until overflow to the south began at Port Huron before 6,100 yr B.P. The pre-Nipissing transgression (table 4) attained the threshold of the Chicago outlet (180 m) after 6,300 yr B.P. From this point, the combined southern outlets modulated lake level in the confluent basins.

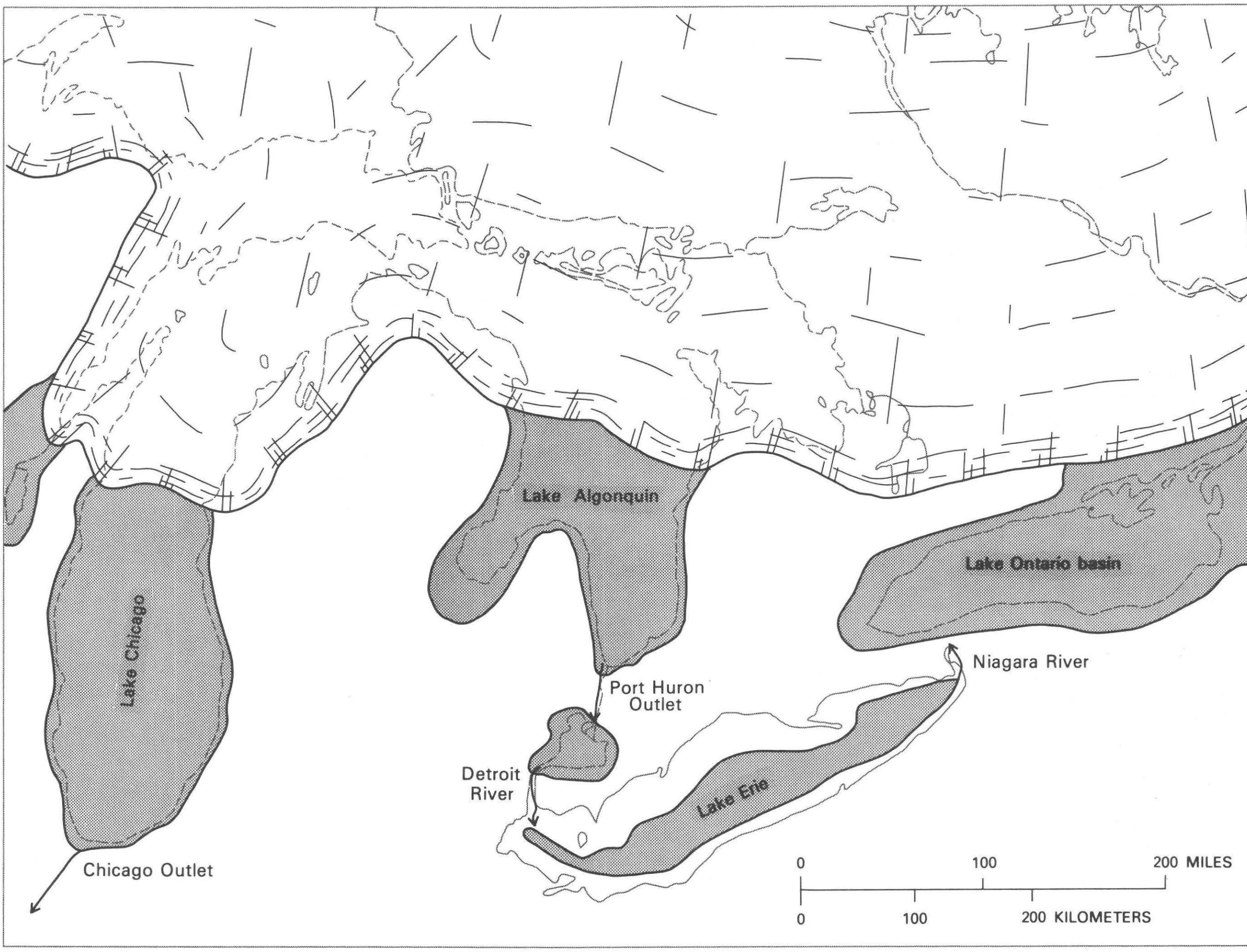


Figure 15. Calumet-level Lake Chicago and Early Lake Algonquin. Overflow was to the south at Chicago and Port Huron at the maximum advance of Two Rivers ice about 11,800 yr B.P. Early Lake Erie drained to the Lake Ontario basin.

Nipissing and Algoma Great Lakes

Once drainage to the south was established, the outlet configurations and probable paleoclimatic influences on water volume became major variables in the system. Lake level fluctuated about a mean altitude adjusted to the cross sections of the southern outlets. Before 4,500 yr B.P., the record of lake-level change is poorly known; however, distinct high levels occurred at 4,500, 4,000, and 3,200 yr B.P. (Larsen, 1985a,b). These highs, referred to as the Nipissing I, Nipissing II, and Algoma levels, are identified by terraces that rise exponentially with distance from the southern shores of Lake Michigan to the North Bay region (Larsen, 1985b). They reflect probable high-amplitude fluctuations related to runoff variations in the drainage basins. The permanent outlet channel linking North Bay with the Mattawa River maintained a level adjusted to its rising sill. Isostatic uplift finally raised the North Bay sill above the southern outlets between 4,500 and 4,000 yr B.P. The Chicago outlet was abandoned after 4,000 yr B.P., and the modern drainage system at Port Huron came into being (fig. 20). Since then, lake levels have continued to fluctuate adjusted to a single outlet channel.

CONCLUSION

The uplifted Lake Algonquin terraces of the northern Lake Michigan and Lake Huron basins are progressively deformed from youngest to oldest to the north. Profiles drawn along the eastern shore of Lake Michigan and erected normal to isobases of historic vertical movement show that these late glacial terraces fit exponential curves directed toward the former centers of glacial-ice loading near Hudson Bay. The Main Algonquin through Fort Brady terraces of Leverett and Taylor (1915) show concave-upward slopes that decrease in steepness with both distance and time, implying a decrease in the rate of uplift. Vertical movement, monitored over the Great Lakes

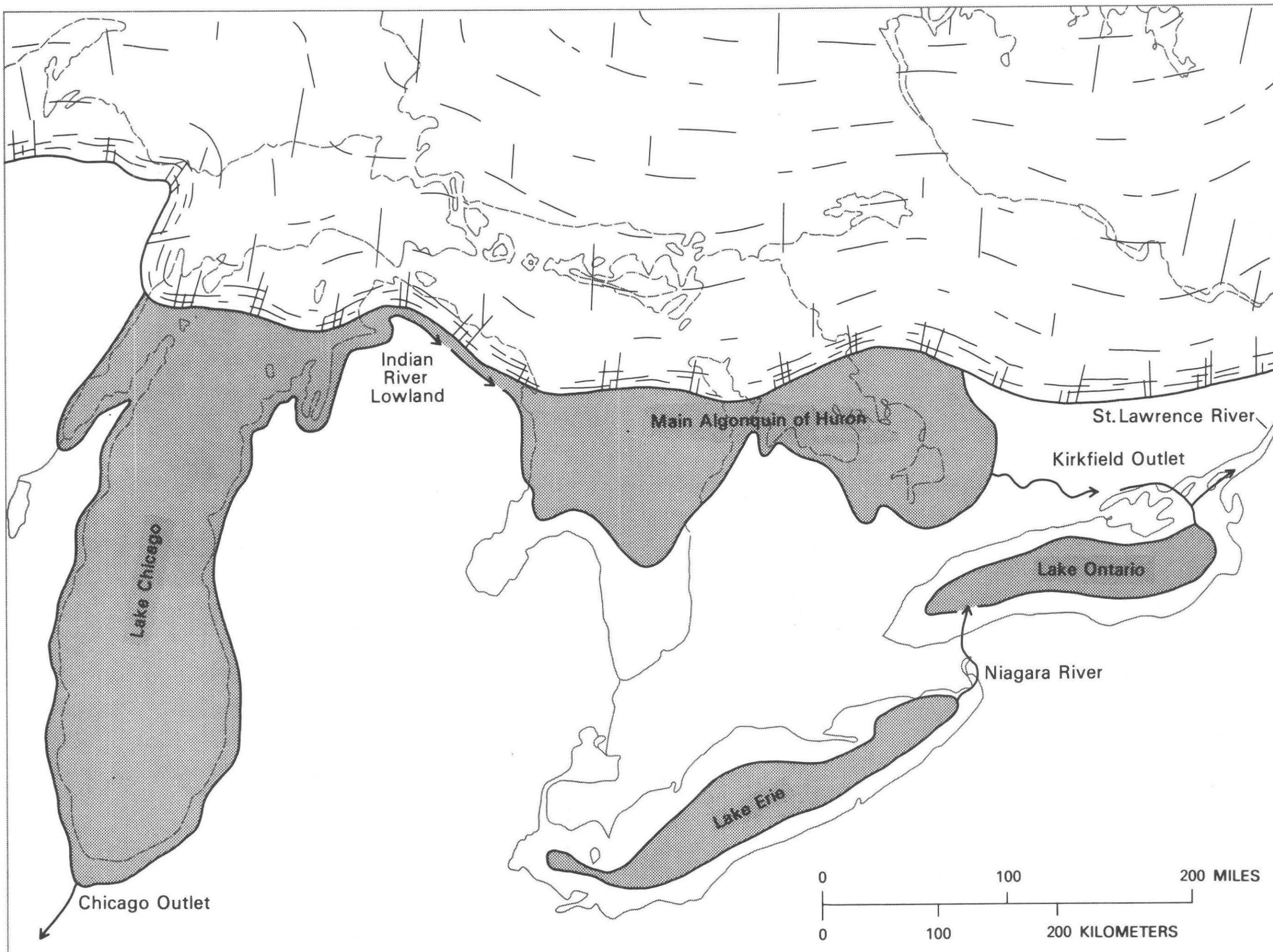


Figure 16. Calumet-level Lake Chicago and the Main Algonquin level of Lake Huron (MAH) (11,600 to 11,300 yr B.P.). Overflow was to the south at Chicago and eastward to Early Lake Ontario at Kirkfield. The Michigan and Huron basins were possibly linked by drainage through the Indian River lowland south of the Mackinac Straits. Lake Erie overflowed to the Lake Ontario basin.

basin during the past century, shows an exponential decrease with distance from the former ice centers. This similarity points to a continuous process of deformation of the Great Lakes basin related to postglacial isostatic uplift of the region that followed deglaciation. The terrace sequences of Lake Michigan and Lake Huron reflect increments of isostatic adjustment; the highest terrace in each lake basin represents the cumulative vertical movement since deglaciation.

The calculated Main Algonquin through Fort Brady shorelines of Lake Michigan descend in altitude to the south and plunge beneath the present surface of the lake south of Traverse City, Mich. This area was chosen as a hinge line by Goldthwait (1907, 1908, 1910b) and Leverett and Taylor (1915). These authors thought that the deformed terraces north of the hinge line merged with a nearly horizontal terrace at the hinge line. The projected Algonquin and post-Algonquin water planes, however, indicate a low lake that did not drain to the south but was controlled initially by the eastern outlet of Lake Huron near Kirkfield, Ontario, and subsequently by deglaciation of the Fossmill outlet system. A low late Wisconsinan lake may be evidenced by the presence and upper altitude of red glaciolacustrine clays in the Lake Michigan basin. The contemporaneous late glacial water planes, projected to the south, represent the upper limit to red-clay deposition and indicate the attitude of the former lake surface. These data delineate an isostatically deformed region extending south of Lake Michigan that rebounded after deglaciation. The concept of continuous isostatic deformation of the basin enables us to derive consistent relative lake-level models for the Lake Michigan and Lake Huron basins. These models are developed on the basis of the observed exponential decay of the rate of uplift following deglaciation and the exponential decrease in the amount of uplift with distance from the former centers of isostatic depression. The change in the position of water planes can also be described by similar functions for critical areas in

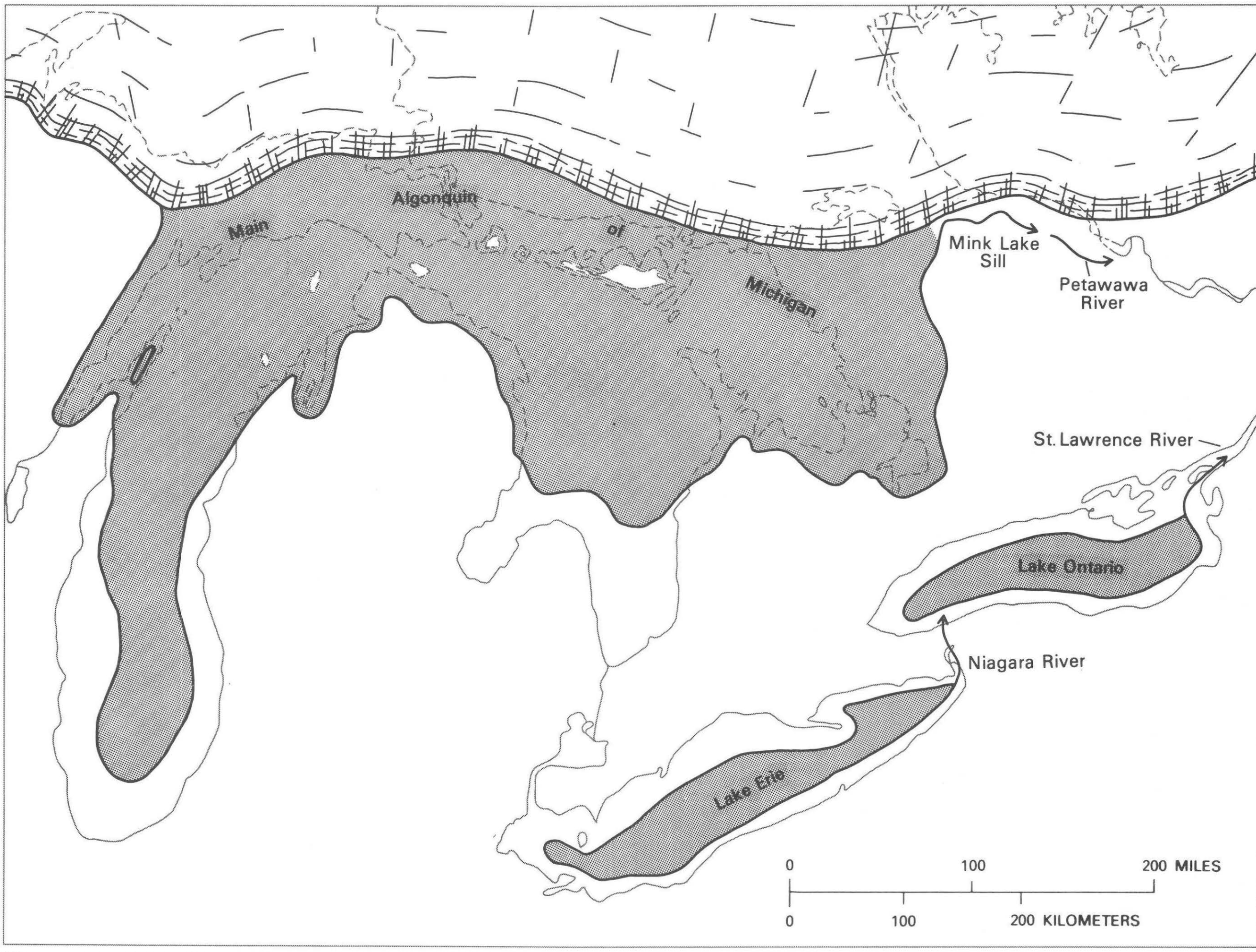


Figure 17. Main Algonquin level of Lake Michigan confluent with the Orillia (?) level of the Lake Huron basin (11,200 to 11,000 yr B.P.). Overflow was eastward to the Ottawa valley at the Mink Lake sill. Lake Erie and Lake Ontario basins contained low lakes controlled by rising northeastern outlets (fig. 5, case 3), which show rising water levels along their western shores.

the paleohydrological system. Such models compare synchronous events throughout the interconnected lake basins and, when coupled with detailed field investigations, will lead to further revisions to the lake-level chronology shown in table 4.

The interpretations presented here differ from those predicated on the early views concerning Lake Algonquin, the hinge line, and stable southern outlet regions. The Great Lakes region is a dynamic, isostatically rebounding system. Main Lake Algonquin of Lake Huron was a low-level lake that drained eastward into an isostatically depressed region at Kirkfield, Ontario. It was not contemporaneous with the Main Algonquin shoreline of Lake Michigan, which also represented a low-level lake, but one that drained via the Fossmill outlet system.

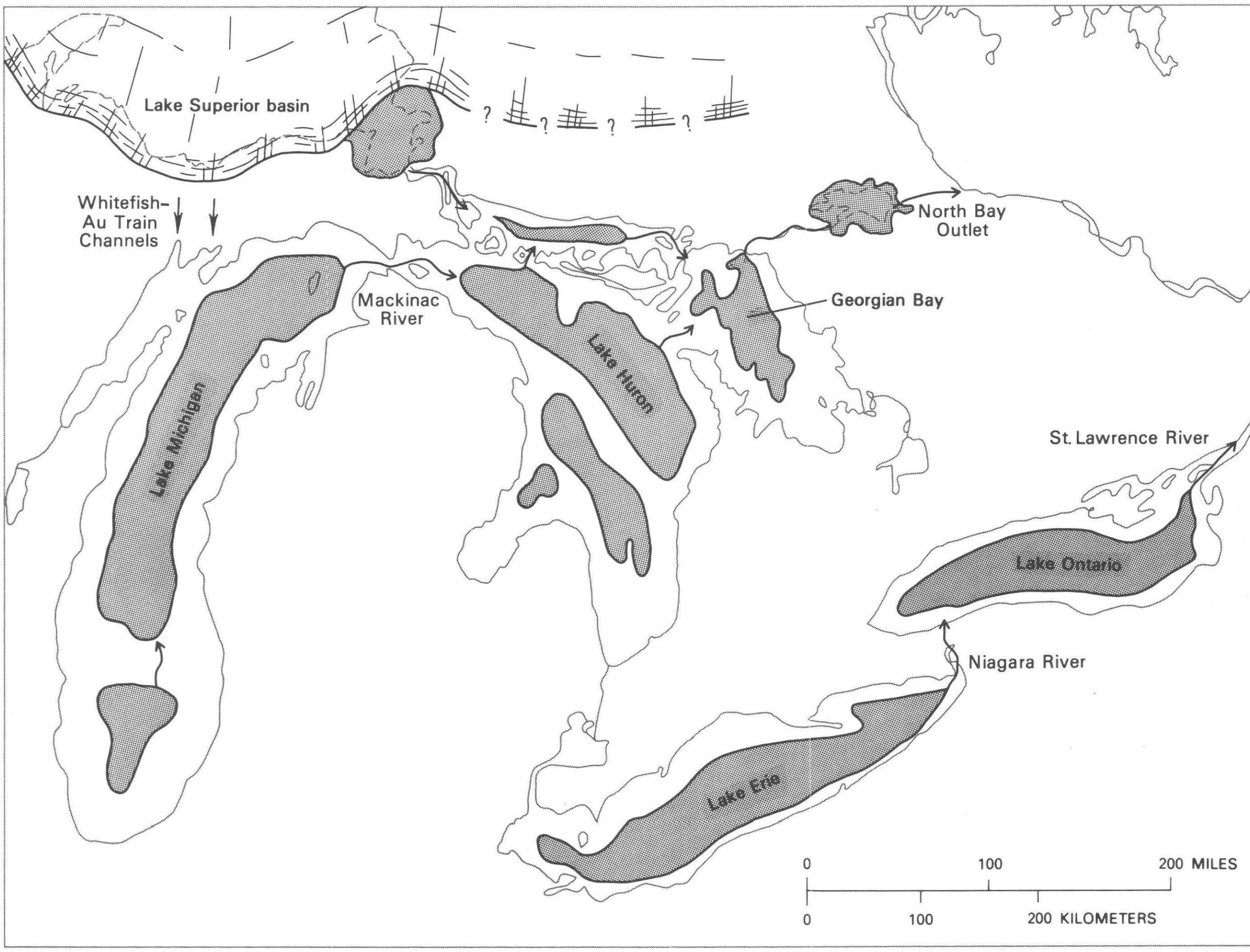


Figure 18. Chippewa and Stanley low levels. Marquette ice filled the Lake Superior basin and supplied overflow through the Whitefish–Au Train channels (9,900 yr B.P.). The upper Great Lakes drained eastward to the Ottawa valley across a controlling sill at North Bay that was deglaciated as early as 10,300 yr B.P. Chippewa-level Lake Michigan overflowed eastward through the Mackinac River channel. Separate lakes occupied the deep basins of Lake Huron and overflowed across the Niagaran escarpment into the Hough low level in Georgian Bay. Lake Erie and Lake Ontario continued to rise and expand westward as their outlets rose.

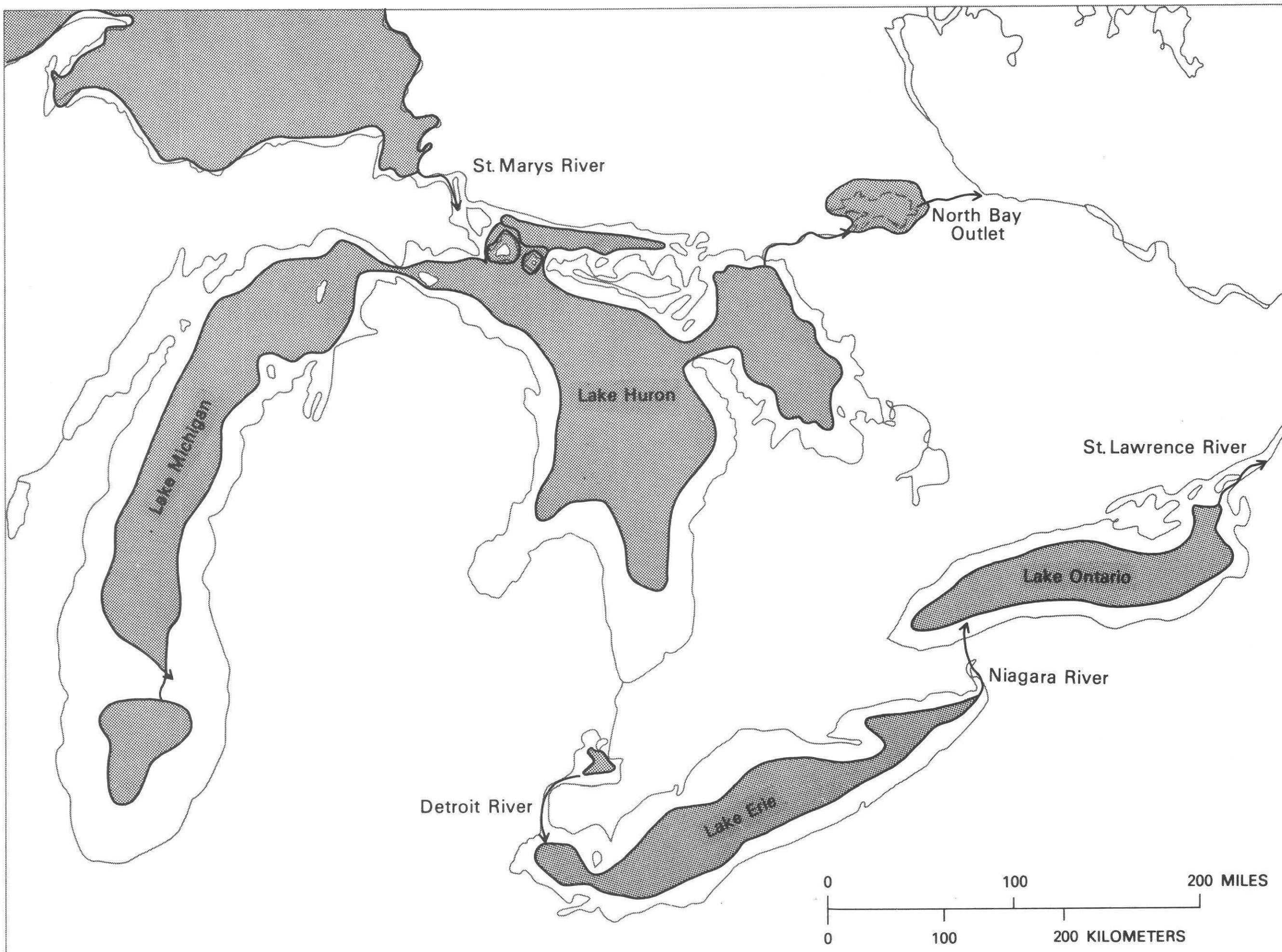


Figure 19. Pre-Nipissing transgression. Overflow through the rising North Bay outlet reflooded the Lake Michigan and Lake Huron basins, creating a confluent lake system (about 8,000 yr B.P.). Lake Erie and Lake Ontario continued their rise westward. Lake Michigan and Lake Huron began a tandem transgression controlled by the rising North Bay outlet (fig. 5, case 3).

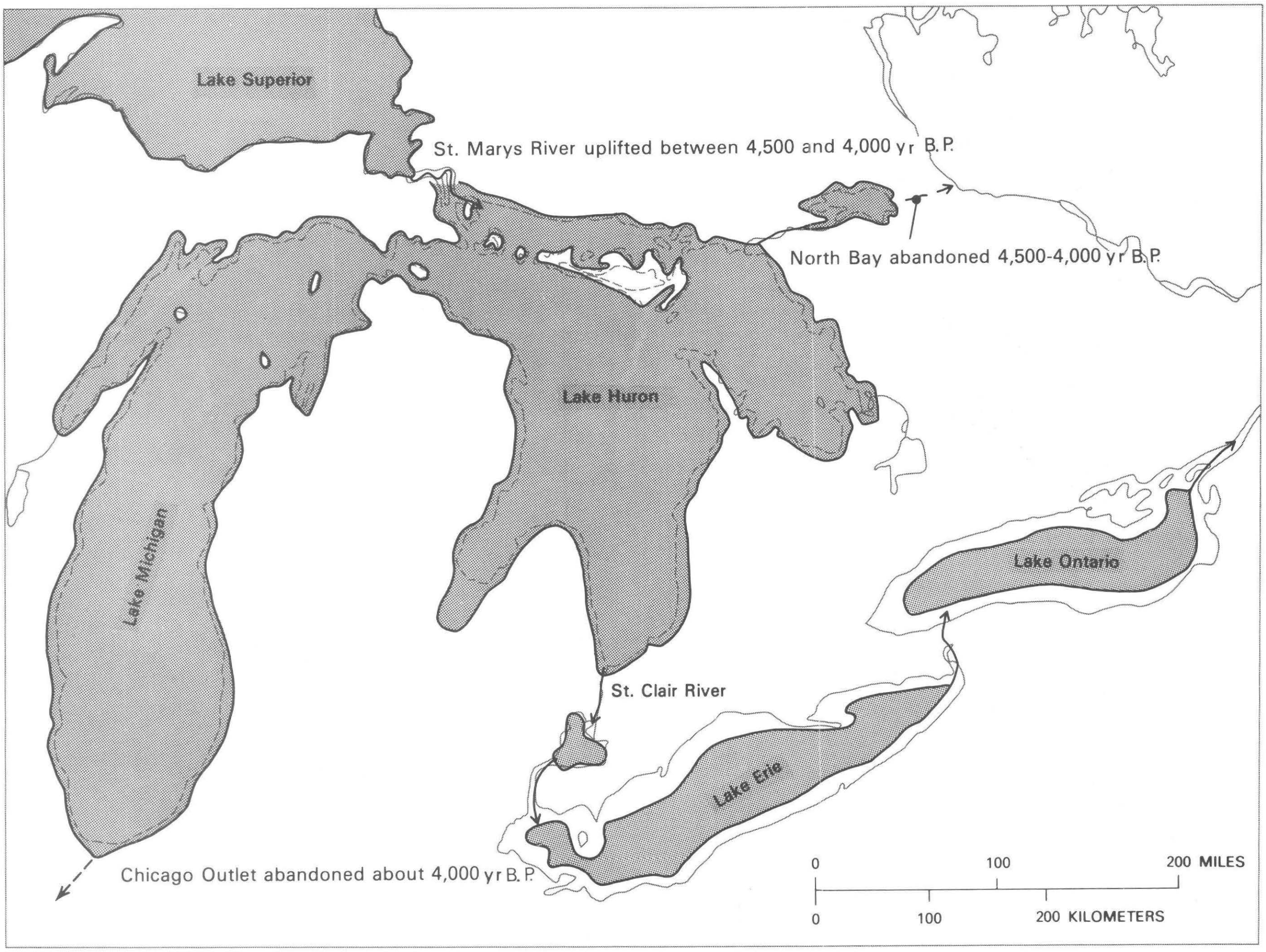


Figure 20. Late Nipissing and Algoma Great Lakes. The rising North Bay outlet reflooded the Lake Michigan, Lake Superior, and Lake Huron basins until overflow returned to first the Port Huron (St. Clair River) and then the Chicago outlets. Lake level rose above the present levels to leave the prominent Nipissing and Algoma terraces. For a brief time, overflow was through three outlets, but the North Bay outlet was abandoned between 4,500 and 4,000 yr B.P. when uplift raised it above the southern outlet controls. Uplift also raised the St. Marys River at about this time, creating a separate Lake Superior. Overflow through the Chicago outlet ceased by 4,000 yr B.P. and may have accommodated a climate-related rise in lake level (Nipissing I). This time period, 4,000 yr B.P., marks the onset of the hydrologically modern upper Great Lakes that continue to overflow through the St. Marys and St. Clair Rivers. Deformation of former Lake Michigan and Lake Huron shorelines now follows the pattern of figure 5, case 2. Lake Erie and Lake Ontario continue to rise in concert with their uplifting eastern outlets.

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Appendix. List of radiocarbon dates

[GSC, Geological Survey of Canada; M, University of Michigan; ISGS, Illinois State Geological Survey; W, U.S. Geological Survey. —, no data]

Lab no.	Date (yr B.P.)	Material	Altitude (m)	Reference
Mackinac Straits/Manitoulin Island				
Unreported	10,305± 78	Wood	145	Sly and Lewis (1972).
GSC–1108	10,150±190	Gyttja	191.7	Lewis (1970).
M–1996	9,780±330	Wood	140	Somers (1969).
GSC–1830	9,770±220	Wood	122.4	Sly and Sandilands (1988).
GSC–1397	9,440±160	Peat	145	Sly and Lewis (1972).
GSC–1971	9,260±290	Detritus	161	Lowdon and others (1977).
GSC–1979	8,310±130	Detritus	162	Lowdon and others (1977).
M–2337	8,150±300	Wood	140	Crane and Griffin (1972).
M–1888	6,788±250	Wood	167	Somers (1969).
GSC–2245	6,500± 70	Wood	167	Lowdon and Blake (1978).
M–1282	6,270±210	Wood	179	Crane and Griffin (1966).
Southern Lake Huron Basin				
GSC–1935	9,370±180	Peat	126	Anderson and Lewis (1974).
GSC–1966	8,460±180	Gyttja	126	Anderson and Lewis (1974).
M–1012	7,250±300	Wood	172	Crane and Griffin (1961).
St. Clair Delta				
Unreported	9,310±210	Wood	172	Mandelbaum (1969).
Unreported	7,300±80	Gyttja	172	Wightman (1961).
Unreported	6,100±80	Wood	172	Wightman (1961).
Grand Traverse Bay				
M–834	7,850±350	Detritus	153	Crane and Griffin (1960).
Southern Lake Michigan Basin				
ISGS–934	11,010±130	Wood	178.3	Hansel and others (1985b).
ISGS–950	10,570±180	Wood	178.6	Hansel and others (1985b).
ISGS–927	8,590±140	*Picea* cones	178.8	Hansel and others (1985b).
M–1736	7,580±350	Shell	80	Crane and Griffin (1968).
M–1972	7,570±250	Shell	69	Crane and Griffin (1970).
M–1571	7,400±500	Shell	73	Crane and Griffin (1965).
ISGS–36	7,050±200	Organic matter	—	Lineback and others (1970).
ISGS–33	6,920±200	Organic matter	—	Lineback and others (1970).
ISGS–185	6,350±200	Wood	177	Larsen (1985a).
W–1017	6,340±300	Wood	177	Larsen (1985a).
ISGS–68	3,460±210	Organic matter	—	Lineback and others (1970).
Chicago Outlet Channel				
ISGS–1241	8,690±80	Peat	180	Hansel and others (1985b).
ISGS–960	6,280±70	Peat	180	Hansel (pers. commun.).
ISGS–1240	3,390±70	Peat	180	Larsen (1985a).
North Bay Region				
GSC–1363	11,800±400	Gyttja	345	Harrison (1972).
GSC–1429	11,400±280	Gyttja	345	Harrison (1972).
GSC–1275	10,100±240	Gyttja	194	Harrison (1972).
GSC–1246	9,860±270	Gyttja	348	Harrison (1972).
GSC–638	9,820±200	Gyttja	312.4	Lewis (1969).
GSC–1097	8,670±140	Wood	290	Harrison (1972).
GSC–821	8,320±170	Gyttja	211.8	Lewis (1969).
GSC–815	8,200±160	Gyttja	213.5	Lewis (1969).
GSC–1263	8,070±190	Wood	212.3	Harrison (1972).
GSC–836	4,650±200	Gyttja	202.2	Lewis (1969).
GSC–843	4,650±160	Gyttja	204.2	Lewis (1969).
GSC–828	4,580±160	Gyttja	206.8	Lewis (1969).
GSC–850	4,490±180	Gyttja	202.3	Lewis (1969).
GSC–808	4,430±160	Gyttja	204.6	Lewis (1969).

U.S. DEPARTMENT OF THE INTERIOR

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