FIGURE 13.6 Map of the ice margin about 17,500 years ago, showing Lake Maumee I (M1). Glacial Lakes Scuppernong (S) and Oshkosh (O) are shown in front of the Green Bay lobe in Wisconsin (Clayton 1997).

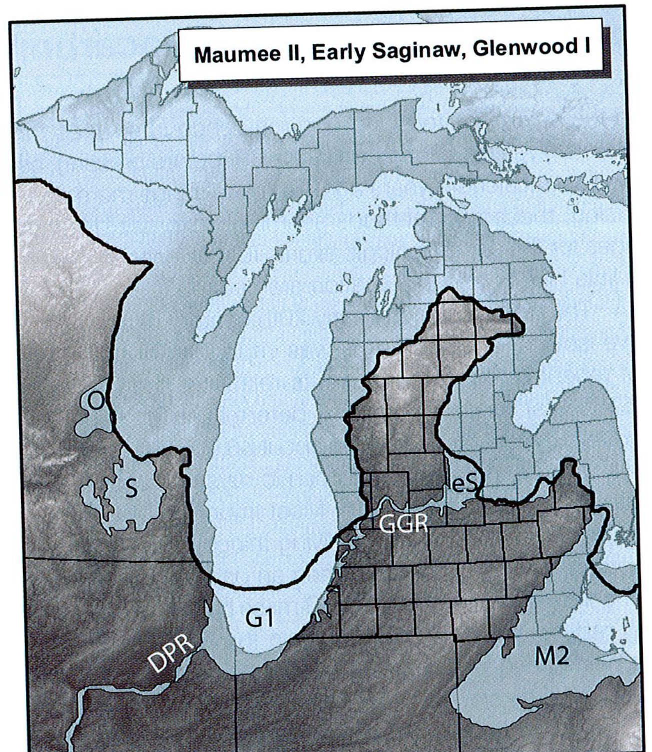


FIGURE 13.7 Map of the ice margin about 17,100 years ago, showing Lake Maumee II (M2), Early Lake Saginaw (eS), and the Glenwood I phase of Lake Chicago (G1). At this time, the Glacial Grand River (GGR) drained Early Lake Saginaw into Lake Chicago, and the Des Plaines River drained Lake Chicago to the Mississippi River drainage basin (via the Illinois River). Glacial Lakes Scuppernong (S) and Oshkosh (O) are shown in front of the Green Bay lobe in Wisconsin (Clayton 1997).

to the Wabash River near present day Fort Wayne, Indiana (Calkin and Feenstra 1985). The Maumee I shoreline (the elevation of the outlet and associated beaches) was at 244 m above sea level and, as the Huron/Erie lobe continued its retreat, extended from Fort Wayne into Michigan through Lenawee County to Macomb County. After the Huron/Erie lobe ice readvanced to the Defiance moraine, Lake Maumee was present only in northeastern Ohio. Ice retreat again allowed expansion of Lake Maumee into southeastern Michigan. But the retreat also uncovered a lower outlet, lowering Maumee I to the Maumee II elevation of 232 m (Fig. 13.7). Shoreline features of Maumee II are not well developed in Michigan and are known mostly from Ohio (Calkin and Feenstra 1985). There is no outlet at 232 m elevation across the Defiance moraine, so it is thought that the ice advance ending Maumee II (and building the Flint moraine) buried the outlet channel (Leverett and Taylor 1915). With the lower outlet buried, the previous and higher (244 m) outlet was used again. Ice retreat from the Flint moraine opened up an impressive channel near Imlay City (Lapeer County) allowing Maumee III to stabilize at 238 m and drain eastward into the Saginaw lowlands. This well-developed channel is clearly visible on a topographic map of Lapeer County, extending from the Lake Maumee plain to the Flint River.

Retreat of the Saginaw lobe margin from the Flint moraine also started opening up the Saginaw lowlands in central Michigan, forming Early Lake Saginaw (Fig. 13.7). This lake drained westward via the Glacial Grand River, through the Maple River valley at the village of Maple Rapids, to eventually empty into Glacial Lake Chicago, Glenwood I phase. The Allendale delta, just east of Grand Rapids, marks the location of the mouth of the Glacial Grand River at this time (Bretz 1953). Strandlines of Early Lake Saginaw exist at 225 m and 222 m in northern Shiawassee County. After the Huron lobe retreated out of Michigan's thumb, Maumee III merged with Early Lake Saginaw into

TABLE 13.1 Post-glacial lakes and levels from 17,000–2000 years ago in the Lakes Superior, Michigan, Huron, and Erie basins[1]

Years ago	Superior basin	Michigan basin	Huron basin	Erie basin
				Maumee I (244)
		Glenwood I (195)	Early Saginaw (225)	Maumee II (232)
				Maumee III (237)
17000			—— Arkona (216–212)	——
		Mackinaw (170?)	post-Arkona low (?)	Ypsilanti (<166)
16000		Glenwood II (195)	Saginaw (212)	Whittlesey (225)
15000			—— Warren I & II -Wayne (210-199)	——
			—— Warren III (206-203)	——
			—— Grassmere-Lundy (195-189)	——
		Calumet? (189)	Early Algonquin (184)	
14000		Two Creeks (170?)	Kirkfield (173?)	Early Erie (<159)
		Calumet (189)	Huron Algonquin (184)	
		Toleston? (184)		
13000		—— Main Algonquin (184)	——	
	Duluth (331)			
	Duluth (331) ——	—— Algonquin (184)	——	
	——	—— Algonquin (descending)	——	
12000	Duluth (331)/Minong (220)	Algonquin (descending)	——	
		Chippewa (75)	Stanley (66)	
11000	Minong (220)			
	Mattawa flood			
10000	Mattawa flood			
		-closed basins?-		
9000		Olson forest bed (153)		
	-Superior basin confluent with Huron basin-			
8000			Sanilac forest bed (165)	
7000				
6000	——	Nipissing (184)	——	
		-coastal dune building begins-		
5000				
4000				
3000	——	Algoma (181)	——	
	-Superior basin outlet rebounds above Huron Basin, present configuration of lakes achieved-			
2000	-lake levels continue to fluctuate due to climate and rebound-			

1. Compiled from Fullerton (1980), Calkin and Feenstra (1985), Eschman and Karrow (1985), Farrand and Drexler (1985), Hansel et al. (1985), Larsen (1987), Lewis and Anderson (1989), Schneider and Hansel (1990), Colman et al. (1994), Larson et al. (1994), Baedke and Thompson (2000), and Lewis at al. (2007).

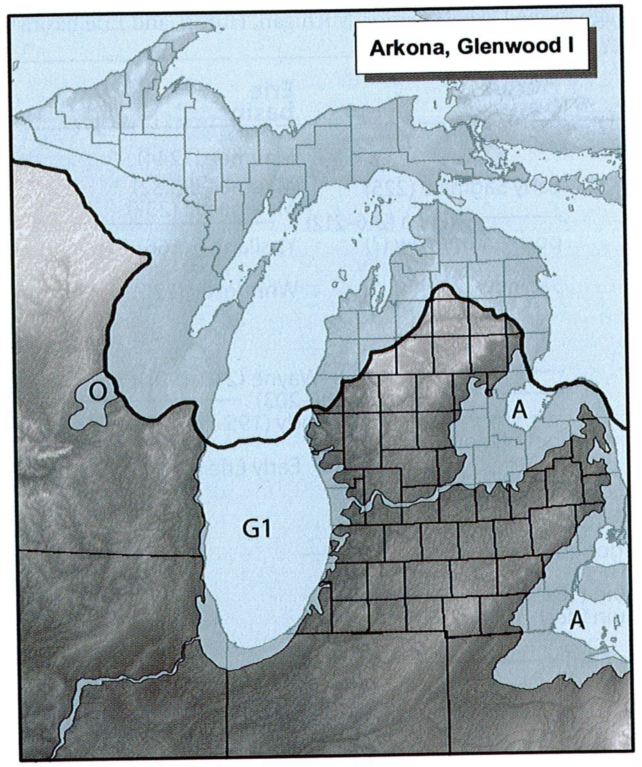


FIGURE 13.8 Map of the ice margin about 16,500 years, ago showing Lake Arkona (A), the Glenwood I phase of Lake Chicago (G1) and Glacial Lake Oshkosh (O) in Wisconsin.

Lake Arkona, at an initial elevation of 216 m (Fig. 13.8). Based on shoreline data, Lake Arkona subsequently declined to 213 m and then to 212 m. The reason for the decline in Lake Arkona's level has been variously attributed to decreases in meltwater production during a glacial readvance, outlet downcutting, climate, and the ability of a single outlet to drain a lake at several elevations (Calkin and Feenstra 1985). Well-developed Arkona beaches exist on the lake plain east of Maple Rapids in southeastern Gratiot County, northeastern Clinton County, and along the Shiawassee-Saginaw County line.

Lake Arkona expanded to the north and east as the ice margin retreated, during a period known as the Mackinaw interstade (Eschman and Karrow 1985). Eventually, the ice margin retreated far enough into southern Ontario that it opened isostatically-depressed outlets (see FOCUS BOX below) in southeastern Georgian Bay, thereby draining the Saginaw lowlands. This event left the Lake Erie basin with no meltwater source (the St. Clair River was dry at the time), as well as an isostatically-depressed outlet in the vicinity of the Niagara River. As a result, a very low level lake named Lake Ypsilanti existed for a short time in the Erie basin, which only had drainage from local rivers (Calkin and Feenstra 1985) and probably occupied about half the area that Lake Erie does today.

FOCUS BOX: Isostatic rebound

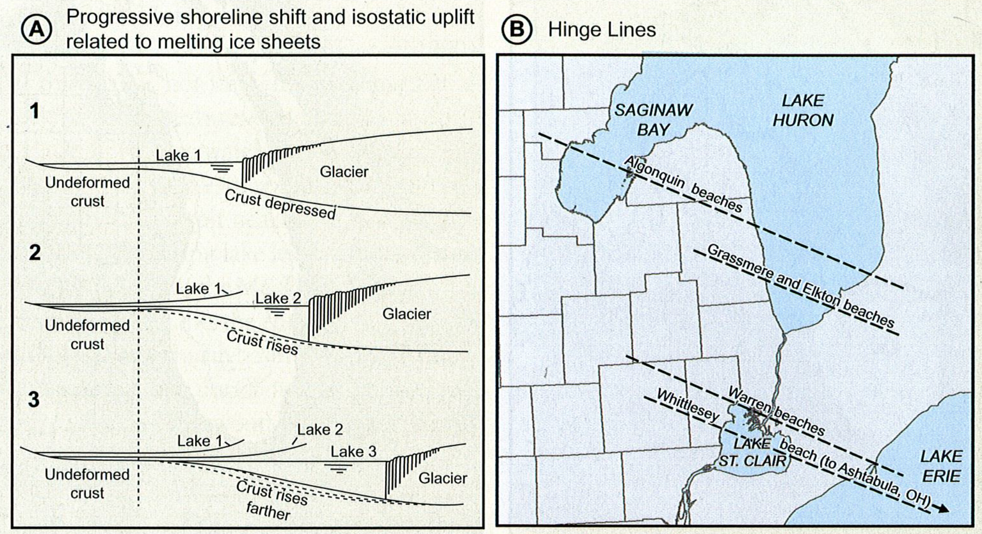
Obviously, the water level of a lake is the same elevation all around its shoreline, making a perfect horizontal "trace" of the water line. Today, however, ancient shorelines of glacial and post-glacial Great Lake phases are often not at the same elevation as which they formed. Instead, they commonly "rise" as they are traced to the north and northeast (Stanley 1936, Deane 1950, Schaetzl et al. 2002). What would cause these shorelines to rise, when they were originally horizontal?

The answer is a concept called *isostasy*. The rigid lithosphere (crust) of the earth "floats" on top of a viscous asthenosphere. Any change in the load placed upon the crust causes the asthenosphere to flow—either toward an area where the load has decreased or away from an area with an increased load. In the case of glacial isostasy, adding *glacial* mass depresses the lithosphere into the softer asthenosphere. Conversely, melting the glacier removes the load and the land bounces back, or rebounds—a process called isostatic rebound (see Figure). Greater amounts of rebound in northern Michigan illustrate that the glacier was thicker, and had more mass there, than in the south (Martini et al. 2001). Glacial Lake Algonquin exhibits the best preserved paleolake shoreline in Michigan (Fig. 13.5) and shows remarkable amounts of rebound. At Manistee, its shoreline elevation is 184 m, while at Sault St. Marie it has been uplifted to nearly 305 m. Other paleo-lakes show similar patterns of uplift (Calkin and Feenstra 1985, Fraser et al. 1990).

The asthenosphere does not react quickly to glacial loading and unloading; it lags behind due to its high viscosity. In fact, Michigan is still very slowly "rebounding" from the ice load that has been gone for almost 11,000 years. Southwestern Lake Michigan and southwestern Lake Superior appear to actually be sinking, i.e., shorezones here are very slowly being drowned, because their outlets (at Port Huron and Sault Ste. Marie, respectively) are rising!

When glacial rebound was first being studied, it was thought that there were structurally-controlled "hinge lines," south of which there was no uplift, on the assumption that the underlying bedrock moves like a door on a hinge. Leverett and Taylor (1915), Hough (1958), and Dorr and Eschman (1970) all developed maps showing hinge lines in

different places for each major glacial lake (see Figure below). However, the mapped hinge lines do not align with either the underlying bedrock (Plate 6) or any known fault systems. Rebound measurements of shorelines from different times, e.g., Algonquin and Nipissing, show that the rate of rebound is initially fast and decreases over time. Isostasy is a better explanation of these observed responses of the earth's surface rather than the old idea of hinge lines.



Illustrations of concepts of isostatic rebound. A. Figure showing how the mass of a glacier causes isostatic depression, whereas the removal of the glacial mass allows for isostatic rebound. Also shown are preglacial shorelines, initially formed horizontally, but now rising as the glacial load decreases and rebound proceeds. After Martini et al. (2001). B. Map showing four separate hinge lines, once proposed as a mechanism for rebound in southeastern Michigan and southwestern Ontario. After Leverett and Taylor (1915, 505).

The Port Huron glacial advance about 16,000 years ago (Blewett and Winters 1995; Chapters 6, 17) ended the Mackinaw interstade and not only closed the outlet in Ontario but also separated the Saginaw lowlands from southeastern Michigan (Fig. 13.9). The Port Huron moraine cuts off Lake Arkona beaches in southeastern Michigan from Lake Arkona beaches in the Saginaw lowlands, illustrating that they preceded the Port Huron glacial advance. Thus separated from the Saginaw Valley, a large lake with well-developed beach ridges at 225 m called Lake Whittlesey formed in the Lake Erie basin (Leverett and Taylor 1915). Lake Whittlesey drained across the Thumb through a channel near Ubly, in Huron County. The Ubly channel ends at a delta (now cut by the Cass River, 4 km upstream of Caro, in Tuscola County), where it emptied into Lake Saginaw at 212 m, which itself overflowed into the Glacial Grand River and eventually into the Glenwood II phase of Lake Chicago (contributing more sediment to the Allendale delta). Lake Whittlesey shorelines in Michigan appear along the eastern edge of the Defiance moraine from Lenawee County through to Sanilac County.

Retreat from the Port Huron maximum exposed lower outlets and reconnected the proglacial lakes of southeastern Michigan with the Saginaw lowland, ending Lake Whittlesey and forming Lakes Warren I and II at 210–205 m, respectively. These Warren lakes drained through the Glacial Grand River to Lake Chicago; there is debate as to whether Glenwood II or Calumet existed at the time. The Warren lakes were followed by Lake Wayne at 201–199 m, when ice retreat exposed a lower outlet to the east through New York state (Fullerton 1980). Closure of the eastern outlet returned drainage to the Glacial Grand River for Lake Warren III at 206–203 m, based on evidence in north-central New York and incision of the Allendale delta (Muller 1977, Fullerton 1980).

The eastern outlet apparently reopened during the ensuing ice retreat, allowing the lower Lake Grassmere (195 m) to follow Warren III (Calkin and Feenstra 1985). Two other drops in lake level stabilized briefly, forming stages known as Lakes Lundy (189 m) and Elkton (187 m). After this event, around 14,400 years ago, the Lake Erie basin was separated from direct meltwater input and dropped to the low, Early Lake Erie level. Isostatic uplift

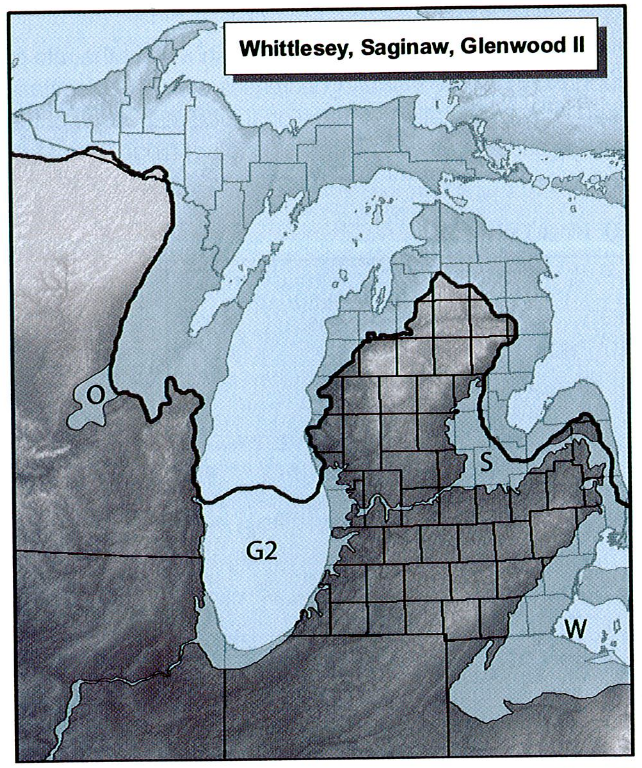


FIGURE 13.9 Map of the ice margin about 15,900 years ago, showing Lake Whittlesey (W), Lake Saginaw (S), the Glenwood II phase of Lake Chicago (G2) and Glacial Lake Oshkosh in Wisconsin.

FIGURE 13.10 Map of the ice margin about 14,000 years ago, showing the low lake levels associated with the Twocreekan interstadial (Two Rivers Phase).

caused the outlet at Niagara River to slowly rise, and as a result the level of Lake Erie also rose over the ensuing 14,000 years, to its present level.

The lake in Lake Huron basin, still in contact with the retreating Port Huron ice margin, probably dropped to the 184 m level of Early Lake Algonquin, most likely draining south via an outlet at Port Huron (Deane 1950). Direct evidence for this lake has not been found, because subsequent lake stages at the same elevation obscured its beaches (Eschman and Karrow 1985). Continued ice retreat past the Straits of Mackinac however, resulted in extension of Early Lake Algonquin into the Lake Michigan basin, eventually leading to the Two Creeks low phase (Fig. 13.10; Hansel et al. 1985). When the retreating ice margin opened a lower outlet near Fenelon Falls, SE of Georgian Bay, Early Lake Algonquin dropped an even lower phase—the Kirkfield Phase. The Kirkfield Phase ended and returned to the Algonquin level when its outlet either rebounded or was covered by a glacial advance. The latter seems more likely, since the timing appears to coincide with the Two Rivers Phase advance (Chapter 6). This glacial readvance also separated the Lakes Michigan and Huron basins again.

Early lakes of the Lake Michigan basin

Whenever the Straits of Mackinac were covered by ice, lake-level fluctuations in the Lake Huron basin did not affect events occurring in the Lake Michigan basin, except for some drainage down the Glacial Grand River. Recall that the Saginaw lobe retreated into south-central Michigan long before the Lake Michigan lobe retreated into the Lake Michigan basin. Meltwater from south-central Michigan, therefore, initially overflowed down the Wabash River, along with overflow from Lake Maumee. Ice retreat to the Valparaiso moraine allowed much of the drainage from south-central Michigan to be redirected to the SW, via the Kankakee River, toward Illinois, and also formed several ice-marginal lakes between the ice margin and the Kalamazoo moraine (Figs. 13.4, 13.6). Only after ice retreated from the Valparaiso position, toward the Lake Border moraine, probably after 17,500 years ago (Farrand and Eschman 1974), did meltwater finally form a lake within the Lake Michigan basin. Known as the Glenwood I phase of Lake Chicago (Fig. 13.7), it stood at 195 m, based on an extensive spit in the Chicago area—about 18 m above current lake level. Lake Chicago drained to the south

into the Des Plaines and Illinois Rivers (known as the Chicago outlet), to the Mississippi River.

Prolonged ice recession from the Lake Border moraine during the Mackinaw Interstade eventually formed a lower level Mackinaw phase lake (also referred to as the intra-Glenwood low phase) in the Lake Michigan basin. This lake drained eastward into the Huron basin via an outlet at or near the Straits of Mackinac (Monaghan and Hansel 1990). The elevation of this lake is not known, but Hansel et al. (1985) cited a lack of shore-feature evidence as reason to believe that the Mackinaw Phase water level was lower than present. Monaghan and Hansel (1990) reported a 16,400 year age from wood at the base of a spit near present lake elevation in Berrien County. The rising lake level, which formed the spit, was caused by closure of the Mackinac Straits by the Port Huron ice advance; this marks the end of the Mackinaw Phase. Isolation of the Lake Michigan basin returned drainage to the Chicago outlet, beginning the Glenwood II phase lake level at 195 m (Fig. 13.9). The Glenwood II phase lasted until at least 15,150 years ago (Karrow et al. 1975). Hough (1963) believed that erosion of the Chicago outlet initiated two later lake phases at lower levels. The first was the Calumet phase at 189.0 m; the second was the Toleston at 184.5 m. Both of these phases were initially based on beaches, spits and wave-cuts near the original Glenwood phase spit. Calumet beaches have been traced into southwestern Michigan. The St. Joseph River also built a large delta in Berrien County during the Calumet phase (Kincare 2007). Tracing Toleston phase beaches is difficult, because two subsequent lake phases were at the same elevation. There exists debate as to when the Calumet phase was initiated, with some researchers arguing it was prior to development of the Two Creeks Forest bed found in eastern Wisconsin that has been dated at 13,760 years ago (Bretz 1951, 1959, Eschman and Farrand 1970, Kaiser 1994). Others have argued that it was later (Hough 1958) and possibly related to the amount of discharge entering the lake (Hansel and Mickelson 1988). Hansel et al. (1985) doubted the existence of a Toleston phase entirely.

FIGURE 13.11 Map of the ice margin about 13,700 years ago, showing Early Lake Erie (eE), Huron Lake Algonquin (hA), the Calumet phase of Lake Chicago (CC) and Glacial Lake Oshkosh in Wisconsin.

Retreat of the Lake Michigan lobe ice margin from the Port Huron moraine, and the opening of the Straits of Mackinac, eventually allowed Lake Chicago to drop to the level of Early Lake Algonquin in the Huron basin, and then to the level of the Kirkfield phase. During the Kirkfield phase, lake level in the Lake Michigan basin must have been lower than present to allow for the growth of the Two Creeks forest, near present lake level.

A glacial readvance then covered the Straits of Mackinac outlet again, during the Two Rivers Phase, burying the Two Creeks forest bed beneath glacial till (Chapter 6). The advance again isolated the Lake Michigan basin from the Huron basin, causing lake level in the Lake Michigan basin to rise to 189 m, the level of the Calumet phase of Lake Chicago, and returning drainage to the Chicago outlet (Fig. 13.11). The ice advance, during the Two Rivers Phase in Michigan, is assumed to have been at about 13,700 years ago by radiocarbon dates on the Cheboygan bryophyte bed in Cheboygan County (Larson et al. 1994; Chapter 6). This was the last oscillation of ice into the Lower Peninsula of Michigan. Its departure across the Straits of Mackinac ended Lake Chicago, allowing free drainage through the Straits of Mackinac and forming Main Lake Algonquin at about 13,000 years ago (Hansel et al. 1985). However, glaciers would enter the Upper Peninsula at least two more times and continue to influence the levels of the Great Lakes.

Main Lake Algonquin to Lakes Chippewa and Stanley

Main Lake Algonquin, the most extensive of the proglacial Great Lakes, probably drained through both the Chicago and Port Huron (St. Clair River) outlets (Leverett and Taylor 1915, Hough 1958). Hansel et al. (1985) and Larsen (1987), however, contended that outlets uncovered in Georgian Bay, Ontario by glacial retreat, also may have been drainage paths. Regardless, this lake left an indelible mark upon Michigan (Fig. 13.12); its shorelines are marked by well-developed wave-cut bluffs (Schaetzl et al. 2002), beaches (Futyma 1981), and extensive spits (Krist and Schaetzl 2001). As the ice retreated, Lake Algonquin expanded northward, covering much of the eastern half of the isostatically depressed Upper Peninsula, with many islands protruding above the water surface (Schaetzl et al. 2002). The Lake Algonquin shoreline eventually reached at least as far as 65 km north of Sault Ste. Marie (Farrand and Drexler 1985).

Continued ice retreat eventually began uncovering a series of lower outlets east of Georgian Bay—similar to outlets used during the earlier Kirkfield Phase. These outlets were isostatically depressed by the weight of the ice, allowing for drainage across the divide through Ontario. Thus, several post-Main Lake Algonquin phases temporarily stabilized at successively lower elevations as each new outlet was opened. Some of these lower beaches are easily visible on Mackinac Island (Stanley 1945) and many other places near the coast along the northern sections of Lakes Michigan and Huron and in the eastern Upper Peninsula (Schaetzl et al. 2002).

The lowest (by far!) lake level began when the North Bay, Ontario outlet opened around 11,200 years ago, allowing most of the volume of Lake Algonquin to suddenly drain eastward, through Canada (Fig. 13.13). As a result, two very low, small lakes formed in the Lake Michigan and Huron basins. Lake Chippewa (in the Lake Michigan basin) may have been as low as 70 m (Larsen 1987) while Lake Stanley (in the Huron Basin) was even lower—about 45 m (Eschman and Karrow 1985). The level of Lake Chippewa was controlled by a river channel eroded into soft bedrock at the bottom of the Straits of Mackinac, where it flowed eastward into Lake Stanley (Hough 1958). Today, we refer to this valley as the Mackinac Gorge. Only about 800 years separated the Main Algonquin high level from the Chippewa low level. Recently, Lewis et al. (2007) suggested Lake Stanley may have only dropped to 127 m, basing their argument on the elevation of seismic reflections and an erosion surface seen in offshore cores. They also have suggested that, by 9000 years ago, Lakes Chippewa and Stanley were temporarily closed basins, i.e. had no outward drainage, and that an early Holocene dry climate played a part in the inability of lake levels to keep pace with isostatically rising outlets.

FIGURE 13.12 Map of the ice margin about 12,900 years ago, showing Main Lake Algonquin (mA), Early Lake Erie (eE), and Lake Ontonagon (O).

FIGURE 13.13 Map of the ice margin about 11,600 years ago, during the Marquette glacial readvance (Gribben Phase), showing Early Lake Erie (eE), Lake Stanley (S), Lake Chippewa (C), and Lake Minong (M).

Opening the Lake Superior basin

In some ways, the development of Lake Superior is simpler than the other Great Lakes, because the Superior basin was the last to be deglaciated. However, complicating its development are the facts that the basin twice had separate eastern and western lakes, and was subjected to inflows from Lake Agassiz—the largest North American glacial lake, covering a large area in Manitoba and western Ontario, Canada, at the time of the inflows. The Lake Superior basin also experienced the largest amount of isostatic depression (and hence, rebound) of the Great Lake basins, and its outlet at Sault Ste. Marie, being on the eastern edge of the basin, is rebounding more than its western margins.

The oldest existing shorelines in the Superior basin were formed during the retreat of the Two Rivers Phase ice, roughly 12,900 years ago (Fig. 6.3). At this time, Lake Duluth formed at the western end of the basin, as well as the much smaller Lake Ontonagon in Gogebic, Ontonagon, and Houghton Counties (Fig. 13.12). Lake Ontonagon's outlet was at 403 m, draining to the SW through Wisconsin (Leverett 1929). Lake Duluth overflowed to the south, through outlets in Minnesota and Wisconsin, at an elevation of ~331 m. As Lake Duluth was expanding northward along the western shore (and extinguishing Lake Ontonagon), Lake Algonquin was also expanding northward across the eastern Upper Peninsula. Once the retreating ice margin cleared the Keweenaw Peninsula and the Huron Mountains, Lake Duluth merged with Lake Algonquin—which was at a lower level. It is not known how far north Lake Algonquin eventually extended, because the subsequent Marquette phase ice readvance wiped away its northern shorelines as far south as Alona Bay, Ontario (Farrand and Drexler 1985). Following the merger of these two lakes, the level of Lake Algonquin did not remain stable, but slowly fell due to the progressive opening of lower outlets to the east (see above). A bedrock drainage divide at Sault St. Marie, however, prevented the water level in the Superior basin from falling to the level of Lake Stanley in the Huron basin, establishing a new lake in the Superior basin named Lake Minong. It was around this time that a pathway also may have opened for water from Lake Agassiz (Moorhead phase) to escape east into the Superior basin and drain into the North Atlantic (Fisher 2003). Farrand and Drexler (1985) pointed out that Minong shorelines are 40 m above the present outlet at Sault Ste. Marie. A barrier to drainage, perhaps a moraine across Whitefish Bay (Saarnisto 1974), must therefore have existed during Lake Minong, to hold this water up. During the peak of the Marquette Phase ice readvance (Chapter 6), Lake Minong was quite small, pinned into the SE corner of the Superior basin. But as the ice retreated, Lake Minong expanded to the north and west. When the ice cleared the Keweenaw Peninsula, Lake Duluth in the west merged with Lake Minong in the east. Shorelines from Lake Minong are found on Isle Royale, and are the highest shorelines along the north shore of Lake Superior.

During the Marquette Phase ice readvance around 11,580 years ago (Fig. 13.13), the advancing ice margin once again separated the eastern and western portions of the Lake Superior basin, leaving a much diminished Lake Minong in the east and reestablishing Lake Duluth in the west. The advance even briefly squeezed Lake Duluth out of Michigan, leaving a renewed Lake Ontonagon in the western corner of the Upper Peninsula. As the ice margin subsequently retreated, Lake Duluth began expanding northward again, subsuming Lake Ontonagon (Fig. 13.14). When the ice margin pulled back from the Huron Mountains in Marquette County, eastern outlets opened up and again allowed the level of Lake Duluth to fall (Farrand and Drexler 1985). Discharge from Lake Duluth initially went south from Munising via the AuTrain-Whitefish channel, and then found a lower outlet on the north side of the Marquette phase moraines in Marquette and Alger Counties toward Lake Minong (Leverett 1929, Blewett 1994).

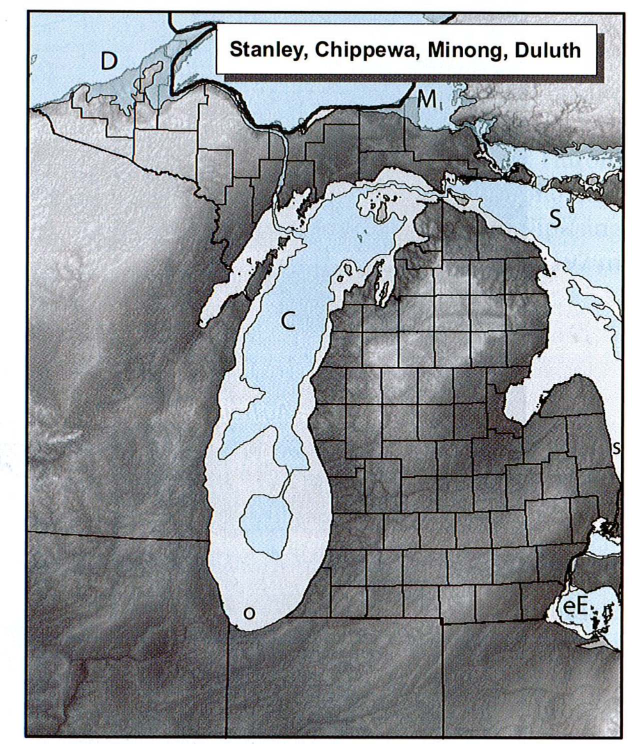


FIGURE 13.14 Map of the ice margin about 11,200 years ago, during retreat of the Marquette ice, showing the rising Lakes Stanley (S) and Chippewa (C), and Lakes Duluth (D) and Minong (M). The locations of the Olson (o) and Sanilac (s) drowned forest beds are also shown.