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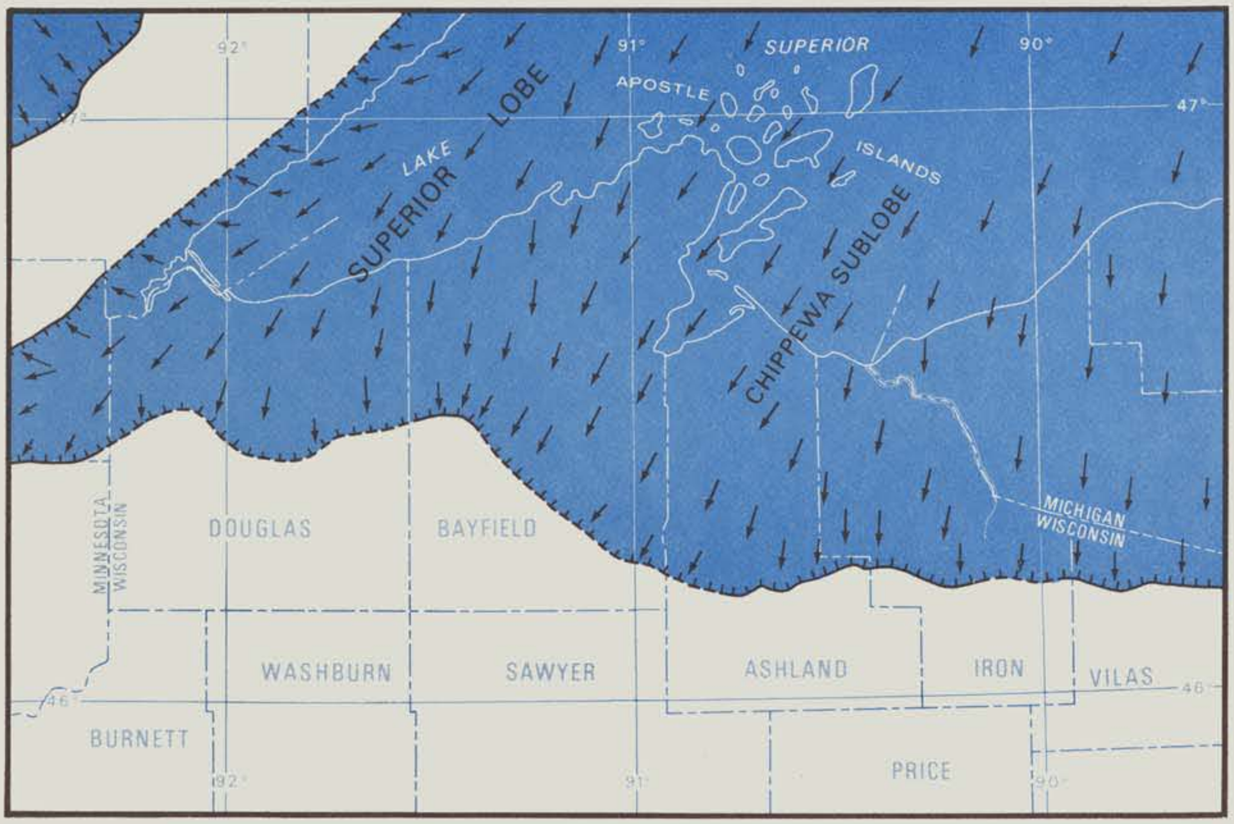
Pleistocene Geology of the Superior Region, Wisconsin

by Lee Clayton



WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY
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A description of the geologic materials underlying the surface soil and overlying the solid rock in the northernmost counties of Wisconsin.

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ABSTRACT

The Superior region of Wisconsin, north of latitude 46° and west of longitude 90°, is underlain by Pleistocene deposits, which are underlain by Precambrian rock. The Pleistocene deposits include (1) the Copper Falls Formation, which consists largely of sandy till and stream-deposited sand deposited before about 11,500 B.P., (2) the Miller Creek Formation, which consists largely of clayey till and offshore clay and silt deposited between about 11,500 and 9500 B.P., and (3) postglacial deposits. During the last part of the Wisconsin Glaciation, the Superior and Chippewa Lobes advanced as far as the St. Croix and Chippewa moraines to the south of the Superior region. This event was followed by general ice-margin retreat interrupted by the Tiger Cat Advance, the Hayward Advance, the Swiss and Airport Advances (when most of the sand in the St. Croix valley was deposited), the Lake Ruth Advance, the Porcupine Advance (around 11,000 B.P.), and the Lake View Advance (between about 10,000 and 9500 B.P.). During the Porcupine and Lake View Advances, Lake Superior was about 150 m above its present level and drained southward through the St. Croix spillway.

INTRODUCTION

This report is a description of the Pleistocene geology of the Lake Superior region of Wisconsin, shown on plate 1. This area, about 14,000 km^2, includes all of Wisconsin north of latitude 46° and west of longitude 90°, which is all of Douglas and Bayfield Counties, most of Ashland and Iron Counties, and the northern parts of Burnett, Washburn, and Sawyer Counties (fig. 1).

The Superior region consists of two quite different areas (fig. 1). The Superior lowland was submerged during higher stages of the lake. This area, between an elevation of 183 m and about 330 m, is characterized by flat to undulating topography underlain by thick red glacial clay (plate 1). The upper margin of this area, between elevations of roughly 270 m and 330 m, is mantled with shoreline sand, and the lowland is cut by widely- spaced, narrow, steep-sided valleys.

South of the Superior lowland (fig. 1), the land rises from an elevation of 330 m to the regional drainage divide, at elevations of about 370 m to 520 m, and then descends into the basins of the Chippewa and St. Croix Rivers. Elevations below 270 m occur in the southwest corner of the region. The area south of the Superior lowland is characterized by rolling hilly topography underlain by sandy till and by sand and gravel deposited by proglacial rivers (plate 1). The largest area of sand extends from the Bayfield Peninsula southwestward along the St. Croix River (plate 1).

The Superior region was glaciated many times during the Pleistocene, but evidence is known for only the last glaciation. The ice sheet last flowed across the region somewhat more than 20,000 years ago. Toward the end of this phase of glaciation, the ice-sheet margin fluctuated several times; each fluctuation probably involved a readvance of the ice margin at least a few tens of kilometres. While the ice margin remained on the upland, the glacier deposited sandy till, derived largely from meltwater deposits and ultimately from the Precambrian sandstone of the Superior basin. The sandy glacial and stream deposits are included in the Copper Falls Formation. Once the ice margin retreated into the Superior

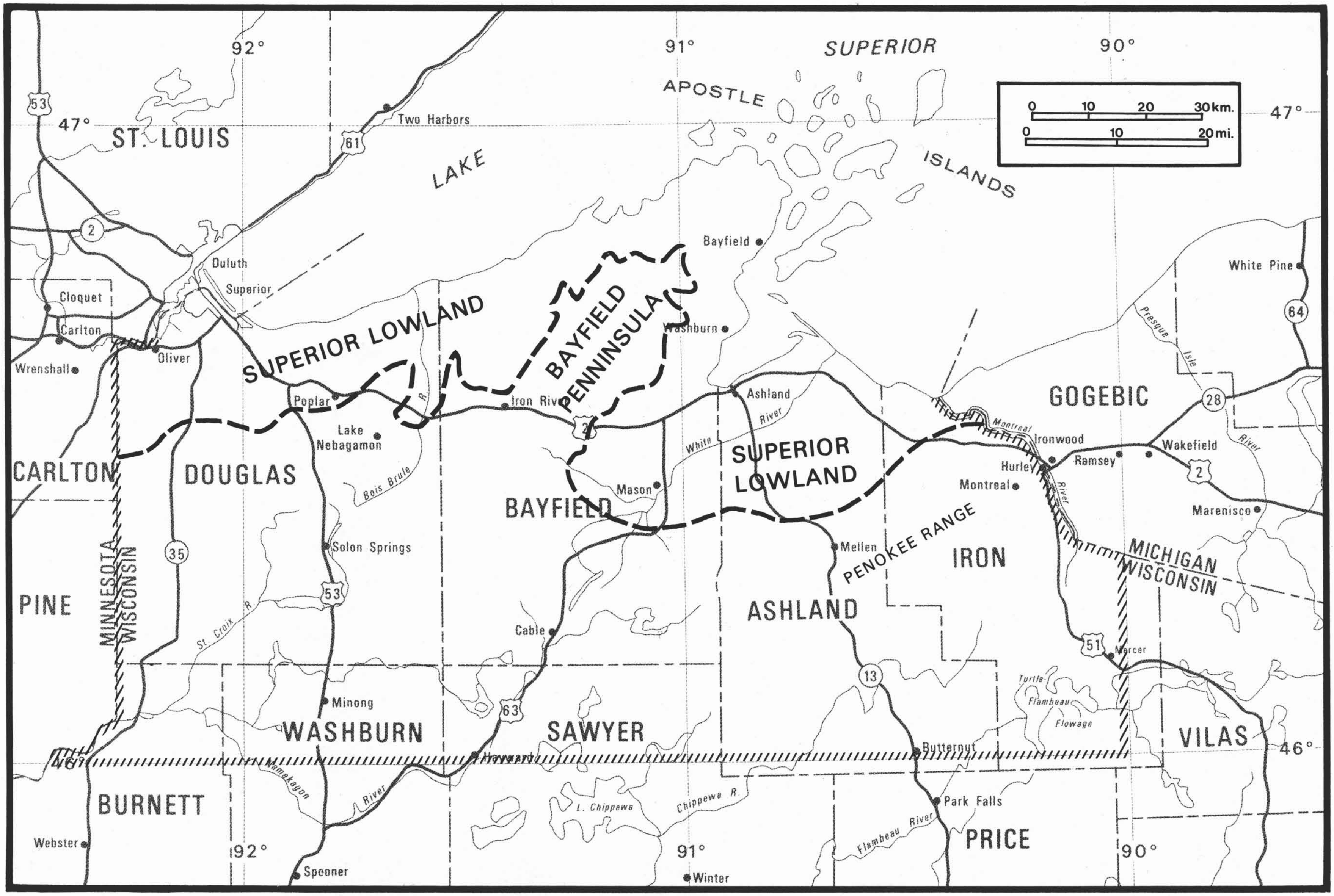

FIGURE 1. Location of the Superior region (hachured area). Heavy dashed line marks south edge of the Superior lowland.

basin, the glacier deposited clayey till, derived from offshore deposits. The clayey glacial and offshore deposits are included in the Miller Creek Formation; the till of the Hanson Creek Member was deposited around 11,000 years ago, and the till of the Douglas Creek Member was deposited between about 10,000 and 9,500 years ago.

This report is based on the following information. Several weeks of field work were carried out during the summers of 1979 and 1980. Thirty holes were augered from depths of 3 to 30 m. Samples were analyzed in the Quaternary laboratory of the geology department of the University of Wisconsin—Madison. Contacts were drawn using the following air-photo stereopairs: (1) a 1:50,000 set covering most of the area, taken in July, August, September, and October of 1953 by the Army Map Service; (2) one or more 1:20,000 sets for each county, taken at various times since 1938 for the U.S. Agricultural Stabilization and Conservation Service; and (3) a 1:12,000 set covering Chequamegon National Forest, taken for the Forest Service in May, 1979. Information was plotted on topographic maps made by the U.S. Geological Survey, including 7.5-minute quadrangles with a 10-ft contour interval for about two-thirds of the area and 15-minute quadrangles with a 20-ft contour interval for the remaining area. Additional lithologic information was provided by the 1:190,000 soil maps of the entire area (Musbach and others, 1914; Whitson and others, 1916) and 1:62,500 soil maps of Bayfield County (Ableiter and Hole, 1961). Information on Bear Island is from a soil map by Kowalski (1976), and information on Rocky, Oak, York, and Raspberry Islands is from soil maps by Cary, McDowell, and Graumlich (1979). The Pleistocene geology of the southeastern third of the region is shown on unpublished 1:48,000 maps prepared by the U.S. Army Cold Regions Research and Engineering Laboratory (1969); this information has been summarized by Hadley and Pelham (1976) at a scale of 1:500,000. The pre-Pleistocene geology shown on the map is from Aldrich (1929), Dutton and Bradley (1970), and Olmsted (1966). Additional information was derived from unpublished township reports and logs of water wells in the files of the Wisconsin Geological and Natural History Survey.

I acknowledge the numerous helpful suggestions made by Dave Mickelson, Adam Cahow, and Fred Madison, who reviewed the manuscript of this report.

PRE-PLEISTOCENE ROCK

Pre-Pleistocene rock occurs at or near the surface in five large areas in the Superior region: (1) along the Penokee Range (fig. 1) and westward to near Grand View, (2) northeast of Minong, (3) west of the St. Croix River, (4) along the south edge of the Superior lowland from Pattison State Park eastward to the Brule River, and (5) along the shore bluffs of the Bayfield Peninsula and the Apostle Islands. Areas of thin Pleistocene sediment and abundant outcrops of pre-Pleistocene rock are indicated on plate 1 by the symbol **r**. Scattered outcrops of occur throughout the region, primarily in areas where the Pleistocene sediment is shown thinner than 15 m in figure 2.

The oldest rock, consisting of Archean and Early Proterozoic igneous and metamorphic rock, occurs southeast of the Penokee Range (map unit **re** on plate 1). The Early Proterozoic rock of the Penokee Range includes dolomite of the thin Bad River Formation, overlain by quartz sandstone and mudstone of the Palms Formation, which forms the south crest of the range (part of map unit **rm**). The north crest is composed of the Ironwood Formation, consisting of iron-rich cherty mudstone, which was mined from 1884 through 1967 (part of map unit **rm**). The rock of the Penokee Range dips northwestward at 50° to 70°. The Tyler Formation, which consists of mudstone and lithic sandstone, overlies the Ironwood Formation and occupies the valley north of the range (part of map unit **rm**). Middle Proterozoic rock unconformably overlying the Tyler includes quartz sandstone of the Bessemer Formation, followed by a thick sequence of dark lava flows, which outcrop in upland areas throughout the central part of the region (map unit **rv**). Intrusive bodies occur west and northeast of Mellen (map unit **ri**). The Oronto Group, which contains a thick sequence of lithic sandstone, conglomerate, and mudstone, overlies the flows and occupies the trough extending southwestward from Chequamegon Bay to the St. Croix valley (part of map unit **rs**). The Bayfield Group unconformably overlies the Oronto in the northern part of the region from the Apostle Islands and Bayfield Peninsula westward. The Bayfield consists of nearly flat-lying quartz sandstone deposited during Cambrian or Late Proterozoic time (part of map unit **rs**). Younger Cambrian rock occurs under the Pleistocene sediment in the Hayward area and along the St. Croix River in the southwest corner of the area.

COPPER FALLS FORMATION

Stratigraphy

The Copper Falls Formation includes the bulk of the Pleistocene deposits south of the Superior lowland (fig. 3). The Copper Falls Formation contains reddish to brownish sandy sediment underlying and south of the Miller Creek Formation of the Superior lowland, discussed later. The type section of the Copper Falls Formation is a river cutbank near Copper Falls in Copper Falls State Park 6 km north of Mellen (Mickelson and others, in press). The Copper Falls Formation is readily distinguished from the overlying Miller Creek Formation, which is more clayey and somewhat redder. It rests on Precambrian rock in the few places where its base has been observed in this region, but other unknown Pleistocene units are likely to be present between the Copper Falls Formation and the Precambrian units. To the west in Minnesota, it is at least in part equivalent to the Cromwell Formation (Wright, Mattson, and Thomas, 1970, p. 19-24). In the Lake Superior shore bluffs west of the Bayfield Peninsula a unit that is equivalent to part of the Copper Falls has been informally referred to as the Jardine

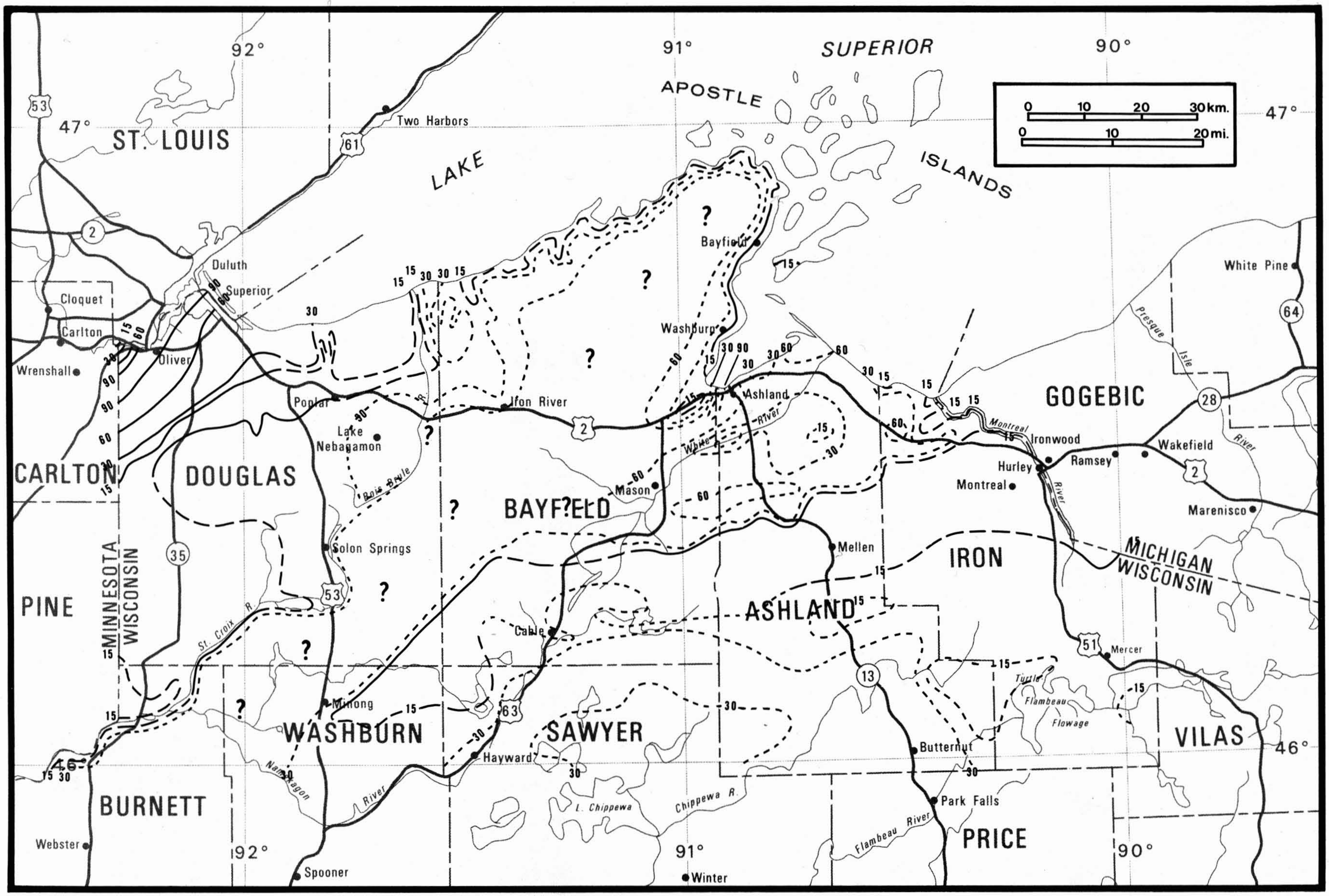

FIGURE 2. Depth to pre-Pleistocene rock in metres. The solid depth lines occur in areas with numerous outcrops or water wells that have gone through the Pleistocene material. Dashed lines indicate sparcer information. Dotted lines indicate poor information.

Creek till by Need (1980), Johnson (1980), and Need, Johnson, and Mickelson (1981).

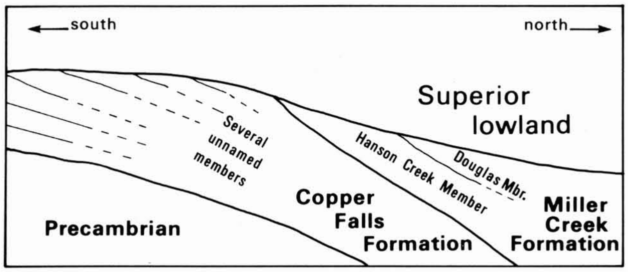

FIGURE 3. Stylized north-south stratigraphic section through the Superior region. (Vertical dimension is greatly exaggerated.)

The Copper Falls Formation extends east of the Superior region as far as the calcareous till of the Green Bay Lobe in northeastern Wisconsin. The southern extent of the unit is unclear at this time, but it may extend to the south edge of the St. Croix and Chippewa moraines; this will have to be resolved by later work. The relationship of the Copper Falls Formation to other lithostratigraphic units in Wisconsin is discussed in a report by Mickelson and others (in press).

The Copper Falls Formation is defined primarily on the basis of its sandy till (described below). However, it includes a large amount of other material, especially sand and gravel deposited by melt-water streams (plate 1). All of the material between the till units of the Copper Falls Formation are considered to be part of the Copper Falls Formation. South of the southern extent of the Miller Creek Formation, material lying on top of the uppermost till unit is considered to be part of the Copper Falls Formation if it is closely associated with the material making up the bulk of the formation. That is, surface deposits of proglacial melt-water streams are included in the Copper Falls Formation because they are interbedded with till deposited at the same time and because they are lithologically similar to stream deposits below the surface till unit. However, deposits of postglacial streams are excluded because they are nowhere interbedded with Copper Falls till and they are lithologically different from the deposits of melt-water streams, which generally lack the organic material characteristic of postglacial stream deposits. Similarly, postglacial lake deposits and peat are excluded from the Copper Falls Formation (plate 1) because they are not interbedded with till and because they are lithologically distinct from the bulk of the formation.

Although subdivisions of the Copper Falls Formation have been recognized locally (for example, at its type section; see Mickelson and others, in press), no members have been named because of the reconnaissance nature of this project. As more detailed work is done in the region, many of the till sheets deposited by the different glacial advances (discussed later) will probably be recognized as parts of formally defined members.

Till

The term "till" is being used here to include the following kinds of material. Lodgement till consists of material deposited from ice as a result of melting at the base of a sliding glacier. Subglacial melt-out till consists of material deposited from ice as the result of melting at the base of a nonsliding glacier. Supraglacial melt-out till consists of material that melts out from the upper surface of a glacier and is then let down and deposited when all the ice melts away. Melt-out till, by definition, undergoes no mass movement after it melts out of the glacier. Melt-out till that undergoes subsequent mass movement is referred to as mass-movement till or, more specifically, as slump till or flow till when mass movement occurs while glacial ice is still present. Material that has been resorted after it melts out of the glacier and material that is transported by the glacier (either supraglacially or subglacially) but is never within the glacier are not considered to be till in this report.

Lithologically, these various kinds of till are similar and are difficult to distinguish in poor outcrops, and, as a result, the distinctions made in this report are commonly speculative and are commonly based on topographic appearance rather than on outcrop appearance of the till. Flow till is sometimes distinguished from melt-out and lodgement till by the presence of interbedded sorted sediment, but in some places it may have been confused with postglacial debris-flow and slope-wash sediment.

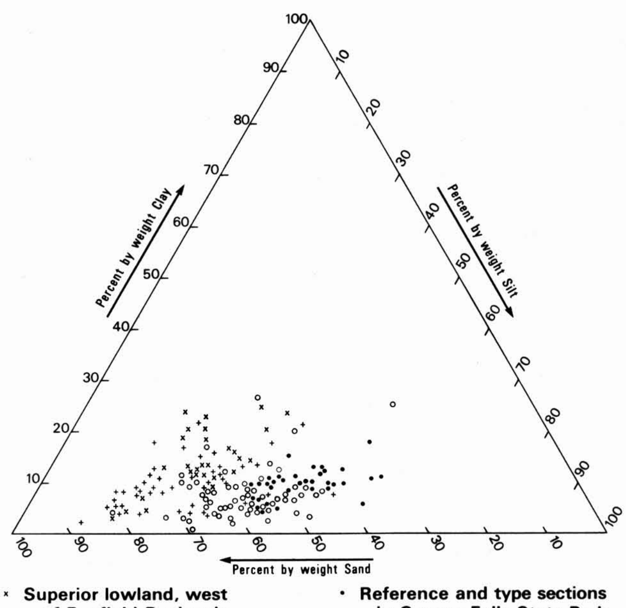

FIGURE 4. Ratio of sand (0.063 to 2.0 mm), silt (0.002 to 0.063 mm), and clay (smaller than 0.002 mm) in till of the Copper Falls Formation. Most of the samples from the Superior lowland west of the Bayfield Peninsula were from Lake Superior shore bluffs (Need, 1980; Johnson, 1980).

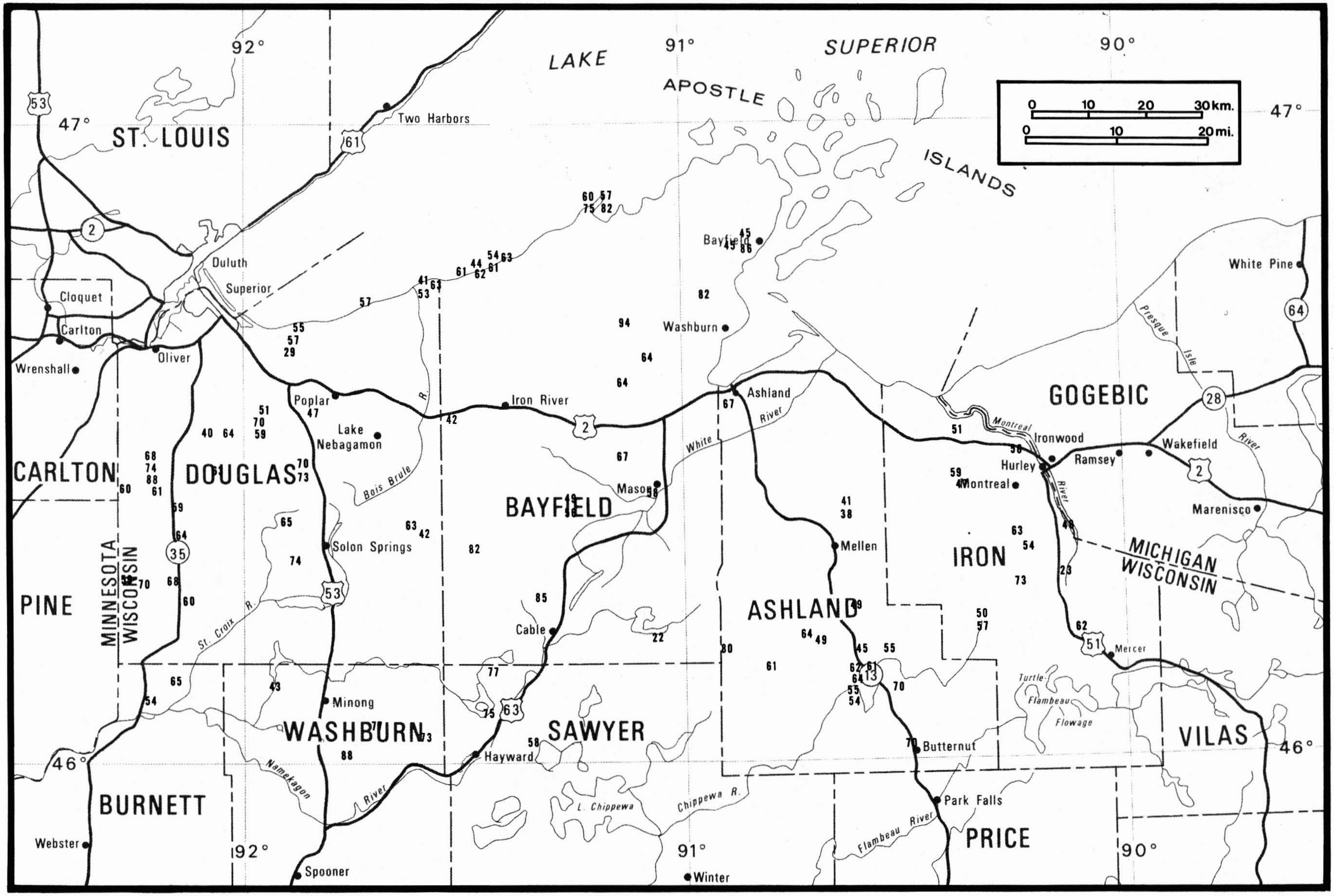

FIGURE 5. Percentage of sand in the smaller-than-2-mm fraction of the near- surface till of the Copper Falls Formation. The values from the Lake Superior bluffs are from Need (1980) and Johnson (1980).

Using U.S. Department of Agriculture terminology, the till of the Copper Falls Formation generally is sandy loam (fig. 4). Analyses from throughout the Superior region indicate that it typically consists of between 40 and 80 percent sand, 15 and 50 percent silt, and 2 and 20 percent clay (fig. 5) and several percent pebbles, cobbles, and boulders.

The till of the Copper Falls Formation is commonly reddish brown, ranging from 2.5YR to 7.5YR 3 to 4/4 to 6 on the Munsell scale. It is generally redder to the north and browner to the south.

The till of the Copper Falls Formation is only slightly calcareous. Gasometric analyses of seven samples from the northwest part of the map area (Need, 1980, p. 13) and 20 samples from the eastern part of the map area indicate that the coarse- silt fraction consists of 0.5 to 1.5 percent carbonates, predominantly calcite.

According to Need (1980, p. 5), the clay minerals in the till of the Copper Falls Formation in the bluffs of Lake Superior consist largely of illite and smectite.

Moraines

Moraines are ridges of material formed along the margin of a glacier. They are also referred to as end moraines, lateral moraines, marginal moraines, terminal moraines, and recessional moraines.

Moraines composed of Copper Falls till are indicated on plate 1 by a line symbol in map units **gc**, **gg**, **gm**, **sg**, and **p**. They are similar to the moraines described in the section on the Miller Creek Formation. They are typically 3 to 20 m high and 50 to 200 m wide (fig. 6). Unlike the thrust ridges of map unit **gt**, these ridges are solitary, can be traced for several kilometres, and probably mark the extent of a glacial readvance.

Glacial Thrust Masses

Map unit **gt** ("glacial, thrust") on plate 1 consists of brownish sandy till, or stream sand and gravel, or both, of the Copper Falls Formation, that is interpreted to have been thrust by the glacier into a series of ridges parallel to the glacier margin. The ridges presumably are the crests of tight folds or the noses of thrust slabs. The ridges are commonly 15 to 30 m high, 100 to 250 m wide, and 1 to 2 km long (fig. 7). Many of the ridges are slightly curved, concave upglacier. These features are thought to form beneath the glacier, but near its terminus, where the subglacial material was frozen onto the glacier's snout (Clayton, Moran, and Bluemle, 1980). The actual struc-

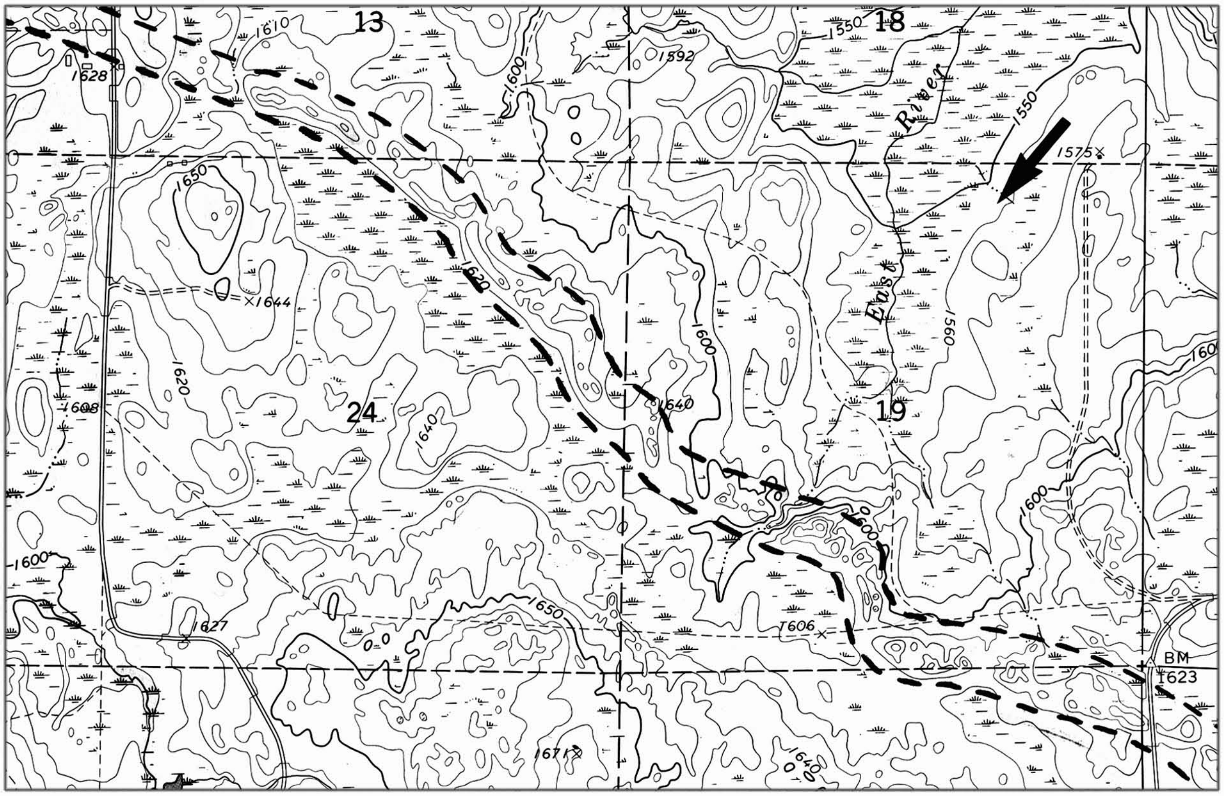

FIGURE 6. Ridge interpreted to be a moraine formed at margin of a glacier moving in direction indicated by arrow; it correlates eastward with the Marenisco moraine of Michigan. U.S. Geological Survey Turntable Creek Quadrangle (7.5-minute, topographic; 10-ft contour interval). T. 45 N., Rs. 1 and 2 E. Area shown is 4 km wide.

ture within these features is unknown, however. They have been recognized only by their surface form, and, as a result, the distribution of thrust masses is shown imprecisely on the geologic map. They are thought to have formed during the last glacial advance, but some may have formed earlier and were only slightly modified during the last advance.

Subglacially molded topography

Map unit **gm** ("glacial, molded") on plate 1 consists of brownish sandy till of the Copper Falls Formation that has been molded beneath a sliding glacier. The resulting topography consists of a series of streamlined ridges (drumlins) and troughs parallel to the direction of ice movement.

In the Hurley area, typical drumlins are simple ridges about 3 m high, 30 m wide, and l km long, and many have knobs of Precambrian rock at their upglacier end. They are indicated on the geologic map by a line symbol with an arrowhead and are interpreted to have formed during the last glacial advance into the area.

In the rest of the Superior region, the drumlins are larger and more complex in form. Some evidence indicates that they formed during an earlier glacial episode and were only partially remolded during the last phase of glacial activity in the area. These drumlins are commonly 5 to 30 m high, 100 to 500 m wide, and 0.3 to 2 km long, and are indicated on plate 1 by a line symbol without an arrowhead. Evidence that these drumlins were remolded occurs in T. 41 N., R. 2 E. (plate 1). Here they are oriented south-southwest whereas the apparently more recent directional indicators are oriented south-southeast. In sec. 13, T. 41 N., R. 1 E., and sec. 18, T. 41 N., R. 2 E., subglacial scratches on outcrops of Precambrian rock are oriented S. 15° to 20° E. A few small fresh-looking drumlins in secs. 14 and 27, T. 41 N., R. 1 E. are oriented south-southeast and seem to be draped across older, larger, more ragged-looking drumlins oriented south-southwest. Most eskers in Tps. 41 and 42 N., Rs. 2 and 3 E., are also oriented south-southeast, which also indicates that the most recent direction of glacial

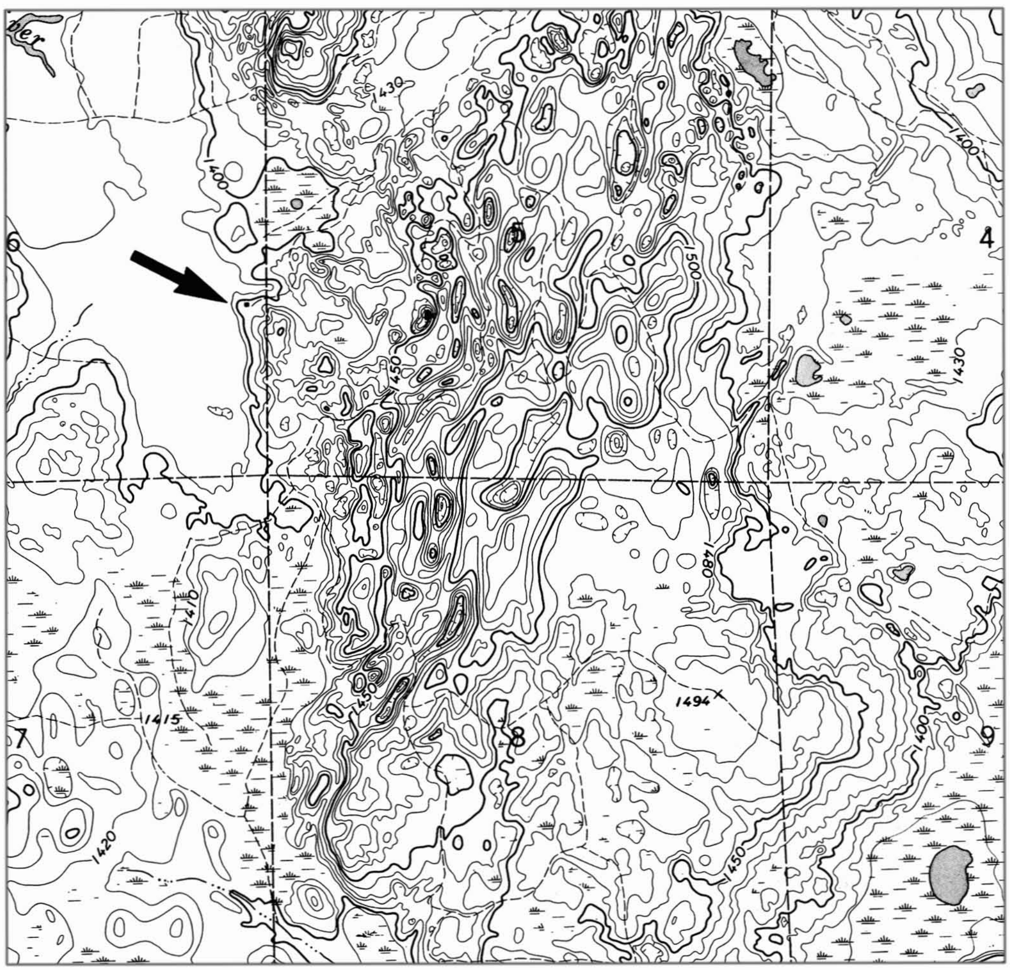

FIGURE 7. Ridges interpreted to be glacial thrust masses; arrow indicates direction of ice movement. U.S. Geological Survey Totagatic Lake Quadrangle (7.5-minute, topographic; 10-ft contour interval). T. 43 N., R. 8 W. Area shown is 3.2 km wide.

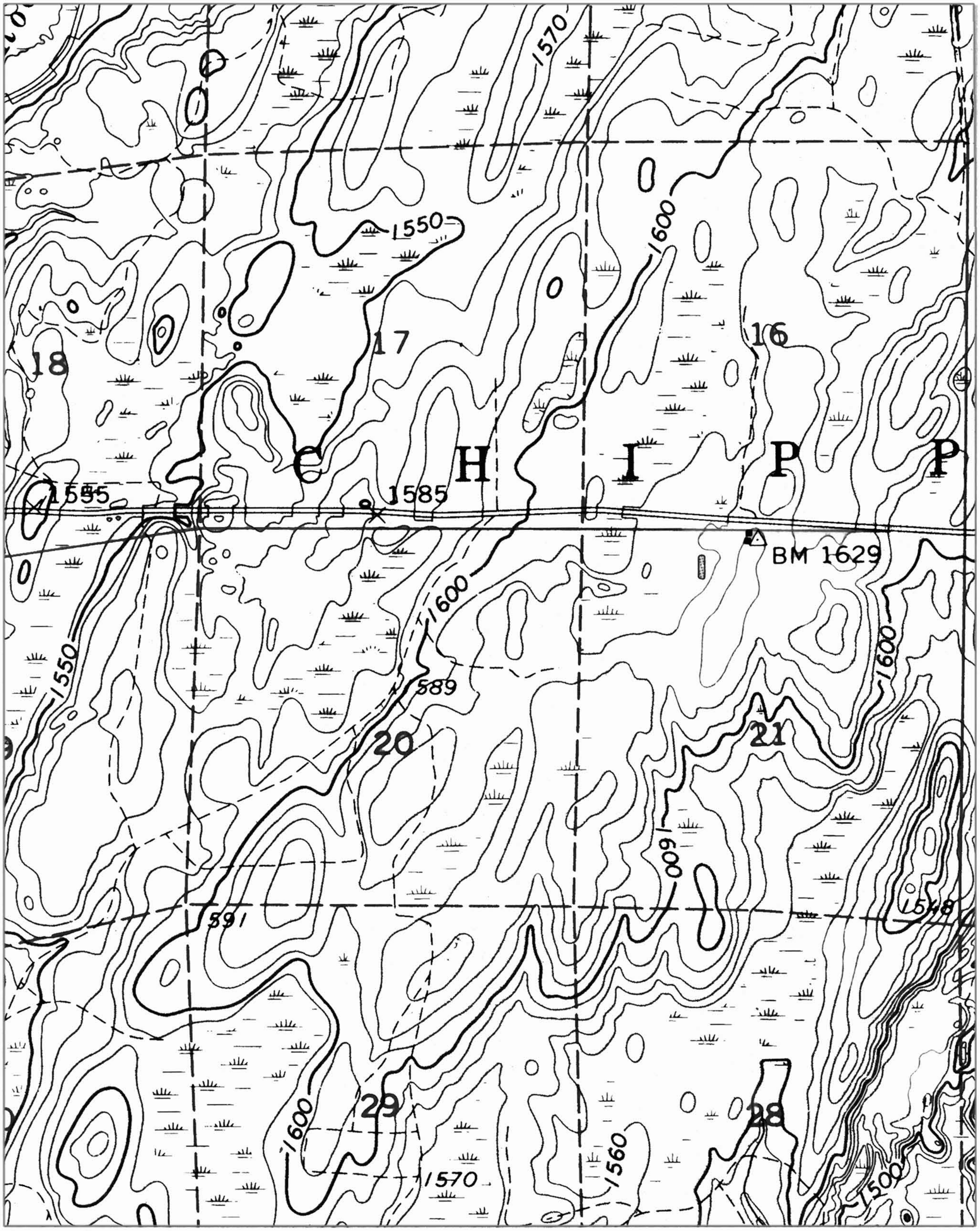

FIGURE 8. Complex drumlins, molded by ice flow about S. 10° to 25° W. U.S. Geological Survey Glidden Quadrangle (15-minute, topographic; 10-ft contour interval). T. 41 N., R. 2 W. Area shown is 4 km wide.

movement was somewhat more easterly than the movement that shaped the main masses of the drumlins. Farther west, the earlier and later directions of movement were more nearly parallel, and the distinction between uniphase and multiphase drumlins is less clear (fig. 8).

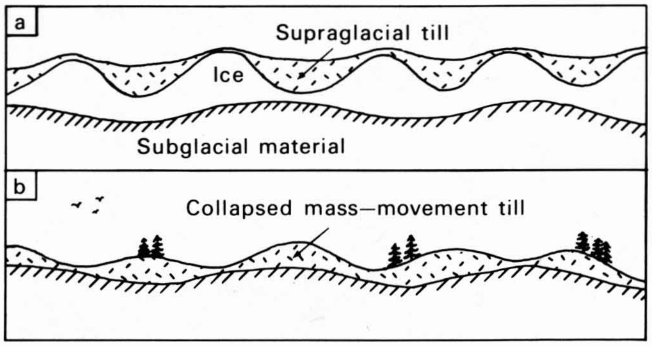

FIGURE 9. Cross sections showing irregularly distributed thick mass-movement till on stagnant ice (a), producing hummocky topography when ice melts (b).

The surface layer of till in the drumlinized areas is typically about a metre thick. This material has been interpreted to be lodgement till because drumlins form at the base of a sliding glacier, although it may also include melt-out till. In many areas the lodgement (or melt-out) till is overlain by a metre or more of till-like material interbedded with sorted sand and gravel. This may be flow till, sorted debris-flow deposits, and supraglacial slope-wash sediment or it may be a postglacial hillslope deposit, perhaps formed in a tundra climate immediately after deglaciation. The core of many, perhaps most, drumlins is composed of older sand and gravel.

Thick mass-movement till

Map unit **gc** ("glacial, collapsed") on plate 1 consists of Copper Falls till. It is interpreted to be thick supraglacial mass-movement till that collapsed as the ice melted to form the hummocky topography characteristic of the area (fig. 9). If this interpretation is correct, the mass-movement till is at least several metres thick because the hummocks are that high. However, the actual thickness of the supraglacial till is unknown in these areas because the stratigraphy of th Copper Falls Formation is yet to be worked out and subsu face information is scarce. Even though the till is thought t

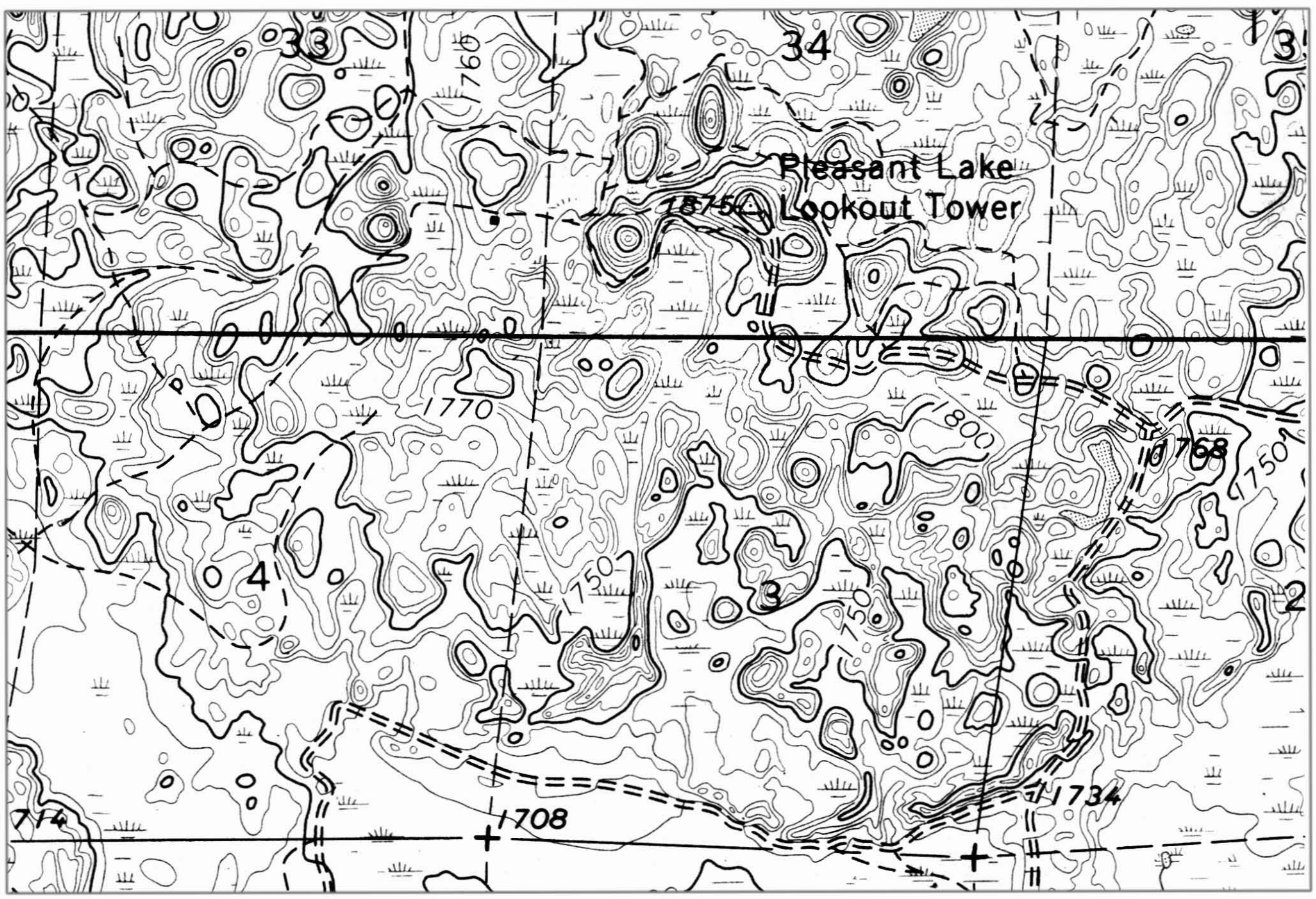

FIGURE 10. Mounds interpreted to be collapse hummocks. U.S. Geological Survey Butternut Quadrangle (15-minute, topographic; 10-ft contour interval). Tps. 44 and 45 N., R. 1 E. Area shown is 4 km wide.

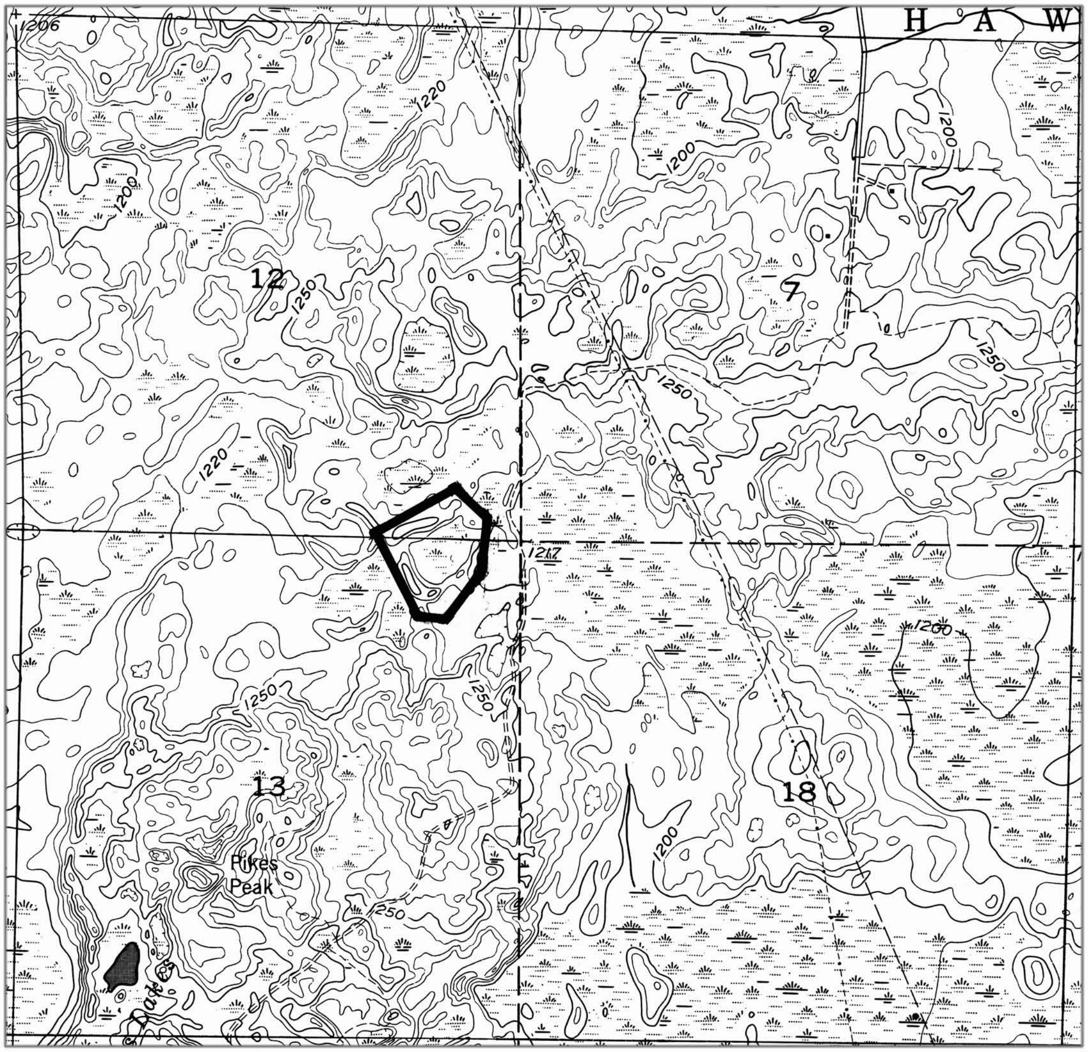

FIGURE 11. Polygonal ridges (one has been outlined) interpreted to be collapse hummocks. U.S. Geological Survey Lyman Lake Quadrangle (7.5-minute, topographic; 10-ft contour interval). T. 46 N., Rs. 12 and 13 W. Area shown is 3.2 km wide.

be thick, this is not end moraine because the thick zone is not parallel to a former ice margin. The collapse hummocks are typically round mounds about 200 m wide and 10 m high. Some are over 20 m high (fig. 10). In some areas the collapse hummocks are ring (torus) shaped, and some tend to be polygonal (fig. 11).

The hummocks have been interpreted to consist of collapsed supraglacial mass-movement till for the following reasons. They are similar in size and shape to hummocks interpreted to be of collapse origin in other areas (Clayton and Moran, 1974; Clayton, Moran, and Bluemle, 1980). They may be composed of melt-out till but there is little evidence that englacial till in modern glaciers is distributed in such a way that hummocks like these would result; however, mass-movement till is known to vary in thickness, as shown in figure 9, on modern stagnant glaciers (Clayton and Moran, 1974). They are probably not composed of subglacial flow till because there is little evidence that the bottoms of glaciers are of the required form; however, the upper surface of modern stagnant glaciers commonly have the irregular form shown in figure 9. They probably are not composed of lodgement till because they are equidimensional in map view, not longitudinally elongated, as in drumlins, or transversely elongated, as in end moraines.

Thin mass-movement till

Map unit **gg** ("glacial on glacial") on plate 1 consists of Copper Falls till. The topography of map unit **gc** consists of evenly spaced, similar-sized collapse hummocks, whereas the topography of **gg** consists of a complex hodgepodge of large and small hummocks superimposed on larger and more irregular hummocks (fig. 12). For this reason, the topography of map unit **gc** is interpreted to be in large part the result of the collapse of thick supraglacial mass-movement till of the last glacial advance, whereas the topography of map unit **gg** is interpreted to be the result of the draping of thin mass-movement till and probably also melt-

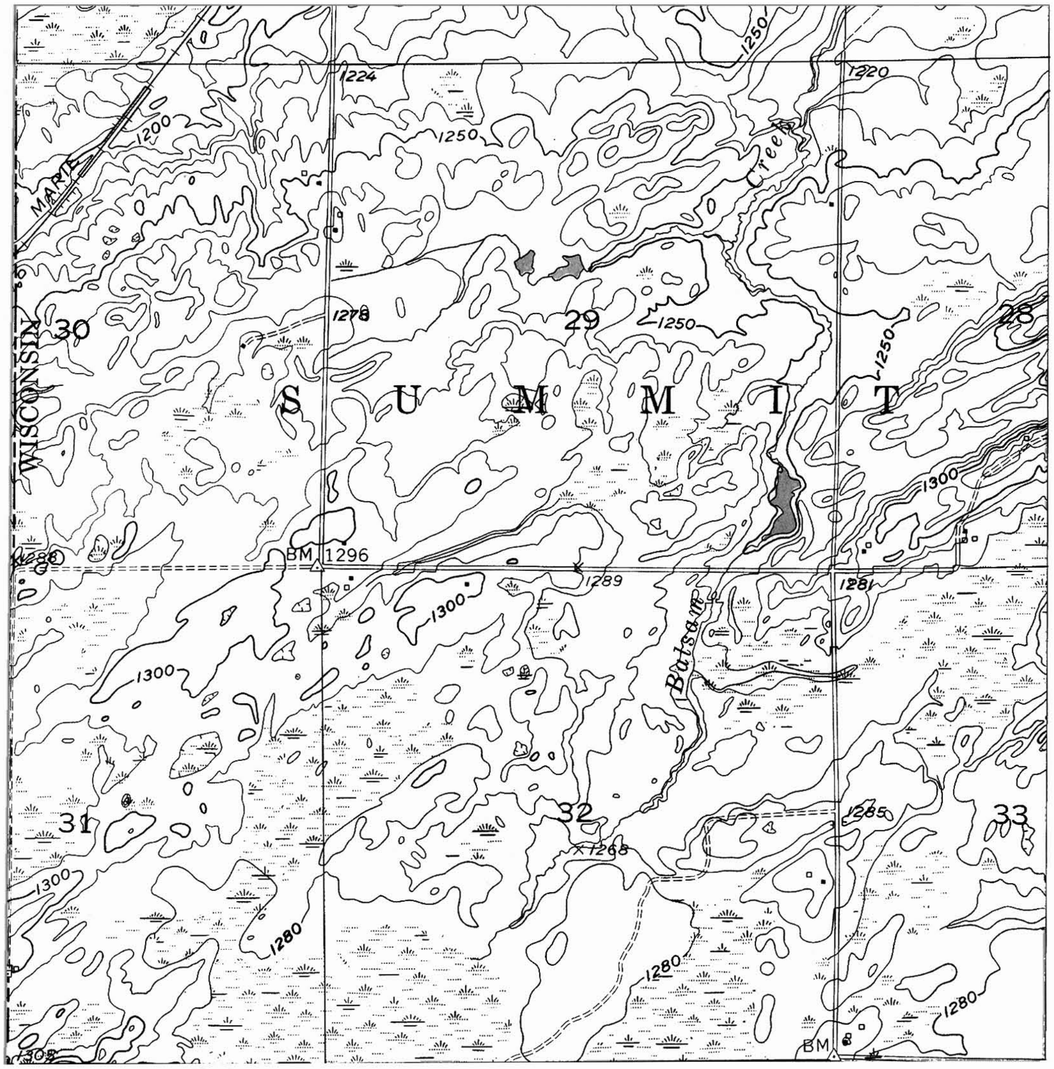

FIGURE 12. Complex landscape interpreted to consist of thin mass-movement till and probably also melt-out till and lodgement till draped over older till and pre-Pleistocene rock. The northeast-southwest ridges have been interpreted to be drumlins (Flint and others, 1959), but they are perpendicular to the probable ice-flow direction and are most likely partly buried basalt hogbacks. U.S. Geological Survey Foxboro Quadrangle (7.5-minute topographic; 10-ft contour interval). T. 45 N., R. 15 W. Area shown is 3.3 km wide.

out and lodgement till over older topography, consisting in most places of older till or pre-Pleistocene rock (fig. 13). That is, the topography of map unit **gg** is probably multistoried, consisting of two or more superimposed landscapes; in many areas the broader elements of the landscape are of preglacial origin (fig. 12). The thickness of the surface layer of glacial sediment is poorly known but may be a few metres in many areas. The distinction between thick mass-movement till (map unit **gc**) and thin mass-movement till (map unit **gg**) is obscure in many areas because of the scarcity of field information.

Stream sediment

Stream sediment makes up roughly half of the Copper Falls Formation. The greater part of it, especially on the Bayfield Peninsula and in the St. Croix valley, consists of sand, with only scattered pebbles, cobbles, and boulders.

Most of the stream sediment in the Copper Falls Formation was deposited by glacial melt-water streams. Some, however, was deposited by streams with nonglacial water. For example, sand was deposited near the mouths of gullies along the east side of the St. Croix spillway (fig. 20); this sand was eroded from deposits of proglacial stream sediment just after the spillway became inactive. It is included in the Copper Falls Formation because it is apparently indistinguishable from the melt-water deposits.

Much of the sediment of melt-water streams can be called outwash in the sense that it was washed out beyond the glacier and deposited in a proglacial plain. Some of it, however, was washed out of pre-existing till or stream depos-

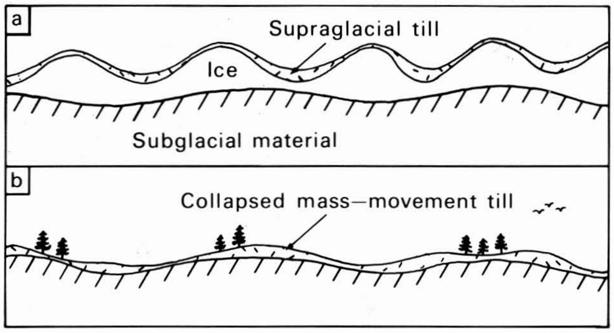

FIGURE 13. Cross sections showing thin mass-movement till on stagnant ice (a), producing complex topography consisting of small hummocks on large hummocks when ice melts (b).

its, rather than out of a glacier, and therefore is not outwash. For example, the sand and gravel in the point bars and in the lower terraces of the St. Croix spillway was derived entirely from the cut banks of the spillway. The sediment of eskers is not outwash because it was deposited in or under the glacier rather than beyond it.

Hummocky sand overlain by silty material

Map unit **sg** on plate 1 includes three undifferentiated combinations of materials. (1) In much of the region, map unit **sg** ("stream sediment under glacial sediment") consists of collapsed supraglacial stream sediment overlain by a thin layer of till. (2) In some areas, such as southeastern Ashland County, the thin till is underlain by subglacial rather than supraglacial stream sediment. (3) In other areas, such as southeastern Iron County, the surface material is a till-like layer of eolian or lacustrine sediment that has been mixed with the underlying fluvial sediment by tree tipping during wind storms (Hole, 1976, p. 33). These three combinations of material have been grouped together on plate 1 because of the difficulty in distinguishing between them in areas of sparce field information. The surface layer is about a metre thick in many areas, although it may be much thicker in some areas, and it is absent in other areas, especially on steep slopes where it has been removed by postglacial soil erosion. Where the surface material of map unit **sg** consists of fluvial sediment mixed with eolian or lacustrine sediment, rather than till, the surface layer is generally no more than about a metre thick, and surface boulders are absent.

Proglacial stream deposits

Map units **su** and **sc** on plate 1 consist largely of sediment deposited by proglacial melt-water streams. These streams issued directly from the melting glacier and therefore carried abundant bed-load sediment. As a result, these proglacial streams tended to be shallow, braided streams, in contrast to the deep, meandering spillway streams, and they formed broad, flat plains rather than deep channels. Proglacial stream sediment in the Superior region generally consists of sand or gravelly sand with cross bedding and less commonly sandy gravel with plane bedding. It is generally finer grained than the sediment of spillways and eskers.

Map unit **su** ("stream sediment, uncollapsed") consists of stream sediment that was deposited on solid ground and still has flat topography (fig. 14). Map unit **sc** ("stream sediment, collapsed") consists of stream sediment that was deposited on top of stagnant glacial ice and was collapsed as the underlying ice melted, resulting in faulted bedding and hummocky topography lying at lower elevations than adjacent areas of uncollapsed stream sediment (fig. 14).

Eskers

Eskers are most common in the southern half of the Superior map area. They are sinuous ridges, generally less than 100 m wide, 15 m high, and 8 km long (fig. 15). Most eskers in the region were probably deposited by rivers flowing in subglacial tunnels rather than in englacial tunnels or supraglacial channels; the eskers were only slightly disrupted when their ice walls melted, leaving sharp undulating crests. Eskers in the Superior region are generally composed of gravel, which is typically coarser and more poorly sorted than proglacial stream sediment.

MILLER CREEK FORMATION

Stratigraphy

The Miller Creek Formation has been named by Mickelson and others (in press). It includes the material in the Lake Superior lowlands that had previously been known only as "Red Clay." It includes clayey glacial and offshore sediment and associated sandy offshore, stream, and shoreline sand. It is generally somewhat redder and more clayey than the older Copper Falls Formation. The Miller Creek Formation is between 11,500 and 9,500 years old.

West of the Bayfield Peninsula, the Miller Creek Formation consists largely of the Douglas Member overlying the Hanson Creek Member (Need, 1980; Johnson, 1980; Need, Johnson, and Mickelson, 1981; Mickelson and others, in press). Both members consist, for the most part, of till. East of the Bayfield Peninsula, the Miller Creek Formation also contains at least two till members, which have not been correlated with confidence to the two members west of the Bayfield Peninsula.

The Miller Creek Formation is in part equivalent to the Wrenshall Formation in Carlton County, Minnesota (Wright, Mattson, and Thomas, 1970). The Wrenshall consists of offshore clay, silt, and sand deposited largely to the west of the western extent of the Douglas till; at least the upper part of the Wrenshall offshore sediment was deposited contemporaneously with the Douglas till. The relationship of the Wrenshall to the Hanson Creek Member is unclear because the western extent of the Hanson Creek Member is unknown. Although no formal redefinition is advocated here, the Wrenshall might be considered a member within the Miller Creek Formation.

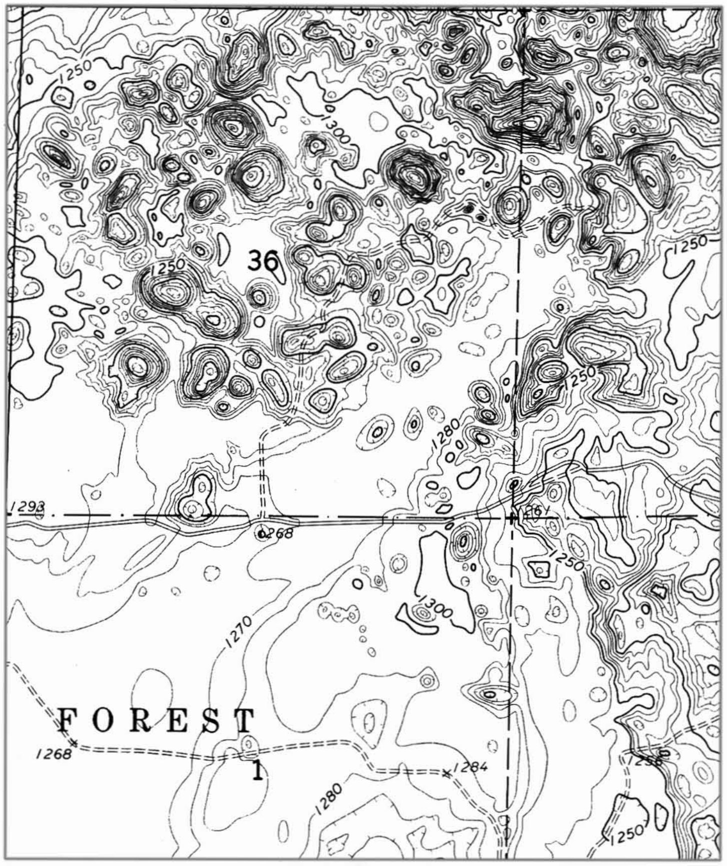

FIGURE 14. Collapsed (depressions) and uncollapsed (flat upland) proglacial stream sediment. U.S. Geological Survey Cornucopia Quadrangle (7.5-minute, topographic; 10-ft contour interval). Tps. 49 and 50 N., Rs. 5 and 6 W. Area shown is 2.2 km wide.

The Nickerson till (Wright, 1972) of Carlton and Pine Counties, Minnesota, is similar to the more sandy till of the Miller Creek Formation (several analyses, supplied by Howard Hobbs, March 20, 1980). However, it apparently underlies all units within the Miller Creek Formation and is the lateral equivalent of the youngest till of the Copper Falls Formation.

The relationship of the Miller Creek Formation to units on the northwest side of the Superior basin (Moss, Zarth, and Matsch, 1979) is unclear. Chronologic, if not lithostratigraphic, equivalents are probably present at similar elevations on both sides of the basin.

The Miller Creek Formation is equivalent to the unit containing reddish, clayey glacial and offshore sediment along the south side of the Superior basin in northwestern Michigan. This unit includes the till deposited during the Sixmile Advance and probably also during the Watton Advance of Peterson (1982).

Till

The till of the Hanson Creek Member (Need, 1980, p. 13-17) in the shore bluffs of Lake Superior is unlaminated and typically consists of between about 45 and 70 percent clay, 20 and 45 percent silt, 3 and 20 percent sand (fig. 16), and a few percent or less of pebbles, cobbles, and boulders. It is commonly dull reddish brown (5YR 4/3) to dark reddish brown (5YR 3/4). It is calcareous, the silt and clay fraction containing about 10 percent carbonates. The unit is typically about 8 m thick in the shore bluffs.

The till of the Douglas Member (Need, 1980, p. 23-26) is similar to that of the Hanson Creek Member but in most outcrops is more clayey and redder. Where it overlies clayey material, the Douglas till typically contains between 45 and 85 percent clay, 10 and 40 percent silt, 3 and 20 percent sand, and a few percent or less of pebbles, cobbles, and boulders, but where it overlies sand, the till contains as much as 60 percent sand (fig. 16). It is commonly dull reddish brown (2.5YR 4/4) and is calcareous. The unit is typically about 8 m thick in the shore bluffs.

The till east of the Bayfield Peninsula is much like that to the west but is less clayey and more silty. Analyses of samples from throughout the area indicate that it typically contains between 5 and 30 percent sand, 30 and 65 percent silt, 10 and 60 percent clay (fig. 16), with a few percent or less of pebbles, cobbles, and boulders. Like the till of the

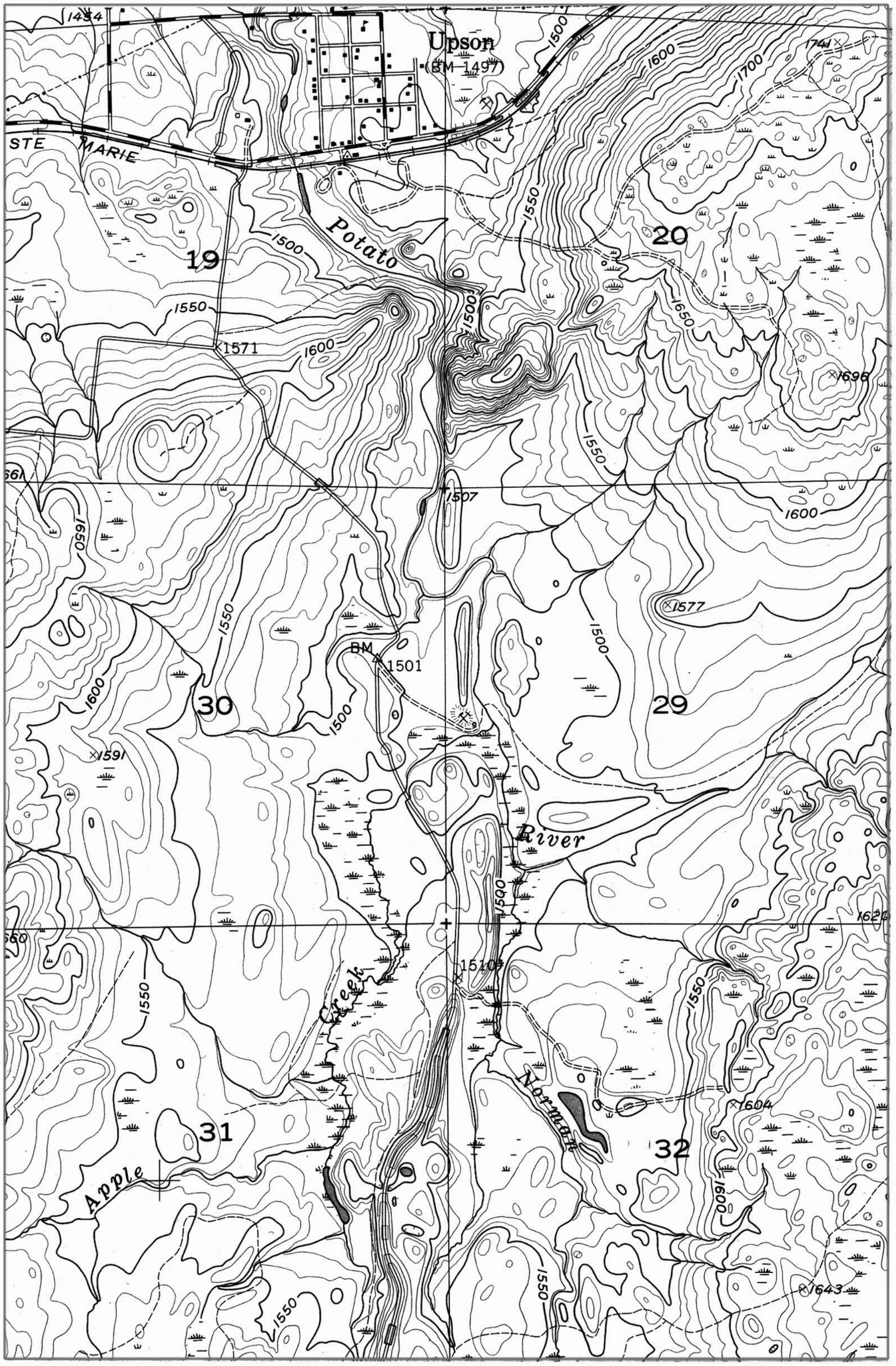

FIGURE 15. Esker extending south from a gap in the Penokee Range. U.S. Geological Survey Upson Quadrangle (7.5-minute, topographic; 10-ft contour interval). T. 45 N., R. 1 E. Area shown is 3.2 km wide.

Douglas Member, it is most sandy where it overlies sand and is commonly reddish brown (2.5YR 4/4).

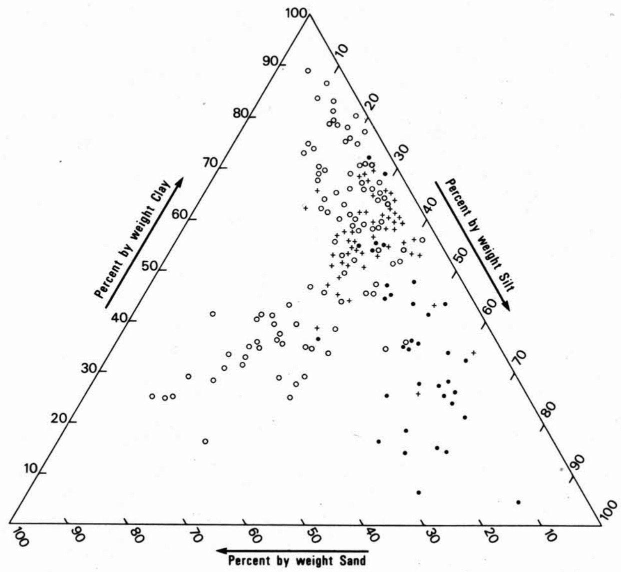

FIGURE 16. Ratio of sand (0.063 to 2.0 mm), silt (0.002 to 0.063 mm), and clay (smaller than 0.002 mm) in till of Miller Creek Formation. Values for Douglas and Hanson Creek Members are from west of the Bayfield Peninsula and are largely from Lake Superior shore bluffs (Need, 1980; Johnson, 1980).

Moraines

Small moraines composed of Miller Creek till are indicated by a line symbol in map unit **gu** of plate 1. These ridges are similar to the moraines of the Copper River Formation and are typically about 6 m high and 100 m wide (fig. 17). They continue northeastward into Michigan where the outermost one has been named the Porcupine moraine (Flint and others, 1959).

Unmodified glacial topography

Map unit **gu** ("glacial, unmodified") on plate l consists of till of the Miller Creek Formation in Tps. 46 and 47 N., R. 1 W. and R. 1 E. In contrast to map unit **gl**, which occurs below the Duluth beach of Lake Superior, the topography of map unit **gu**, which occurs above the Duluth beach, has not been modified by wave action. The topography is hummocky (fig. 17), suggesting that the surface material is collapsed supraglacial flow till.

This hummocky till occurs in two east-west ridges, each about 1 km wide (fig. 17), which Leverett (1929, p. 31) identified as moraines. However, a drill hole in the middle of the southernmost ridge, in the southeast corner of NE¼, sec. 5, T. 46 N., R. 1 E., showed that the upper member of the Miller Creek Formation here is only 5 m thick, suggesting that the bulk of the ridge is made of older material and that the ridges are merely remnants left from the cutting of the spillways (from proglacial Lake Ontonagon in northern Michigan) indicated by a line symbol and map unit **sp** on plate 1. However, small moraines, described in the previous section, occur on these interchannel ridges.

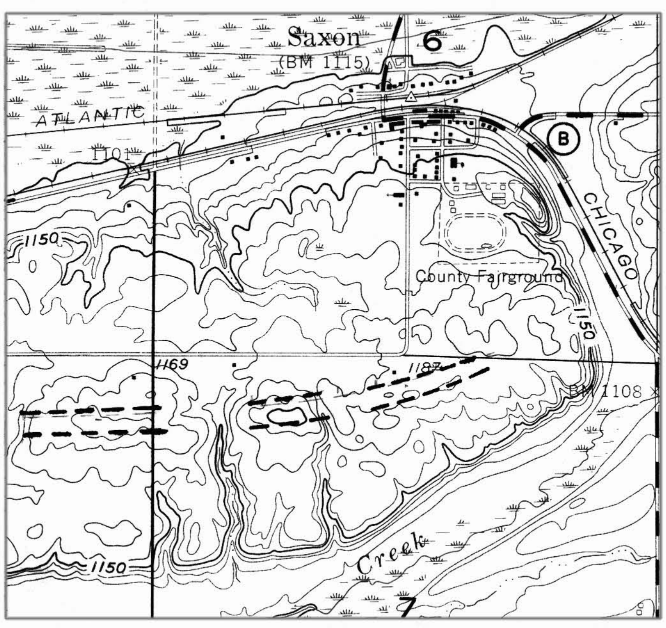

FIGURE 17. Ridge (between dashed lines) interpreted to be a moraine on a larger ridge (above the 1150-ft contour) interpreted to be a remnant left from the cutting of spillways (one on the north side, one on the south side, and a smaller one east of the fairground). U.S. Geological Survey Saxon Quadrangle (7.5-minute, topographic; 10-ft contour interval). T. 46 N., Rs. 1 W. and 1 E. Area shown is 2.1 km wide.

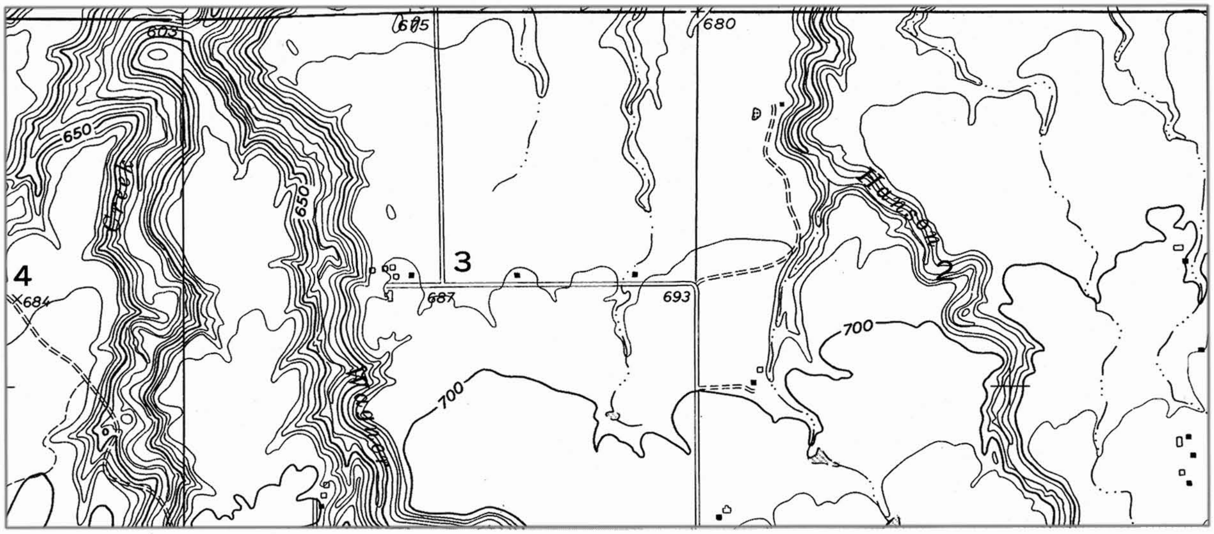

FIGURE 18. Lake-modified glacial topography intersected by small valleys. U.S. Geological Survey Poplar NE Quadrangle (7.5-minute, topographic; 10-ft contour interval). T. 48 N., R. 12 W. Area shown is 3.8 km wide.

Lake-modified glacial topography

Map unit **gl** ("glacial, lake-modified") on plate 1 occurs throughout most of the Superior lowland. The surface material in this region consists of reddish clayey till of the Miller Creek Formation. The topography is flat to undulating (fig. 18), probably at least in part as the result of wave action, but probably also because the clayey till was water logged and highly fluid, causing it to be deposited with a gentle surface slope.

In much of the area, subdued hummocky topography with about a metre of relief can be seen on air photos. In some areas, low drumlins can be seen on air photos, indicating lodgement till with little flow till on the surface. The drumlins, which are indicated by a line symbol on plate 1, are typically about 1 km long, about 200 m wide, and roughly a metre high. Similar drumlins in northern Michigan have been described by Hack (1965). The grain-orientation data of Johnson (1980) indicates that most of the Miller Creek till exposed in Lake Superior bluffs is lodgement till or melt-out till rather than flow till.

In some areas the glacial sediment is overlain by a thin layer of offshore silt and clay; where this material is thicker than about 1 m and occupies an area wider than about 300 m, it has been shown as map unit **ou** or **oc** on plate 1. In some areas the boundary between map unit **gl** and map units **ou** or **oc** is imprecise, because, in poor outcrops, poorly laminated offshore sediment is difficult to distinguish from glacial sediment with few pebbles.

Wave-planed topography

Map unit **gw** ("glacial, wave-planed") on plate 1 consists of wave-planed areas around the margins of the Superior lowland. This unit is similar to map unit **gl**, but the wave action has obliterated the original glacial topography (fig. 19). In much of the area, the reddish clayey till of the Miller Creek Formation is overlain by about a metre of nearshore sand. In some areas, the Miller Creek Formation has been entirely removed by wave action, exposing older material in the Copper Falls Formation, most commonly brownish sandy till, less commonly stream or shoreline sand and gravel. Glacial topography was most completely obliterated between elevations of 270 and 340 m, which is probably the zone that was subject to wave action for the longest period of time. In addition, wave action was most intense where the slopes are steepest and in areas where the waves had the longest fetch. The contact between map units **gl** and **gw** is least accurate on the Apostle Islands and around the former islands on the northeast end of the Bayfield Peninsula.

Valley sides

Map unit **gh** ("glacial, hillslope erosion") on plate 1 consists of steep hillslopes (10° to 15°) bordering streams that cross the Superior lowland (fig. 18). Hillslope erosion processes (slopewash, soil creep, and landsliding) have completely obliterated the original glacial topography. In many areas, till of the Miller Creek Formation occurs at the top of the slope, but in some areas, the Miller Creek Formation has been entirely removed, exposing the older Copper Falls Formation or pre-Pleistocene rock. Slope deposits have accumulated at the base of the hillslopes, and stream sediment occurs in the valley bottoms.

Offshore sediment

Much of the offshore sediment of the Miller Creek Formation consists of laminated red silt and clay. Most was deposited from cold and turbid, and, therefore, dense underflow currents introduced into the lake by melt-water streams. These turbidity currents for the most part flowed to the deepest part of the Superior basin, below the present level of Lake Superior. Most of the Superior plain slopes

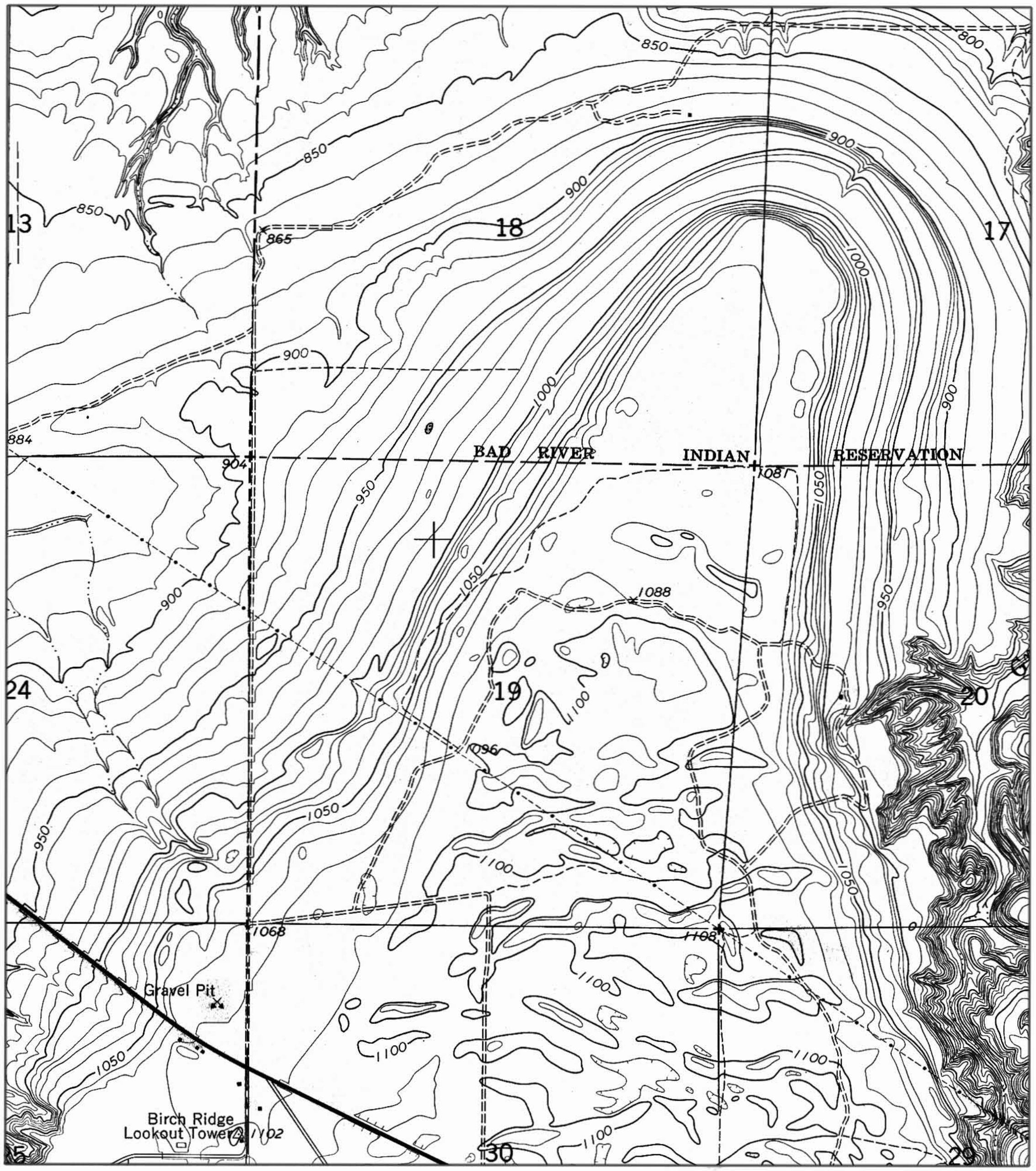

FIGURE 19. Miller Creek till with glacial topography obliterated by wave action (lowland); beaches and shore terraces (between an elevation of about 890 and 1080 ft); and transverse dunes (east-west ridges on upland). U.S. Geological Survey Cedar Quadrangle (7.5-minute, topographic; 10-ft contour interval). T. 47 N., Rs. 1 and 2 W. Area shown is 3.6 km wide.

lakeward and therefore retained little offshore sediment. Furthermore, there were few source streams in this region at the time the lake occupied the Superior plain because there was no ice to the south to supply melt water.

The offshore sediment in T. 47 N., R. 15 W., southwest of the city of Superior, is in a level area at the top of a slope. The silt and clay was prevented from being carried deeper into the basin by the glacier front, possibly at the time the till of the Douglas Member was deposited. Melt water flowing directly from the ice margin may have been one source of this offshore sediment. Some of it may also have been carried from the west by the St. Louis River, which flowed through the area covered by the St. Louis Sublobe of the Red River Lobe (Wright, Mattson, and Thomas, 1970, p. 26-27). The till of the St. Louis Sublobe contains carbonates derived from the Paleozoic limestone and dolomite of Manitoba and gray smectitic clay derived from the Cretaceous shale of northwest Minnesota, northeastern North Dakota, and southern Manitoba; this may account for the calcareous, smectitic clay found in the offshore deposits at the southwest end of the Superior basin (Wright, Mattson, and Thomas, 1970, p. 26-27; Need, 1980, p. 1-46; Haszel, Gilner, and Omernick, 1978; Peterson, Lee, and Chesters, 1968; Mengel and Brown, 1980). The St. Louis source may also account for the gray color of some of the clay, but most of the surface occurrences of offshore sediment in the southwest end of the basin are reddish.

The offshore sediment in the southwest part of T. 49 N., R. 14 W., southwest of the city of Superior, is younger than that discussed in the previous paragraph. It lies on top of the Douglas Member, on one of the flattest parts of the lake plain. The offshore sediment shown on the geologic map in T. 47 N., R. 13 W., south of South Range, and in Tps. 47 and 48 N., R. 10 W., near Brule, occurs in basins somewhat isolated from the main lake basin. The sediment was probably derived from older till by wave erosion.

The offshore sediment around Bibon Marsh (Tps. 45 and 46 N., Rs. 5, 6, and 7 W.) also occurs in a separate basin but was probably derived from melt water coming directly from the ice front when it stood on the northeast side of the depression. The offshore sediment is included in map unit **oc** ("offshore, collapsed") on plate 1. It was probably deposited on stagnant glacial ice and later collapsed as the ice melted, because the topography is hummocky and the bedding is folded or highly contorted. Elsewhere, offshore sediment is included in map unit **ou** ("offshore, uncollapsed"), because the topography is flat and the bedding is horizontal.

Most of the reddish clay in the Miller Creek till was probably originally deposited deep in the lake basin. Because the till of the Copper Falls Formation is sandy whereas the till of the Miller Creek Formation is clayey, this deposition must have occurred between Copper Falls time and Miller Creek time or during Miller Creek time; the reddish clay in the till of the Miller Creek Formation was derived from offshore deposits as the glacier passed through the Superior basin. Like the offshore sediment in the southwest end of the basin, described above, the sediment deep in the basin may have been in part derived from the St. Louis River, which explains the calcareous, smectitic, and clayey nature of the till in the Miller Creek Formation (Need, 1980), but not its red color. A second possible source, water from the Lake Nipigon lowland in Ontario, may also have supplied calcareous, smectitic, and clayey sediment from southern Manitoba. Lake Agassiz, in the Red River lowland, spilled eastward through the Nipigon region and into Lake Superior (discussed below in the section on glacial history). Like the St. Louis source, however, the Agassiz source should also have supplied gray, not red, clay. The ultimate source of the red coloring material was probably Precambrian sediment in and around the Superior basin.

Shoreline sediment

The shoreline sediment around the margins of the Superior basin is indicated by the symbol **b** ("beach") on plate 1. It is here considered to be part of the Miller Creek Formation because it lies on Miller Creek till in many areas and it presumably is interbedded with Miller Creek offshore

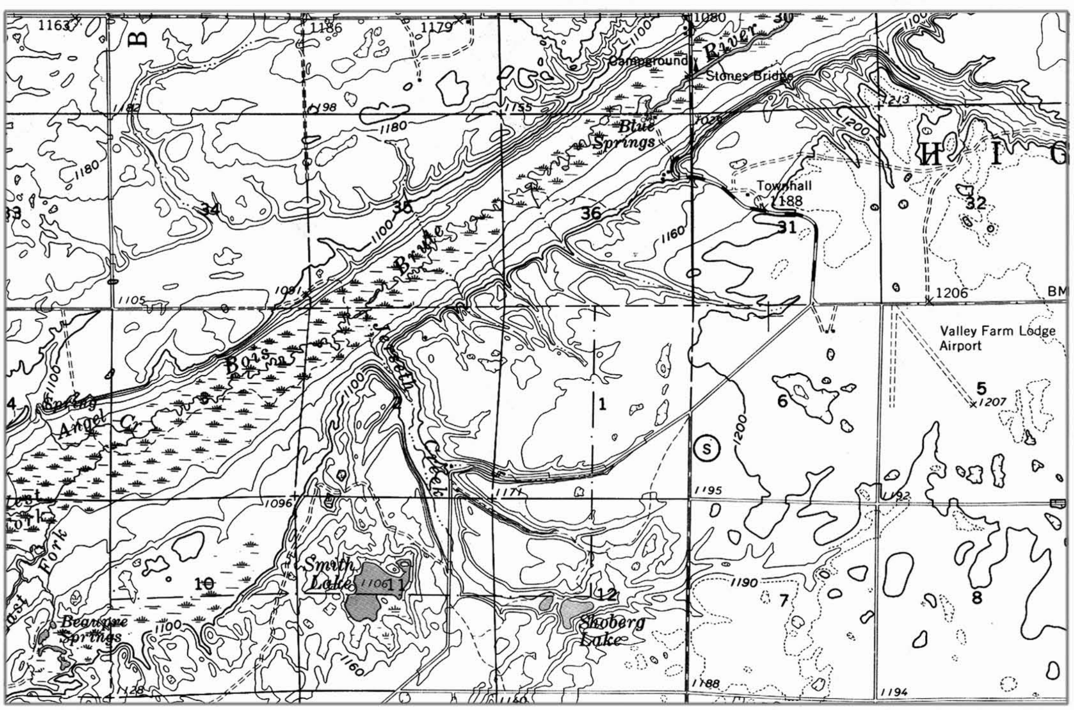

FIGURE 20. The St. Croix spillway. The collapse depressions, such as at Shoberg Lake, formed after the gullies along the sides of the spillway, indicating that the gullies were cut immediately after deglaciation, before all the buried ice melted. U.S. Geological Survey. Ellison Lake Quadrangle (15-minute, topographic; 20-ft contour interval). Tps. 45 and 46 N., Rs. 10 and 11 W. Area shown is 9 km wide.

sediment in some places. Deposits narrower than 300 m are indicated by a dotted line, and some thin, undifferentiated shoreline sediment is included in map unit **gw**. The shoreline sediment is generally well-sorted sand or gravelly sand, but sandy gravel occurs in some areas. It is most extensive where the adjacent uplands are underlain by stream sand.

Sand commonly occurs between the Douglas and Hanson Creek Members (Need, 1980; and Johnson, 1980) and between the units east of the Bayfield Peninsula where they are exposed in modern shore bluffs; sand has also been recorded between these units in water-well logs throughout the Superior lowland. This sand may be shoreline or offshore sediment and some may be stream sediment.

Spillways

Map unit **sp** ("spillway") on plate 1 occurs in the bottoms of the St. Croix spillway and the spillways in the Hurley-Saxon area.

The St. Croix spillway drained Lake Superior during its highest stage; it is a true channel, which was filled bank to bank by water (the cutbanks are indicated by a line symbol on plate 1). It begins just south of the town of Brule and continues south along the upper Bois Brule (fig. 20) and upper St. Croix Rivers and along the Wisconsin-Minnesota border to the Mississippi River. It ranges from 0.8 to 3 km in width, with cutbanks from about 6 to 60 m high. The bedload sediment is thin in many areas, with outcrops of Precambrian rock being common in the reach indicated by map unit **rs** on plate 1, downstream from the St. Croix Flowage. In many reaches the bottom sediment consists of boulder gravel, which produces rapids in the present- day river. In places this boulder gravel is overlain by sand and gravel bars several metres thick.

The spillways in the Hurley-Saxon area drained Lake Ontonagon, a proglacial predecessor of Lake Superior in northern Michigan, entering Wisconsin 6 km northwest of Hurley (Leverett, 1929, p. 57, plate 1). The spillway continues westward for 25 km to near Gurney, where it entered an early proglacial version of Lake Superior called Lake Ashland. Somewhat later, when the ice margin was about 2 km farther north, the outlet of Lake Ontonagon shifted north into a slightly lower spillway, on the north side of Saxon (fig. 17). Like the St. Croix spillway, the Ontonagon spillway is floored with only a thin layer of bed-load sediment (map unit **sp** on plate 1), which consists of boulder gravel overlain in places by bars of sand and gravel.

The spillway sediment has been included in the Miller Creek Formation rather than in the Copper Falls Formation because, like the shoreline sediment, it presumably is interbedded with other material in the Copper Falls Formation.

Wind-blown sediment

The most conspicuous sand dunes in the region occur in secs. 19, 29, and 30, T. 47 N., R. 1 W., in the area indicated by map unit **w** on plate 1. They occur at an elevation of about 335 m at the level of the Duluth beaches of Lake Superior, on a ridge that was jutting out into the lake (fig. 19). These transverse dunes are as high as 6 m and are as long as 1.3 km. They have an east- west orientation, with slipfaces on their north sides, indicating a prevailing south wind at the time of formation. They probably formed at the end of the Duluth time, about 9500 B.P., before vegetation became established, or perhaps during middle Holocene time, about 8500 to 5000 B.P., when the climate was dry. The wind-blown sand probably averages a few metres thick and overlies beach sand in this area.

The stratigraphic position of this material is unclear, but because it seems to be closely associated with the underlying beach sand, it has been included in the Miller Creek Formation.

No other areas of wind-blown sand are indicated on the geologic map. Some small patches of dune sand in the Copper Falls Formation occur on the well-sorted sand of the St. Croix valley, but it is more abundant south of the area mapped; north of Grantsburg, the transverse dunes seem to be steepest on their northeast sides, indicating wind from the southwest.

Wind-blown silt is present in the region, but it is generally not thick enough to extend below the surface soil horizons. In southeastern Iron County (map unit **sg** on plate 1), a layer of till-like material overlies stream sand and gravel. This has been interpreted to be wind-blown silt mixed with underlying stream sediment by tree tipping during wind storms.

POSTGLACIAL DEPOSITS

The postglacial deposits include all the material overlying the Miller Creek Formation. Most of this material is Holocene in age. However, not all Holocene material is included here. Much of the Miller Creek Formation is Holocene, and some of the peat and postglacial stream sediment in the southern part of the region and elsewhere is probably pre-Holocene in age. The postglacial sediment is distinguished from most of the Miller Creek Formation by the absence of reddish clayey sediment. It is distinguished from the Copper Falls Formation and from sandy parts of the Miller Creek Formation by the presence of fairly abundant organic sediment, which is generally lacking in older units. The shoreline sediment of map unit **c** may be lithologically more like the shoreline sediment in the Miller Creek Formation (map unit **b** on plate 1) than it is like the rest of the postglacial deposits, but it has been included here because it does have more organic material than the shoreline sediment of map unit **b**, and in most places it is probably separated from the Miller Creek Formation by more typical postglacial deposits.

Organic sediment

Organic sediment is indicated on plate 1 by the symbol **p** ("peat"). It consists of grass-sedge peat, moss peat, and woody peat. It occurs in low areas occupied by open

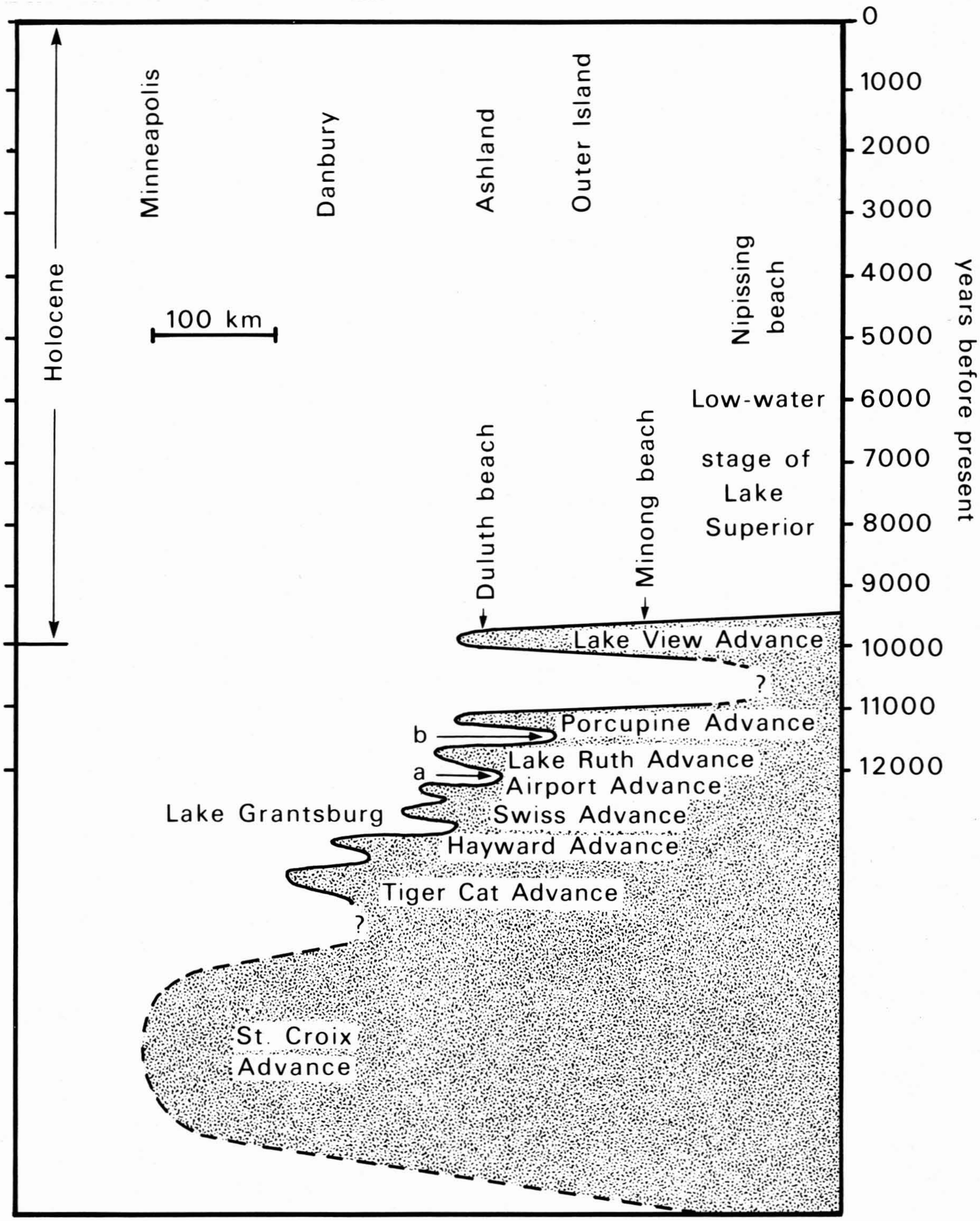

FIGURE 21. Time-distance diagram showing fluctuations of the Superior Lobe (dotted) during the last part of the Wisconsin Glaciation. The till of the St. Croix through Lake Ruth Advances is included in the Copper Falls Formation. The till of the Porcupine Advance, where the glacier overrode lake sediment, is included in the Hanson Creek Member, and the till of the Lake View Advance is included in the Douglas Member of the Miller Creek Formation. Points a and b are discussed in the text.

bog, marsh, or swamp with white cedar, black spruce, and tamarack.

The distribution of peat shown on plate 1 is largely the result of air-photo interpretation. It is probably typically a few metres thick, but in some of the areas indicated on the map, it is probably less than 1 m thick.

The underlying material is unknown in most areas, but some of the peat is underlain by water; where bordered by an open lake, this floating bog occasionally breaks loose, resulting in floating islands. The underlying material in most areas is probably the same as the material surrounding the wetlands. In some areas these materials are separated from the peat by a layer of clayey, silty, or sandy sediment or marl deposited before the peat-forming vegetation became established.

The oldest peat probably was deposited soon after the area was deglaciated. Most of it, however, has probably been deposited in late Holocene time, in about the past 5,000 years.

Stream sediment

Modern streams have been depositing sediment on their floodplains since the last glaciation. The character of this material varied through time as the climate and the level of Lake Superior changed, and it varies from place to place, depending on the character of the material in the adjacent uplands.

The floodplains of the highly sinuous streams on the red- clay plain are underlain by sandy channel sediment, which is overlain by thick overbank silt and clay or peat. In the lower reaches of these streams, the floodplain sediment must all be late Holocene in age, deposited since Lake Superior rose to its present level about 5000 B.P.

South of the red-clay plain, the streams are less sinuous, and their floodplains are underlain by more sandy and gravelly channel sediment, which is overlain by thinner overbank sediment or peat. In many areas, modern channel sediment is lacking and the streams are flowing directly on rock or on coarse gravel deposited by earlier melt-water rivers. Stream sediment is indicated on plate 1 by symbol **sm** ("stream, modern").

Shoreline sediment

Postglacial shoreline sediment is included in map unit **c** ("coastal") on plate 1. Small deposits occur around all modern lakes, but mappable deposits occur across the mouth of Chequamegon Bay, across the mouth of the harbor at the city of Superior, and on some of the Apostle Islands. This material was not analyzed in detail, but it presumably differs from the shoreline sediment at higher elevations (map unit **b** on plate 1) in containing more organic material. However, it was differentiated on the basis of elevation rather than lithology: unit **c** occurs within a few metres above the present-day Lake Superior, whereas unit **b** occurs up to 165 m above the lake.

LATE PLEISTOCENE HISTORY

The history of the Superior region through most of Pleistocene time is unknown, but presumably the area was repeatedly glaciated. Abundant evidence is available for only the last part of the Wisconsin Glaciation, which began somewhat before 20,000 B.P. The major geologic events in the region since that time are summarized below and in figure 21.

In the following discussion, the term "Advance" is used to include not only the advance of the glacier margin but also the subsequent retreat. For example, in figure 21, The Lake Ruth Advance includes not only the southward advance of the ice margin beginning at time "a," it also includes the northward retreat of the ice margin ending at time "b." "Advance" is here used the same way that others in the Midwest have used the term "phase" in recent years (Wright, 1972; Clayton and Moran, 1982); "phase" has been abandoned to avoid confusion with the diachronic "phase" of the recently revised code of stratigraphic nomencalture (North American Commission on Stratigraphic Nomenclature, 1983). Advances are geologic-event units, which differ from geochronometric units and geochronologic units (like Holocene Age) in having time-transgressive boundaries and in being defined in terms of interpreted geologic events rather than in terms of time or in terms of type sections. Advances differ from chronostratigraphic units (like Holocene Stage), lithostratigraphic units (like Copper Falls Formation), and allostratigraphic units in that they are nonmaterial units. Advances differ from diachronic units in being genetic rather than descriptive units. That is, although geologic-event units are interpretations derived from various kinds of evidence, they are defined in terms of the interpreted events rather than in terms of the evidence. In contrast, diachronic units are defined in terms of the evidence: their definitions are tied to type sections.

The ice-margin positions shown in the accompanying maps (figs. 22 to 31) are based on a variety of criteria. (1) They are in part based on lithostratigraphic evidence. For example, the Porcupine and Lake View ice margins are interpreted to have been at the southern extents of the Hanson Creek and Douglas Members west of the Bayfield Peninsula, and the Porcupine ice margin is interpreted to have been at the southern extent of the Miller Creek Formation east of the Bayfield Peninsula. Some of the earlier ice margins locally coincide with the southern extents of unnamed members of the Copper Falls Formation, but in most places the interpreted ice margins correspond to no known lithostratigraphic boundary. (2) In many places, the ice margins shown on the maps are based on the presence of ice-margin features such as proglacial spillways, proglacial stream deposits, or moraines. (3) In some places, no evidence of a margin exists. In those areas, the interpreted ice margins are indicated by dashed lines connecting more-confidently identified margins to the east and west. The obvious potential for miscorrelation exists where the gap is long and where ice margins of different age are closely spaced.

St. Croix Advance

Radiocarbon dates from trees buried by the advancing

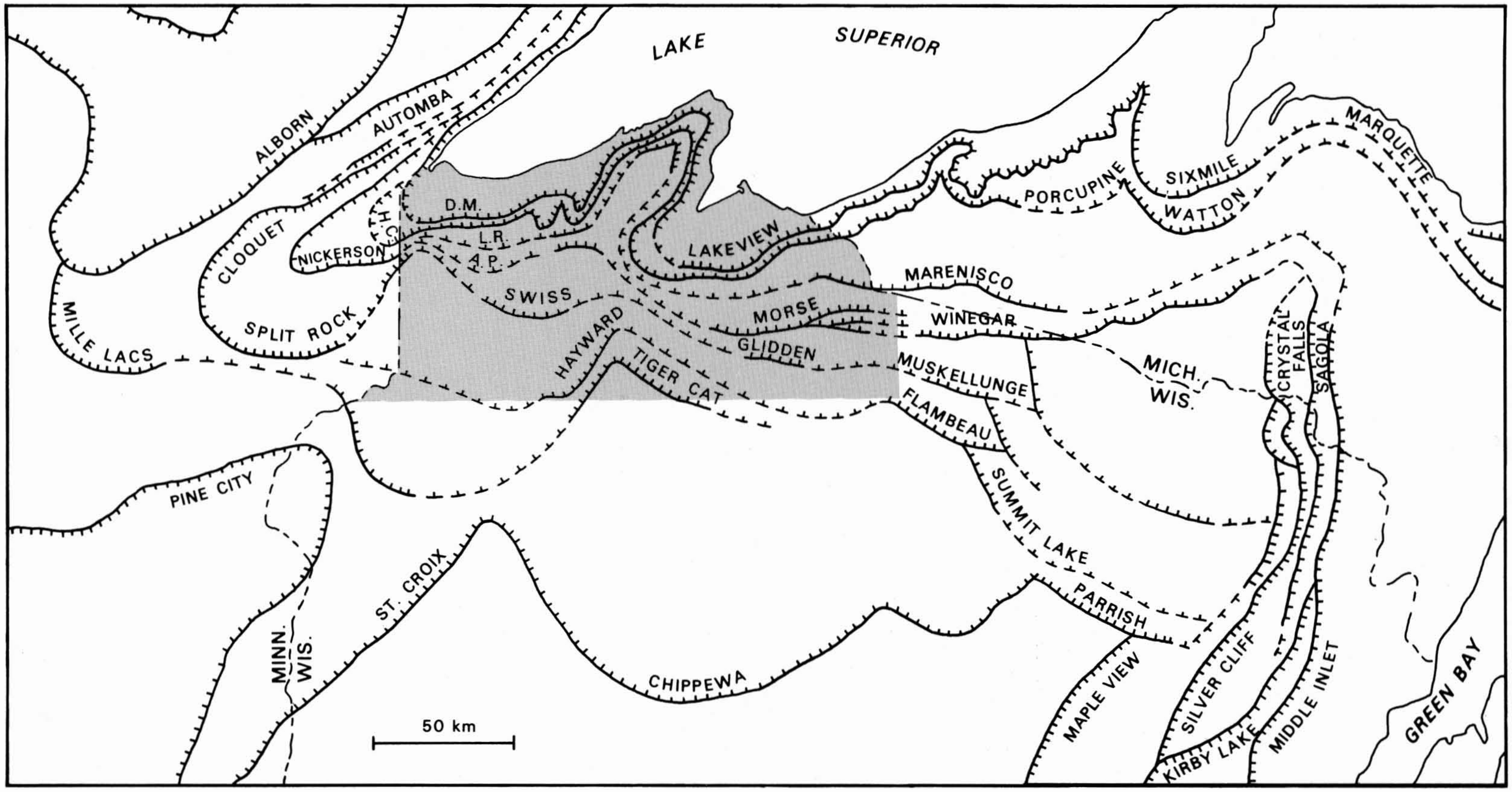

FIGURE 22. Correlation of ice margins in northern Wisconsin, eastern Minnesota, and northern Michigan. Tick marks and names are on the up-glacier side of the ice-margin lines. A.P. = Airport Advance. L.R. = Lake Ruth Advance. H.C. = Hanson Creek Member. D.M. = Douglas Member. Ice margins are from a variety of sources, including Wright (1972), Attig (Vilas and Oneida Counties, unpublished), Peterson (1982), Clayton (Florence County, unpublished), Mickelson and others (northeast Wisconsin, in press), and Drexler (1981). The Superior region of Wisconsin is shaded.

glacier indicate that the Des Moines Lobe of the Late Wisconsin ice sheet reached Iowa by 20,000 B.P., about the same time that the Lake Michigan Lobe reached Illinois (Clayton and Moran, 1982). In western Wisconsin, the glacier apparently reached as far as St. Croix, Polk, Barron, Rusk, Chippewa and Taylor Counties. The ice moved southwestward from an ice sheet that was centered in northern Quebec. It was funneled down the Superior lowland to form the Superior Lobe. Uplands such as the Bayfield Peninsula and the Apostle Islands divided the Superior Lobe into two sublobes. The main lobe, to the west, formed the St. Croix moraine, and the Chippewa Sublobe, to the east, formed the Chippewa moraine (fig. 22).

Tiger Cat Advance

The ice sheet may have stabilized at the St. Croix margin for hundreds or thousands of years, but sometime later it had shrunk and then stabilized at the position shown in figure 23, at the head of the Tiger Cat surface (map unit **suh** on plate 1). The Tiger Cat surface, like the later surfaces, consists of scattered remnants of uncollapsed stream sediment (map unit **suh**) separated from each other by areas of collapsed stream sediment (unit **sc**), indicating that the Tiger Cat Advance was separated from the previous glacial advance by no more time than required for the melting of the buried mass of ice—perhaps no more than a few thousand years. The Tiger Cat Advance is here named for Tiger Cat Flowage in northern Sawyer County.

The Tiger Cat ice margin is marked by glacial thrust masses (map unit **gt** on plate 1). This ice margin has not been traced beyond the Superior map sheet, but to the southwest it seems to be aligned with a series of hills, which may also be thrust masses, in Sawyer, Washburn, and Burnett Counties. The closest likely correlative in Minnesota is the Automba and Mille Lacs ice margin (Wright, 1972, fig. VII-2-h), as suggested in figure 22.

Hayward Advance

Following a minor wastage, the glacier margin stabilized at the position shown in figure 24. Melt-water discharge shifted from the Tiger Cat surface to the Hayward surface, (map unit **sug** on plate 1), along the Namekagon River. The Hayward Advance is here named after the community of Hayward, in northwestern Sawyer County; at Indian School Lake, just north of Hayward, in sec. 15, T. 41 N., R. 9 W., the Hayward surface is at an elevation of about 375 m, and the younger Swiss (?) surface is at about 367 m.

Swiss Advance

The separate fluvial surfaces that can be recognized in the St. Croix valley are shown in figure 25 and on plate 1. The highest wide-spread surface was formed during the Swiss Advance, here named after Swiss Cemetery in the southeast corner of sec. 9, T. 41 N., R. 15 W., in Swiss Township. It is indicated by symbol **suf** on plate 1.

The Swiss surface is at an elevation of about 306 m and is nearly level in Swiss Township. From here, it can be traced almost continuously northeast for 80 km, with a gradient of about 1 m/km, to the position of the ice margin at the time it formed (fig. 26). The flattened gradient in Swiss Township may represent a delta into Lake Grantsburg, which was dammed in the St. Croix valley during the Pine City Advance (fig. 22) of the Grantsburg Sublobe of the Des Moines Lobe (Wright, 1972, p. 535). If this is in fact a delta, the sand associated with the Swiss surface below an elevation of about 308 m is offshore sediment deposited by underflow currents, rather than stream sediment. North of the Namekagon River, above an elevation of 310 m, the Swiss surface has channel scars, indicating that here it is a stream surface, but south of the Namekagon, below about 308 m, channel scars seem to be lacking.

The Swiss ice margin may be the equivalent of the Cloquet (Split Rock) ice margin on the west side at the Superior Lobe (Wright, Mattson, and Thomas, 1970, fig. 9) and the ice margin at Glidden in the southeastern part of the Superior region (figs. 22 and 26). The ice margins are all marked by ice-contact faces at the head of outwash plains, and the Cloquet and Swiss ice margins occur at roughly similar elevations on opposite sides of the Superior Lobe. Wright (1972) correlated the Split Rock ice margin with the Pine City ice margin of the Grantsburg Sublobe (fig. 22).

Airport Advance

The formation of the Swiss surface was followed by glacier- margin retreat and entrenchment of the Swiss surface. The glacier then readvanced and deposited the fluvial sediment of the Airport surface (map unit **sue** on plate 1) in the St. Croix valley (fig. 27). This advance is here named after the airport in sec. 5, T. 45 N., R. 10 W. (fig. 20). The Airport surface occurs throughout the St. Croix valley east of Solon Springs, where it is several metres below the Swiss surface. To the southwest, the distinction between the Swiss and Airport surfaces is less clear (fig. 25), and they may merge with each other.

The Airport ice margin, at the head of the Airport surface, may correlate eastward with the Morse moraine in the southeastern part of the Superior map area as shown in figures 22 and 27. The Morse till consists of thick supraglacial material that buries the older drumlins characterizing the area south of the Morse ice margin. The eastward equivalent of the Morse ice margin is the Winegar (Watersmeet) ice margin of northern Michigan, which Peterson (1982) correlated with the Sagola ice margin, which probably correlates with till of the Silver Cliff or Kirby Lake Members (Mickelson and others, in press) in northeastern Wisconsin.

Clayton and Moran (1982) correlated the Airport ice margin with the Split Rock ice margin of Minnesota. This is unlikely, however, because the Airport terrace extends down the St. Croix valley through the area of the Pine City Advance (Clayton, 1983), which Wright (1972) correlated with the Split Rock Advance. The Airport Advance must have therefore occurred after the Split Rock Advance.

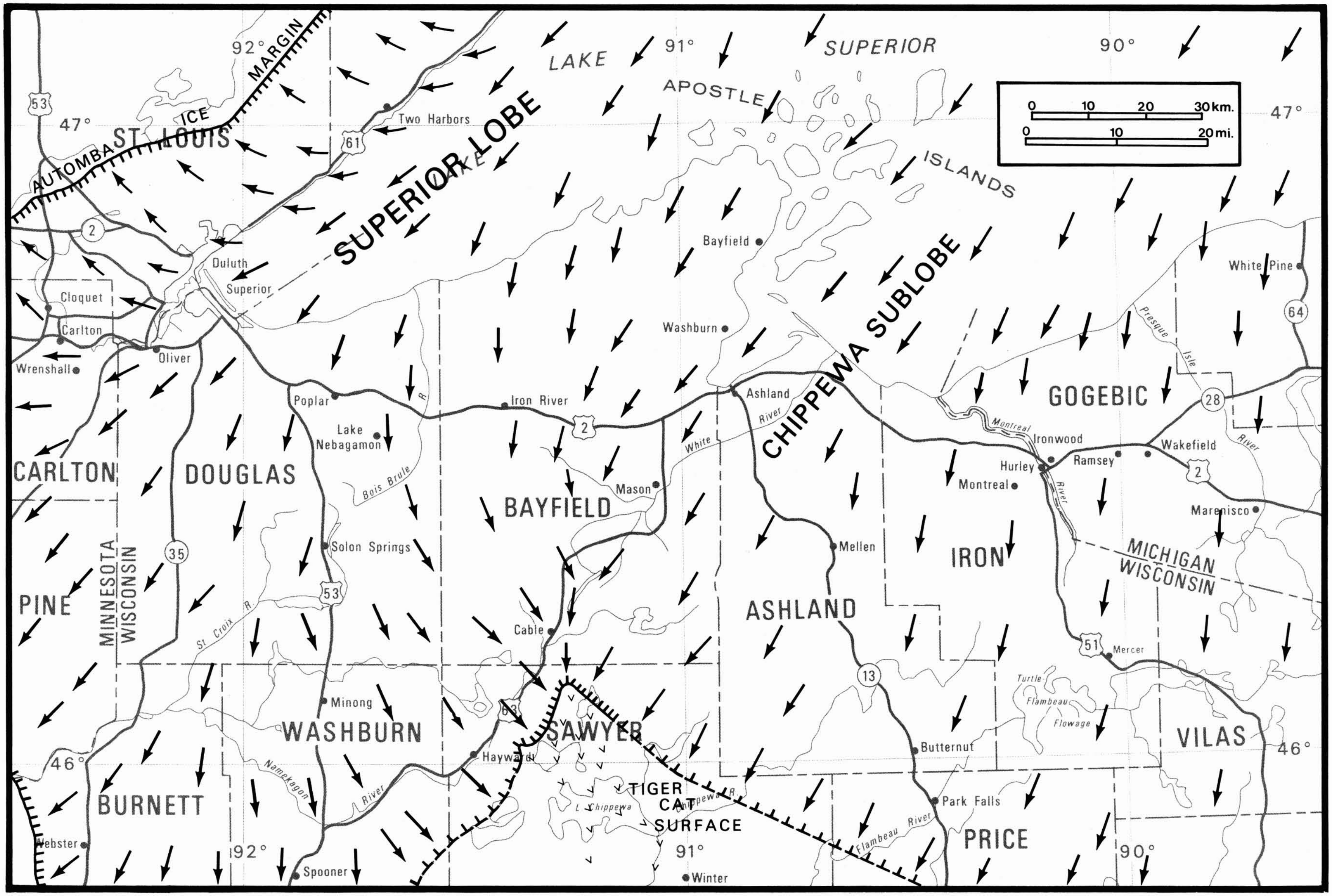

FIGURE 23. Tiger Cat Advance, during the last part of the Wisconsin Glaciation. Line with tick marks indicates the ice margin. Arrows show probable ice-flow direction. Small arrow heads indicate direction of melt- water flow.

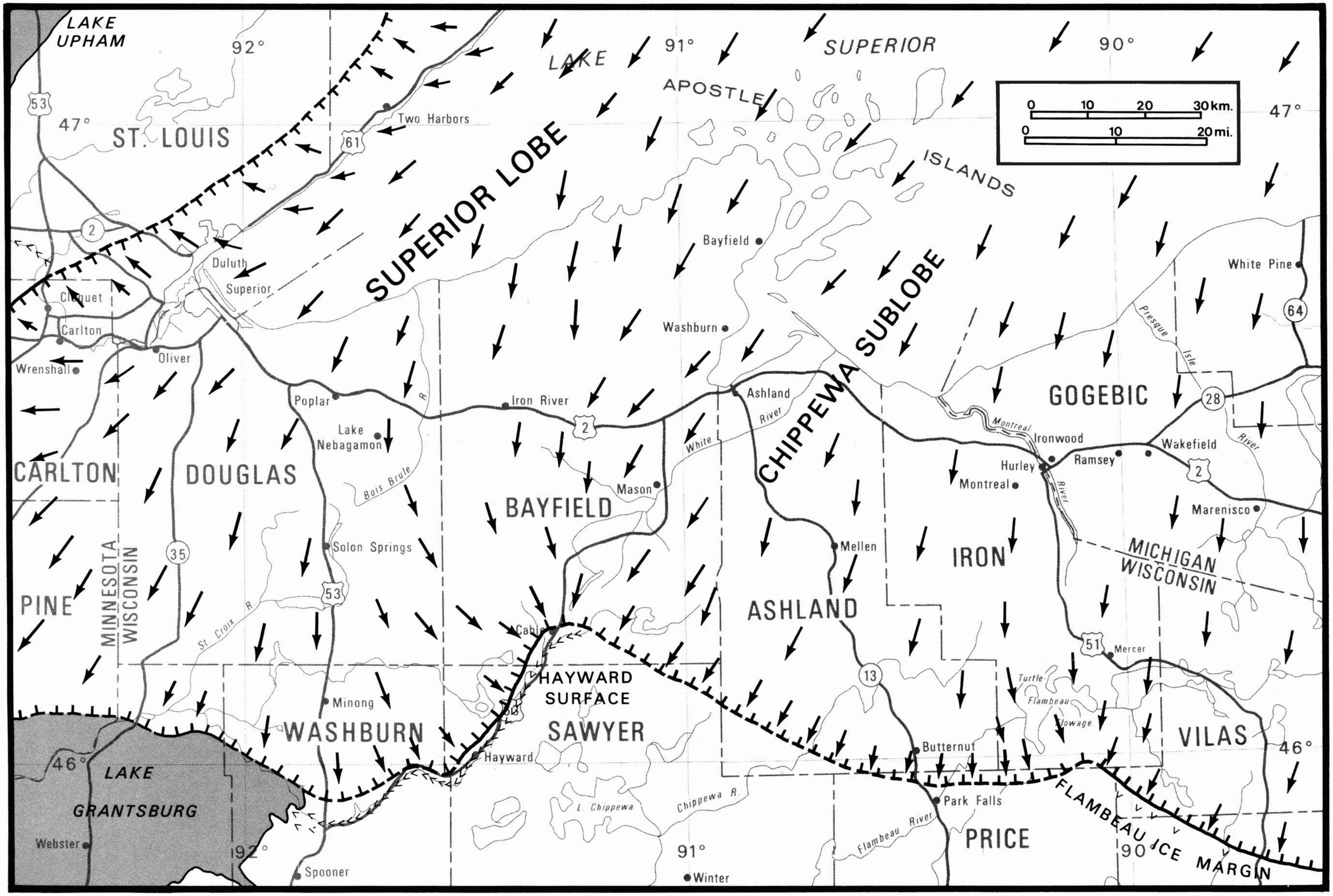

FIGURE 24. Hayward Advance. The Flambeau ice margin is from John Attig (in preparation). Symbols explained in caption of figure 23.

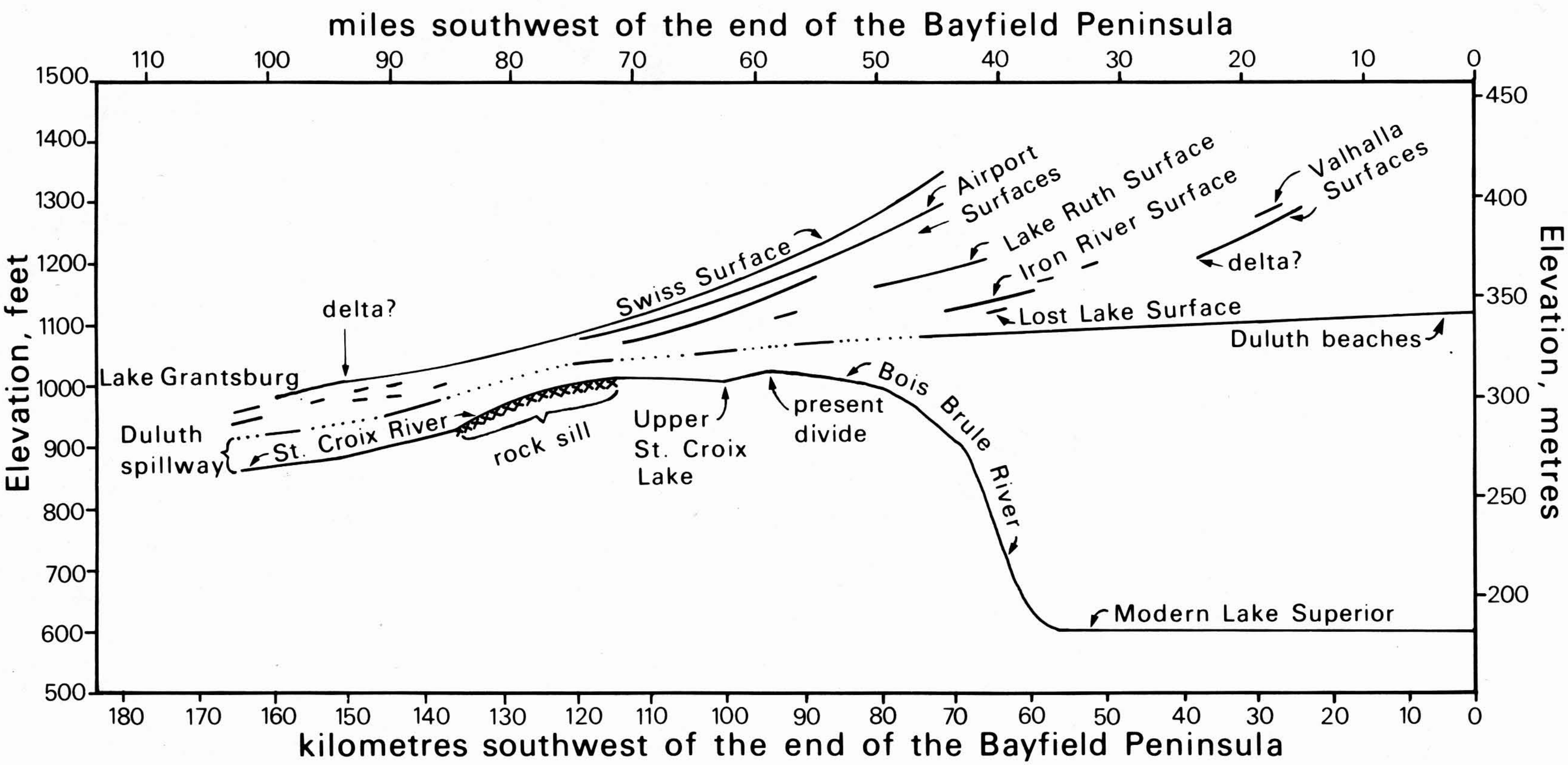

FIGURE 25. Fluvial stability surface measured along the centerline of the St. Croix lowland and Bayfield Peninsula.

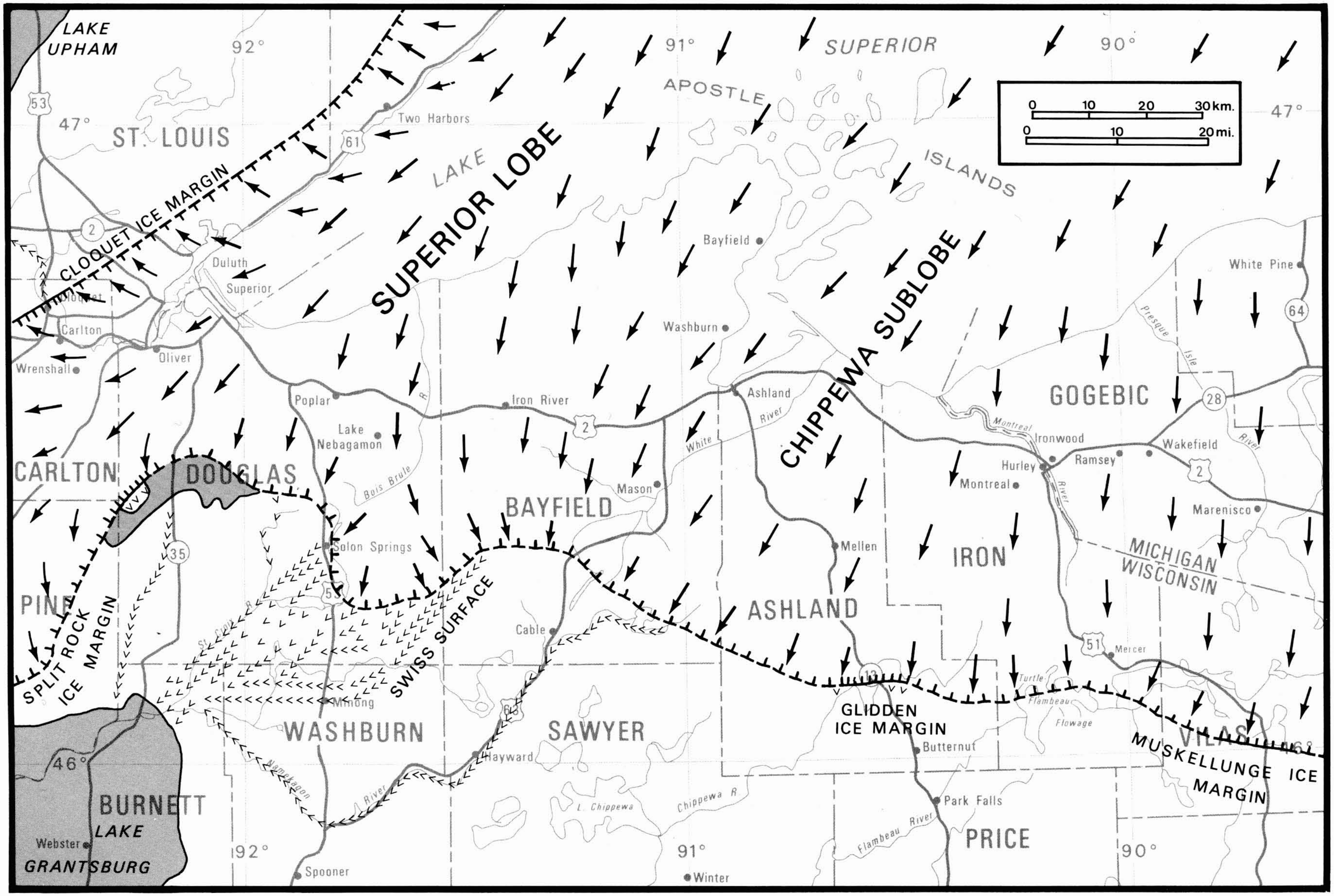

FIGURE 26. Swiss Advance. The Muskellunge ice margin is from John Attig (in preparation). Symbols explained in caption of figure 23.

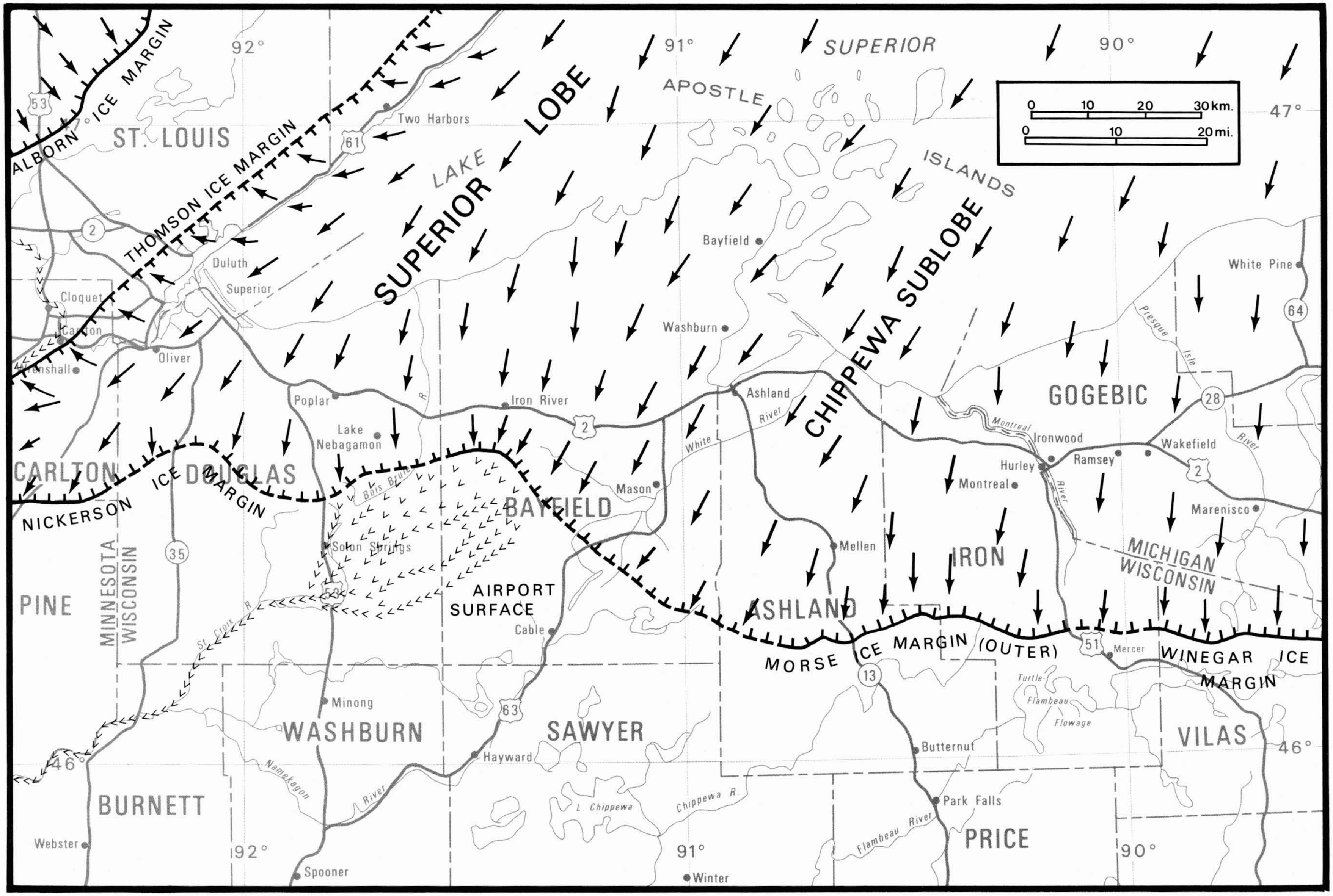

FIGURE 27. Airport Advance, perhaps about 12,300 B.P. Symbols explained in caption of figure 23.

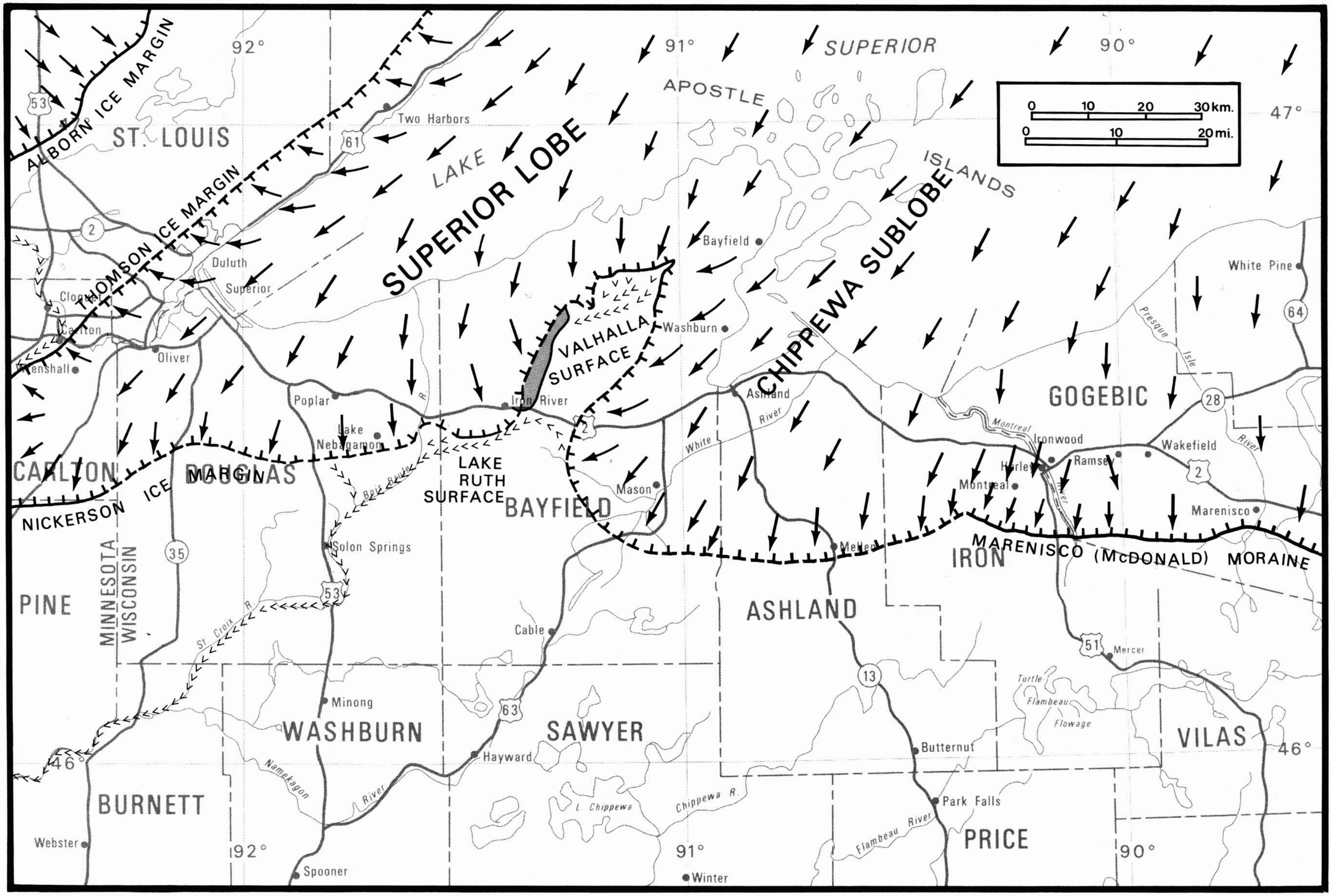

FIGURE 28. Lake Ruth Advance, about 11,500 B.P. Symbols explained in caption of figure 23.

Lake Ruth Advance

As the ice margin wasted back from the Airport surface, the St. Croix River downcut at least 30 m, probably because it was fed by water lacking bedload from a proglacial lake in the Superior basin. During the following Lake Ruth Advance (fig. 28), the lake disappeared, and the fluvial sediment of map unit **sud** (plate 1) was deposited in the area below (north of) the Airport ice-contact face and in the St. Croix trench, up to an elevation 30 m below the head of the Airport surface (fig. 25). The Lake Ruth Advance is here named for a lake in sec. 31, T. 47 N., R. 8 W., and sec. 6, T. 46 N., R. 8 W.

At least two fluvial surfaces occur below the Lake Ruth surface near the community of Iron River (plate 1, fig. 25). The Iron River surface is indicated by symbol **sub** on plate 1. It occurs just above the level of the Duluth beach west of Iron River and appears to rise to the east. It may consist of two separate surfaces at slightly different elevations. Southeast of Iron River, near Lost Lake, in secs. 20, 21, 28, and 29, T. 47 N., R. 8 W., another surface occurs just above the 1,120 ft (341 m) contour (Iron Lake 15-minute quadrangle, 1961). This surface, here called the Lost Lake surface, is indicated by symbol **sua** on plate 1. It seems most likely that the Iron River and Lost Lake surfaces formed at the end or shortly after the Lake Ruth Advance rather than during the Porcupine Advance (fig. 30) because the proglacial spillway draining Lake Ontonagon during the Porcupine Advance (see below) entered Lake Superior at the Duluth level, below the Iron River and Lost Lake surfaces.

Farther northeastward, on the Bayfield Peninsula, are a pair of surfaces here called the Valhalla surfaces (symbol **suc** on plate 1). In sec. 13, T. 49 N., R. 6 W., northwest of Mt. Valhalla, the upper one is at an elevation of about 390 m and the lower one, which is much more widespread, is at about 380 m (both surfaces are shown in fig. 14). If the slope of the main part of the lower Valhalla surface were continued southwestward, it would be below both the Iron River and Lost Lake surfaces (fig. 25). However, the surface in sec. 20, T. 49 N., R. 7 W., which is shown as part of the Valhalla surface on plate 1, appears to be a delta-like protrusion into the Superior basin. If this is a delta, the Valhalla surfaces are older than the Iron River surface, which formed after the lake stood at the elevation of the delta (fig. 25).

To the west, the Lake Ruth ice margin may correlate with the Nickerson ice margin (Wright, 1972). The clayey till of the Barnum Formation in Carlton County, Minnesota, (fig. 28) (Wright, Mattson, and Thomas, 1970) may have been deposited at this time; the clay was probably derived from offshore sediment deposited in the westernmost part of the Superior basin just before the Lake Ruth Advance. To the east, on the south side of the Chequamegon lowland (fig. 28), an ice margin at the same elevation as the Valhalla margin most closely corresponds to the Marenisco (McDonald) moraine, 11 km south of Hurley, which Peterson (1982) correlated with an unnamed moraine of the Green Bay Lobe, which appears to correlate with the western edge of the Middle Inlet till and the Two Rivers till of eastern Wisconsin (fig. 22), which were deposited about 11,500 B.P. (Mickelson and others, in press).

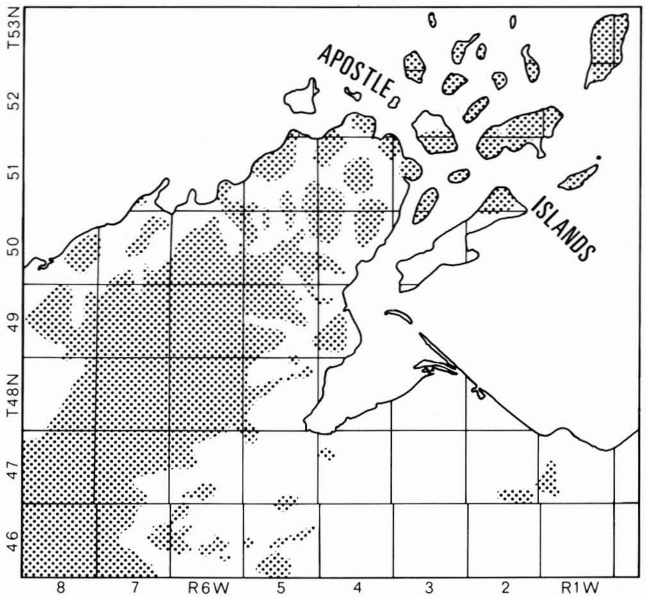

FIGURE 29. Hills of the Bayfield Peninsula, shaded.

Bayfield hills

The Bayfield Peninsula is made up of a series of hills averaging about 3 km across and about 200 m high (fig. 29). They continue offshore to form the Apostle Islands. In the middle of the peninsula they coalesce to form one continuous upland—the Bayfield interlobe ridge.

Undoubtedly they were formed by a variety of processes acting at various times. The form of many of the Apostle Islands is in part the result of the form of their rock core; Precambrian or Cambrian sandstone crops out around much of their shore. The hills on the Bayfield Peninsula may also be cored by rock, but few outcrops exist back from the shoreline, and subsurface information is scarce. The general impression gained from scattered roadcuts, excavations, and water-well drillers' logs is that the Bayfield hills are made up largely of Pleistocene sand. The hills might be ice-contact fans deposited at the mouths of large subglacial tunnels. Perhaps the sand of the Bayfield hills, the sand of the interlobe ridge in the middle of the peninsula, and the sand of the St. Croix valley was eroded from Precambrian or Cambrian sandstone in the bottoms of the tunnel channels. The hills were later modified somewhat by glacial activity (till occurs on some of them). The valleys between the hills may be in part erosional features, cut by the tunnel rivers that fed sand to the St. Croix valley, or molded by glacial flow into the valleys. The last of these features may have formed during the Lake Ruth or even during the Porcupine or Lake View Advances.

Porcupine Advance

The Superior Lobe wasted from at least the west end of the Superior basin and then again filled the basin, to

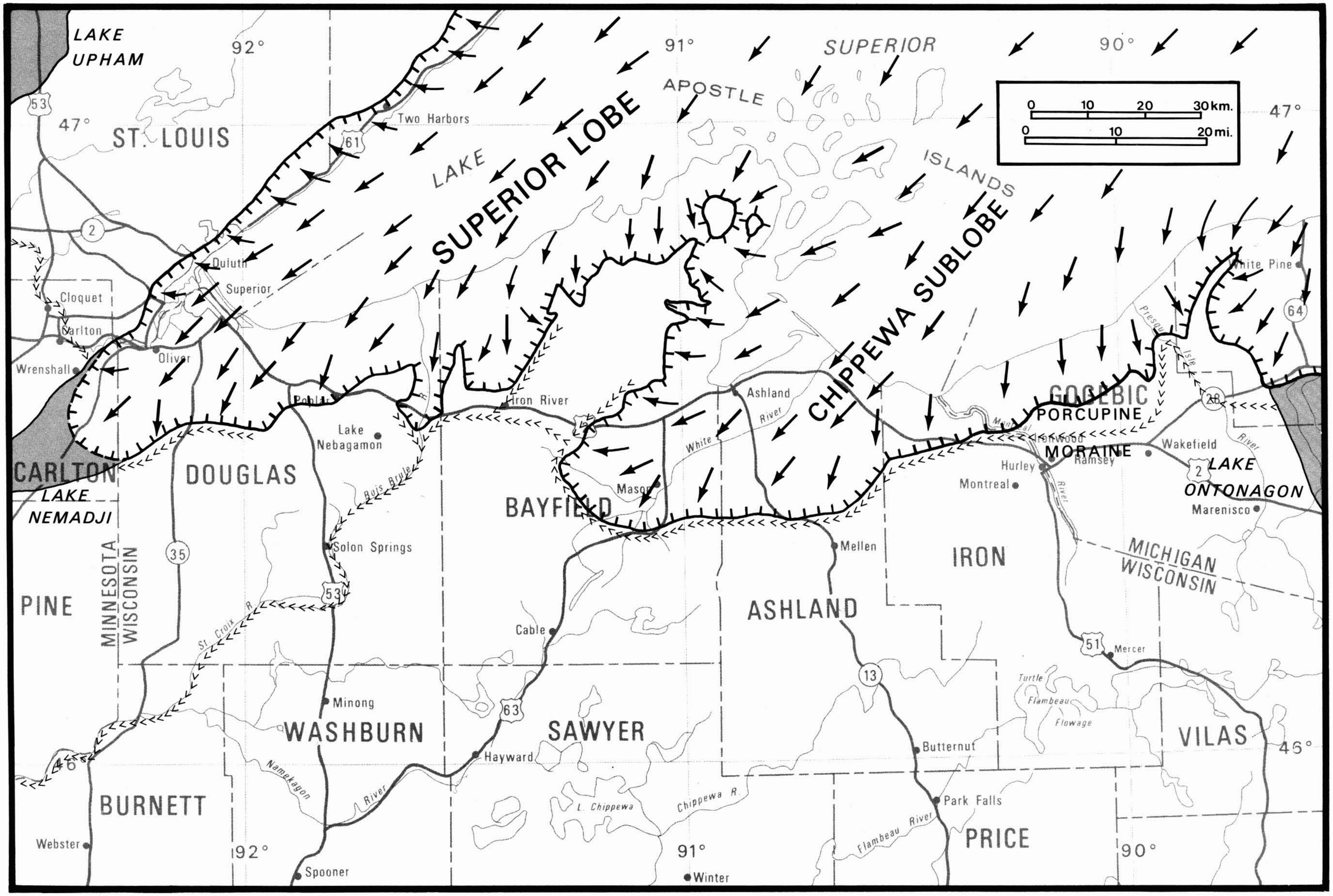

FIGURE 30. Porcupine Advance, about 11,000 B.P., when till of Hanson Creek Member was deposited. Symbols explained in caption of figure 23.

deposit the clay till of the Hanson Creek Member (fig. 30). The glacier rose above the highest level of Lake Superior near Gurney, in the eastern part of the Superior map area, and formed the Porcupine moraine north of Ironwood and Bessemer in Michigan (Martin, 1957).

To the east (fig. 22), the Porcupine ice margin has been correlated with the Watton margin of northern Michigan (Warren Peterson, conversation, 1982). The Porcupine moraine north of Ironwood is known to be contemporaneous with the Watton moraine because the pro-Watton delta in Lake Ontonagon formed when the lake spilled westward through the proglacial channel north of Ironwood.

On the northwest side of the Chippewa Sublobe, the ice margin probably rose slightly above the highest level of Lake Superior near the northeast end of the Bayfield Peninsula (fig. 30). On the northwest side of the Superior Lobe, the ice margin probably rose above the highest level of the lake near Two Harbors (fig. 30); the deepest part of the Superior Basin is to the northwest of the midline, and, as a result, the northwest margin of the Superior lobe was probably somewhat higher than its southern margin.

The Porcupine Advance has not been dated, but it probably occurred around 11,000 B.P.

Lake View Advance

The Superior Lobe then wasted back far enough to open the eastern outlets of Lake Agassiz between about 10,800 and 9900 B.P. (Clayton and Moran, 1982). During this time, Lake Superior drained southeastward to Lake Huron. The Superior Lobe then readvanced again about 10,000 or 9900 B.P. to the Marquette margin in Michigan and to an ice margin here named the Lake View margin, just north of Saxon, Wisconsin (fig. 31; Hughes, 1978; Clayton and Moran, 1982; Clayton, 1982). Two dates from the Superior map area are 9730 ± 140 B.P. (I-5082) and 10,100 ± 100 B.P. (WIS-409), from wood in reddish clay till 5 km west of Saxon (Black, 1976). In addition, this advance of the Superior Lobe, which closed the eastern outlet of lake Agassiz, is known to have occurred about 9900 B.P. based on several radiocarbon dates from wood buried in lake sediment in North Dakota. The Lake View moraine has tentatively been correlated with the Sixmile and Marquette moraines of Michigan by Warren Peterson (conversation, 1982). A direct correlation has never been made, but the till of the Lake View moraine (at the Lake View graveyard north of Saxon) presumably correlates with the till of the Douglas Member west of the Bayfield Peninsula. Lake Agassiz again drained eastward into Lake Superior when the Superior Lobe wasted from the western Superior basin about 9600 or 9500 B.P. (Clayton and Moran, 1982).

Ice-marginal lakes

As the Superior Lobe began to wane for the last time, proglacial lakes came into existence around its southern margin (Farrand, 1960). Lake Nemadji formed southwest of Duluth (figs. 30 and 31). Offshore sediment (map unit **ou** on plate 1) was deposited above an elevation of about 240 m, probably beyond the western edge of the Douglas till, deposited during the Lake View Advance. Lake Ontonagon in northern Michigan (fig. 30) spilled westward, through the channel at the south edge of the Porcupine moraine into an early version of Lake Ashland. From Lake Ashland, melt water flowed westward to Lake Brule, possibly across stagnant glacial ice on the south end of the Bayfield Peninsula (Lost Lake surface; map unit **sua** on plate 1), but more likely around the north end of the Bayfield Peninsula (fig. 30). As the ice margin retreated, these lakes coalesced to form Lake Superior, whose subsequent history is recorded in the beaches around the margin of the Superior basin. During the Lake View Advance, Lakes Nemadji, Brule, and Ashland stood at or near the Duluth level (fig. 32), but earlier, perhaps during the Porcupine Advance and at the end of the Lake Ruth Advance, Lake Nemadji at least, stood at the epi-Duluth level (fig. 32).

Age of St. Croix spillway

In the previous sections, the basic form of the St. Croix spillway, as seen today, was assumed to have been the result of long-continued flow from Lake Superior whenever it was at the Duluth level. That is, the St. Croix spillway was cut by steady discharge of melt water from the Superior Lobe. However, this discharge may have been inadequate to cut such a large channel, because the Minnesota River spillway carried only about twice as much water (Matsch, 1983), but it was derived from an ice margin roughly ten times as long and a proglacial basin with roughly ten times the area, and in addition it carried catastrophic floods from suddenly draining proglacial lakes (Kehew, 1982).

If the St. Croix spillway is in fact too large to have been cut by melt water from the Superior Lobe, additional sources of water must be sought:

(1) Clayton (1982, 1983) has suggested the possibility that the St. Croix spillway was cut by the catastrophic draining of proglacial lakes in Saskatchewan and North Dakota, which discharged through the Sheyenne Spillway to Lake Agassiz, then through the McIntosh spillway to Lake Koochiching in northern Minnesota, through the Prairie spillway to Lake Upham-Aitkin in northeastern Minnesota, and through the St. Louis spillway to Lake Superior. However, Hobbs (1983) concluded that the Superior Lobe probably filled the Superior basin at that time.

(2) Lakes along the northwest margin of the Superior Lobe, such as Lake Kaministikwia, west of Thunder Bay, Ontario, (Teller and Thorleifson, 1983, fig. 7) might have suddenly drained when their ice dams were breached, causing large volumes of water to drain southwestward into Lake Superior in a short period of time. However, evidence for such floods is unknown.

(3) The level of Lake Ontonagon, in northwestern Michigan, dropped a total of 60 m from the level of the Sidnaw delta to the Duluth level of Lake Superior when the ice wasted back from the Watton moraine (Peterson, 1982), at the end of the Porcupine Advance (fig. 30). The water level may have dropped suddenly when the ice dam was breached, producing a flood big enough to have cut the St.

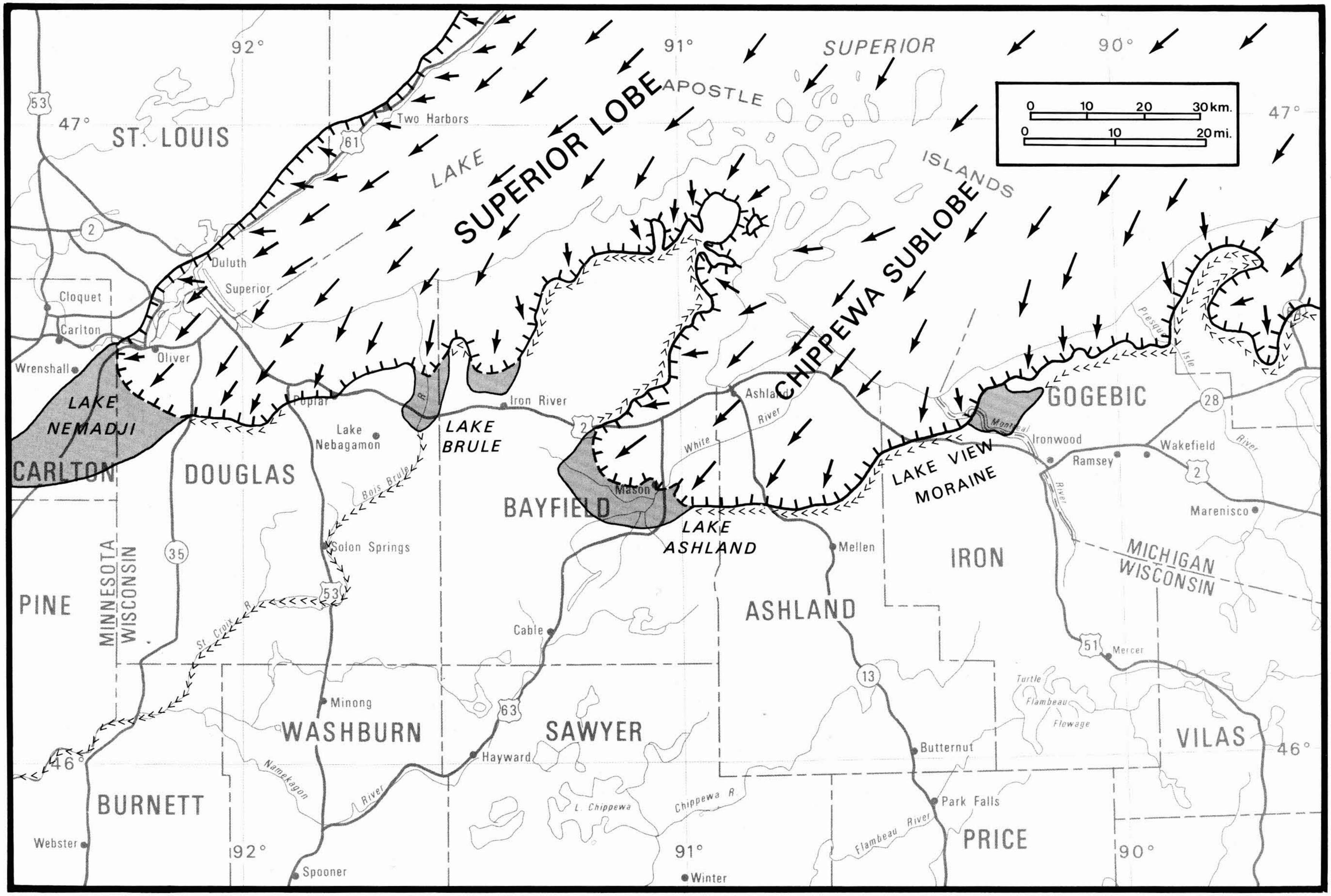

FIGURE 31. Lake View Advance, between 10,000 B.P. and about 9500 B.P., when till of Douglas Member was deposited. Symbols explained in caption of figure 23.

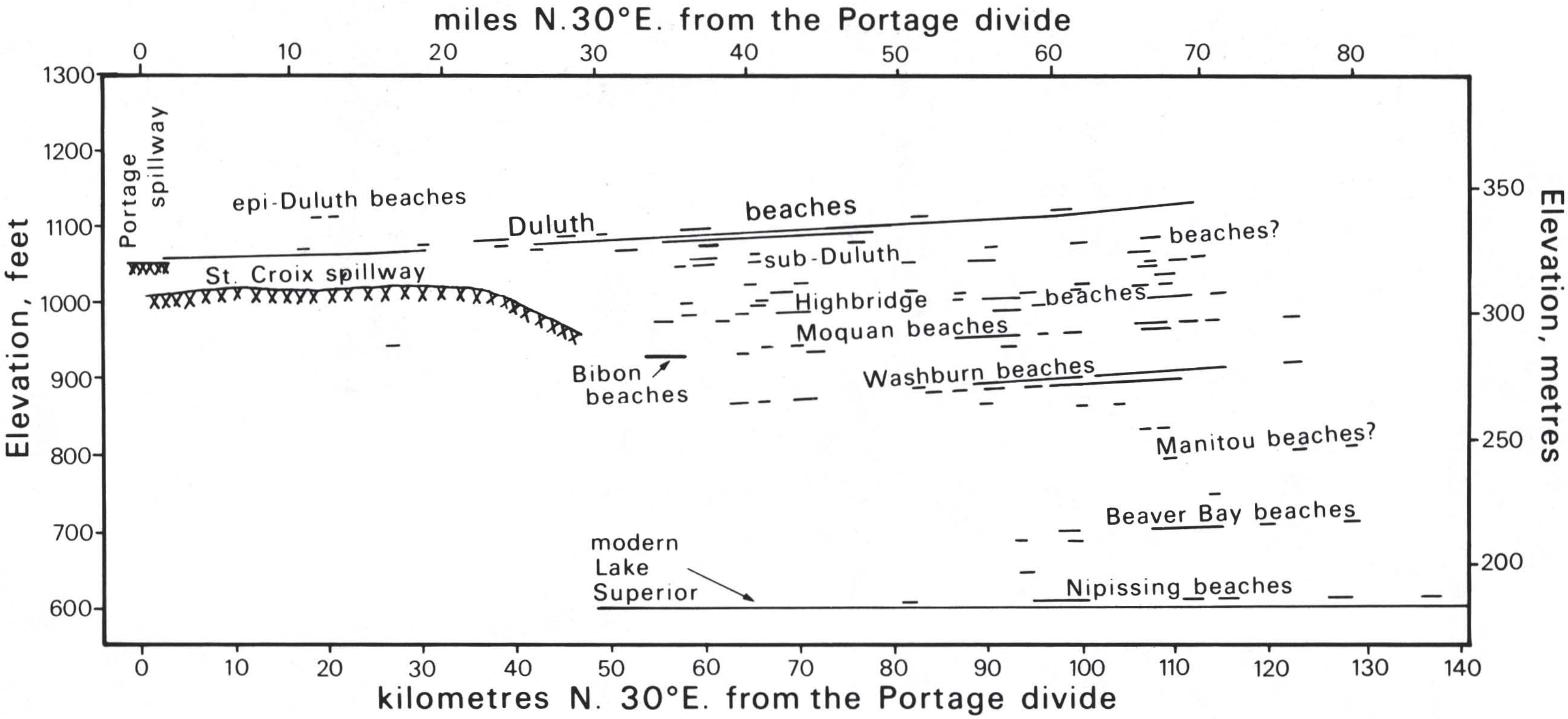

FIGURE 32. Profile of Lake Superior beaches.

Croix spillway. The ice-marginal spillway 1 km southeast of Saxon, in northern Iron County, was cut by discharge from Lake Ontonagon when the glacier wasted back from the Porcupine moraine. This channel is about 1 km wide and several metres deep. The Saxon spillway is somewhat smaller than the St. Croix spillway, but the St. Croix spillway was augmented by discharge from the rest of the Superior Lobe.

If a large flood is required to explain the large size of the St. Croix spillway and if that flood was from Lake Ontonagon, which seems most likely, the basic form of the St. Croix spillway was cut at the end of the Porcupine advance, about 11,000 B.P.

Lake Superior events

The history of Lake Superior beaches has been studied by Farrand (1960, 1969). Since that time, improved topographic maps have become available, and some modifications of his history can be made. Figure 32 shows the elevations of the beaches plotted along a line N. 30° E. from the southwest end of the lake basin, parallel to the direction of glacial rebound. An attempt has been made to choose the elevation of the lake at the time the beach formed (fig. 33). The elevations presented here average about 9 m higher than those determined by Farrand. The higher beaches rise in elevation to the northeast at a rate of about 0.2 m/km, because of glacial rebound. Only those beaches that are conspicuous on air photos are plotted (others were mapped by Cahow, 1971), and their elevation was determined from topographic maps. In areas with 7.5-minute quadrangles, the elevations shown for most beaches are generally within 2 to 3 m of the true elevations, and in areas with 15-minute quadrangles, they are probably plotted within 3 to 6 m of their true elevations. The section of the profile between mile 35 and mile 50 on the west side of the Bayfield Peninsula is covered by 15-minute quadrangles; all the rest of the area, including the section of the profile between mile 35 and mile 50 on the east side of the Bayfield Peninsula, is covered by 7.5-minute quadrangles.

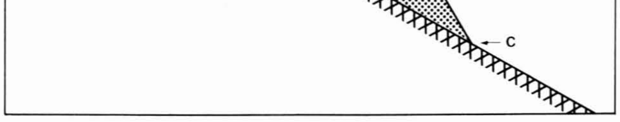

FIGURE 33. Profile showing elevation (a) used in figure 32, which was picked to represent lake level at the time the beach was formed, not the outer edge of the wave-built terrace (b) or the base of the wave-built terrace (c).

The best developed of the high-level beaches of Lake Superior is the Duluth beach. On the north shore, it occurs along the Skyline Parkway in the city of Duluth, at an elevation of 327 to 330 m. It can be traced along the south shore almost continuously from Carlton County, Minnesota, to Gogebic County, Michigan (fig. 32) and beyond.

The identification of a particular beach and the assigning of a name like "Duluth" to it is frequently difficult, for several reasons. Many of the beaches are poorly developed, and segments that can be identified in a reconnaissance survey may be so isolated from each other that correlation is uncertain. Others, such as the Duluth beach, are multiple, with several beaches occurring close in elevation to each other. The identity of the main Duluth beaches seems to be clear, but it is unclear how many of the slightly higher and lower beaches should also be referred to as "Duluth beaches."

An added confusion is the variety of criteria that have been used to name beaches. For lakes with horizontal beaches, no names at all may be needed because elevation alone is adequate. For proglacial lakes with tilted beaches, elevation is variable, and the beaches may be named, with each name defined by its elevation in one area. Farrand (1960, p. 19) tied the name "Duluth" to the outlets of the lake: all beaches formed when water was discharging through the Moose Lake Spillway, the St. Croix spillway, or both are called "Duluth". In contrast, Leverett (1929, p. 57) thought only the St. Croix spillway was operating at this stage, and Wright, Mattson, and Thomas (1970, fig. 29) used the name "Duluth" for the first strandline formed after the Moose Lake (Portage) spillway was abandoned. (However, neither outlet could have been in use when the lake was at Wright, Mattson, and Thomas' (1970) "Duluth strandline" because it is 15 m below what is here considered to be the Duluth beach, which they considered to be the "Nemadji strandline," and therefore lower than the St. Croix outlet.) In addition, a beach might be named for the period of time during which it was formed; that is, the Duluth beach is that beach formed during the Duluth Event.

Beach names tied to stage may be confusing in areas of differential rebound if a lake fluctuates up and down rather than continuously drops; more than one beach might form at a single stage, and a single beach might cross earlier beaches formed at more than one stage. ("Stage" is used here in the hydrologic sense to mean lake elevation.) Beach names tied to outlets can be confusing for several reasons. (a) The elevation of the bottom of the outlet may be unknown because of recent valley- bottom sedimentation. (b) The relationship between the elevation of the outlet sill and the elevation of the lake may be unclear if the sill is some distance downstream, because the gradient of the outlet river between the lake and the sill may be unknown. (c) Lake stage is equivalent to river stage at the outlet, but the relation of river stage to the elevation of the channel bottom is unclear if the river depth is unknown. Beach names here are tied to neither stage nor outlet but to the event that formed them.

Even though the main Duluth beach is the best developed of the high beaches, no one, to my knowledge, has identified the sill that stabilized the lake at that level. The beach is at an elevation of about 330 m at the head of the St. Croix spillway. The divide between the present St. Croix and Bois Brule Rivers in the St. Croix spillway is a little above 312 m, but the thickness of modern sediment here is unknown. In any case, because of postglacial rebound and because of the gradient on the surface of the river, the effective sill must have been farther down stream where the river was shallowest, probably at the head of the rock- floored reach below St. Croix Flowage (about mile 75 in fig. 25). The spillway is about 1 km wide and has a meander length of about 15 km; therefore, it had a discharge of roughly 20,000 m^3/s, was roughly 12 m deep and has a gradient of roughly 0.1 m/km (Leopold, Wolman, and Miller, 1964, figs. 7-21, 7-23, and 7-41). The rock sill at mile 75 is at an elevation of about 305 m, nearly 45 km downstream from the lake. Using a gradient of 0.1 m/km, the river surface was nearly 5 m below lake level at that point. Rebound accounts for another 6 m (fig. 25). Sill elevation, plus water depth, plus elevation differences due to water gradient and rebound give 328 m, nearly the elevation of the Duluth beach. Admittedly this is only a rough calculation, but it seems obvious that lake level was stabilized at the Duluth beach by rock in the bottom of the St. Croix spillway some distance south of the present divide.

If the melt water emptying into Lake Superior fluctuated enough to cause the river to fluctuate between 10,000 m^3/s and 30,000 m^3/s, for example, the river depth would have fluctuated about 9 m (Leopold, Wolman, and Miller, 1964, fig. 7-21), and the lake level would have fluctuated 9 m. Therefore, fluctuation in the supply of melt water to the lake, as well as glacial rebound, can explain why the Duluth beaches are multiple. This also suggests that great concern about the precise elevation of the beaches is unwarranted.

Farrand (1960, p. 20) determined that the divide in the Moose Lake (Portage) spillway is at 325 m. This elevation is above the main Duluth beach (fig. 32), indicating that the Moose Lake spillway was dry when the main Duluth beach formed. However, Farrand (1960, p. 19) suggested that it was in use then; his beach correlations and elevations were somewhat different from those used here (fig. 32). Wright, Mattson, and Thomas (1970, fig. 9) determined the divide to be at 320 m. This elevation is less than 3 m below the main Duluth beach (which they identified as the "Lake Nemadji strandline"). It seems likely that the Moose Lake spillway would have been deeper than 3 m and was therefore probably cut before the main Duluth beach formed. Leverett (1929, p. 56) identified a spillway from Lake Ashland to Lake Brule near Pike Lake in sec. 21, T. 47 N., R. 8 W. between an elevation of 338 and 340 m, but the present topographic map (Iron Lake 15-minute quadrangle, 1961) shows no divide elevations below 341 m (1120 ft), and the Lost Lake surface (fig. 25), slightly above that level, is probably a proglacial stream surface rather than the bottom of a spillway, because no channel form is present.

Farrand (1960, p. 26-27) identified a sub-Duluth beach about 15 m below the main Duluth beaches. Not enough beach segments were recognized in this study to confirm its existence (fig. 32).

Farrand (1960, p. 27-28) identified the Highbridge beach about 30 m below the main Duluth beaches. The present topographic map (Mellen 15-minute quadrangle, 1967), places the Highbridge beach at Highbridge at about 299 m, not at 291 m as stated by Farrand, in sec. 9, T. 45 N., R. 3 W.

Farrand's (1960, p. 28-29) Moquah beach occurs about 15 m below the Highbridge beach. Farrand (1960, p. 135) identified the beach at about this level around Bibon Marsh (fig. 32) in T. 45 N., Rs. 5 and 6 W., and T. 46 N., R. 6 W., as a Superior beach. However, it probably formed much later, in a postglacial lake, which was drained and converted into a marsh by the down cutting of the White River (Cahow, 1971, p. 50).

The most prominent of the middle beaches are the Washburn beaches (fig. 32). Near Washburn, in the north part of sec. 32, T. 49 N., R. 5 W., they are at an elevation of about 268 to 272 m, about 9 m above the elevation given by Farrand (1960, p. 139).

The Manitou and Beaver Bay beaches (fig. 32) are based on deposits in Minnesota (Farrand, 1960, p. 30-35). Most of the segments at the Beaver Bay beach indicated in figure 32 are around the end of the Bayfield Peninsula, an area not visited by Farrand; they are about 9 m above the projected elevation of his main Beaver Bay beach (Farrand, 1960, plate II).

The sub-Duluth, Highbridge, Moquah, Washburn, Manitou, and Beaver Bay beaches formed during the wastage of the Superior Lobe from the Huron Mountains in Michigan (Drexler, 1981). Water stood at the Duluth level for the last time later than about 9900 B.P. because the Duluth beach is on the Lake View till, which was deposited later than about 9900 B.P. The Beaver Bay beach formed before about 9380 ± 150 B.P. (radiocarbon date GSC- 287), when the lowest Minong beach formed (Zoltai, 1967) in Ontario. The Minong beach is below the present level of Lake Superior in Wisconsin but is above present lake level in Ontario. The age of the Minong beach is confirmed by a date of 9200 ± 600 B.P. (W-1057) from wood in a beach of Lake Agassiz (northwestern Minnesota) formed as it began to drain into Lake Superior, which Zoltai (1965) determined then stood at the Minong level. This leaves no more than a few hundred years, between about 9600 B.P. (if 300 years is alloted for the deposition of the Lake View till) and, at the latest, 9200 B.P. for the formation of the Minong beach. Much of this time is required for the well- developed Duluth beach, leaving only a few tens of years for each of the other beaches.

Beaches about 3 m above modern Lake Superior (fig. 32) have been identified as the Nipissing beach by Farrand (1960, p. 49- 56, plate II). This beach is tilted less steeply than the earlier beaches. It formed in middle Holocene time.

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Cover map: Airport Advance from figure 27, page 29.