UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
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Prepared and Published with the Support of
THE AITKIN COUNTY BOARD OF COMMISSIONERS,
THE MINNESOTA DEPARTMENT OF NATURAL RESOURCES, AND
THE MINNESOTA ENVIRONMENT AND NATURAL RESOURCES TRUST FUND
AS RECOMMENDED BY THE LEGISLATIVE-CITIZEN COMMISSION ON MINNESOTA RESOURCES

COUNTY ATLAS SERIES
ATLAS C-52, PART A
Aitkin County
Plate 3—Surficial Geology

SURFICIAL GEOLOGY

By

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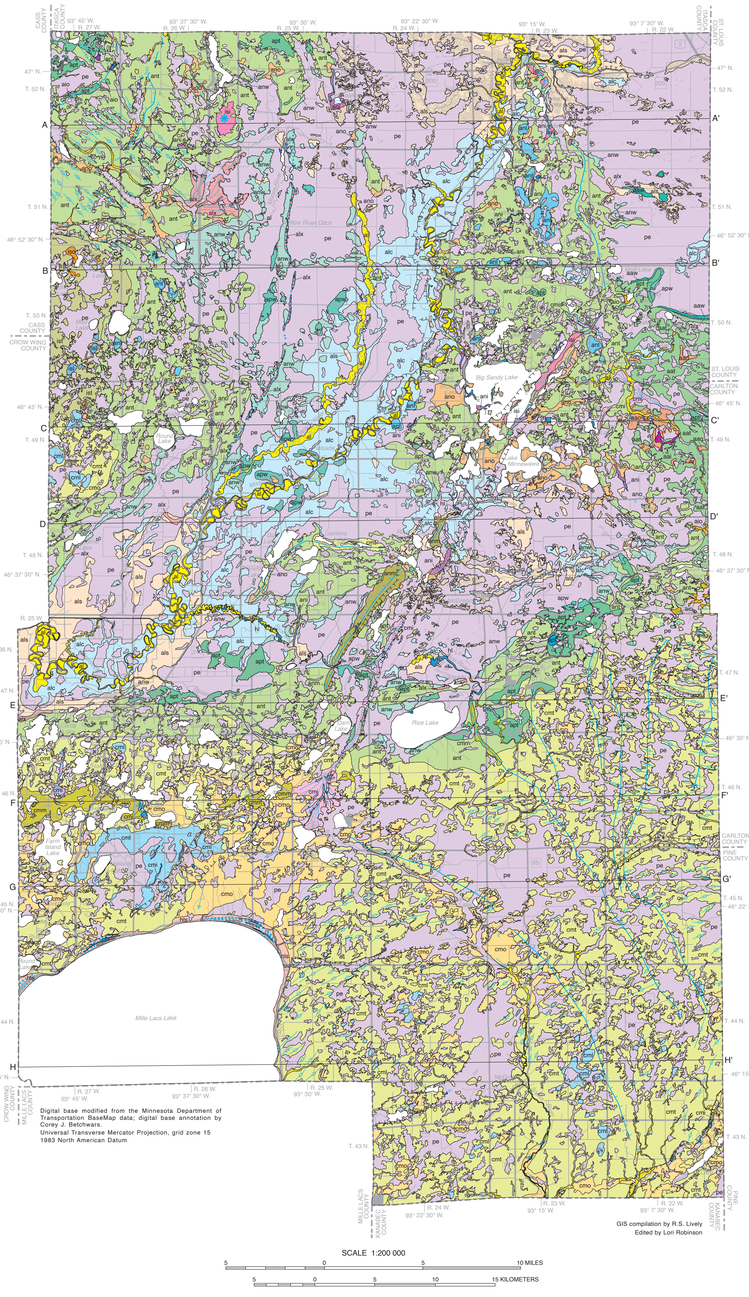
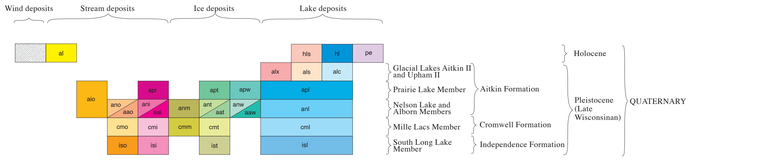
2022



LOCATION DIAGRAM

CORRELATION OF MAP UNITS



MAP SYMBOLS

Geologic contact—Approximately located.

Drumlin—A streamlined hill or ridge composed typically of glacial till; in places includes sand and gravel. The length of the symbol is approximately equivalent to drumlin length. The feature formed at the base of moving ice and is commonly composed of subglacial sediment, but may be partially covered by supraglacial sediment. The landscape in the southeast portion of the county contains drumlins trending west and southwest deposited by ice of the Automba phase of the Superior lobe that are composed primarily of sediment of unit cmt (Figs. 2, 4D). Drumlins in the northwest corner of the county were formed by St. Louis-sublobe ice, trend to the southeast, and are composed primarily of Nelson Lake Member sediment (unit ant), but may also contain underlying material of the Brained-sublobe South Long Lake Member (unit ist).

Esker—A sinuous, narrow ridge of predominantly sand and gravel; interpreted to have been deposited in an ice-tunnel or ice-walled channel by a glacial meltwater stream. Fluvial sediment may be mantled by a thin layer of till. Arrowheads point in the direction of meltwater flow and sediment transport. In the northern two-thirds of the county, eskers assigned to the Mille Lacs Member (unit cmt) are generally covered by sediment of the younger St. Louis-sublobe Nelson Lake Member (unit ant).

Kame—A conical hill composed predominantly of sand and gravel. Interpreted to be a deposit within the confines of supporting ice. When the ice melted, the sand and gravel formed a mound on the surrounding topography. Collapsed bedding is common. See unit description ist.

General flow direction of a meltwater stream—Occurs in sand and gravel deposits. The arrow points in the direction that glacial meltwater last flowed as it deposited outwash.

Meltwater fan deposit—Consists of sand and gravel; interpreted to be an esker-sourced alluvial fan at an ice margin.

Stream-cut scarp—Marks the approximate boundary of a former glacial meltwater channel (dashed where discontinuous). Where paired, scarps bound stream-scoured areas. The scarp line is drawn near the top of the slope, with the ticks pointing down slope. Till deposits down slope of scarps are fluvially scoured and are mantled in places by sand and gravel too thin and patchy to map separately. Boundaries of alluvium and outwash are commonly at scarps and are not shown by a scarp symbol on the map.

Recessional ice margin—Marks an approximate ice margin as ice retreated. Ticks point in the up-ice direction.

Broad, irregular trough—Interpreted to be a buried subglacial drainage channel (tunnel valley) or a preexisting drainage valley that was subsequently filled by sediment. Ticks point down slope. The Brained sublobe appears to have formed a long, wide, southeast-trending tunnel valley extending from the glacial Lake Upham basin to at least the present-day Mille Lacs Lake area. The modern chain of lakes along this former valley attests to stagnating ice that may have been buried by later deposits. Includes eskers and recessional moraines of the Superior lobe and St. Louis sublobe that later formed in the tunnel valley low.

Transverse ridge—A series of discontinuous ridges 1 mile (1.6 kilometers) southwest of Moose Lake composed of ice thrusted local material (Fig. 2). Probably formed while ice of the St. Louis sublobe that deposited the Nelson Lake Member advanced to the southeast over the area.

Glacial lake shoreline—A linear sand or sand and gravel bench (strandline) formed by waves along the shoreline of glacial Lakes Aitkin II and Upham II during their maximum extent as well as later, lower lake levels. Also includes shorelines of a proglacial lake that formed in front of Superior-lobe ice as it retreated to the east as Mille Lacs Lake formed. These beach ridges mark the shoreline when water was at a higher elevation than the present lake.

Bedrock outcrop—Undifferentiated Proterozoic bedrock exposed at the surface. See Plate 2, *Bedrock Geology*.

Tribal land—In accordance with the wishes of the tribal government, the lands of the Mille Lacs Band of Ojibwe are not included in this publication.

INTRODUCTION

This surficial geologic map explains the origin and shows the distribution of sediment or bedrock expected to be encountered at the land surface beneath the topsoil. These glacial and post-glacial deposits range in thickness from 0 to more than 675 feet (206 meters; see Plate 6, *Depth to Bedrock*). Figure 1 is a simplified materials map of surficial geologic units grouped into three types based on their textural composition: sand and gravel, glacial till (diamicton), and fine-grained lake sediment. For permeability discussion of the material types, see the introduction to Plate 5, *Sand-Distribution Model*.

The geologic interpretation of landforms was based on 3-foot (1-meter) resolution lidar elevation imagery (available from the Minnesota Department of Natural Resources, <http://www.mngeo.state.mn.us/chouse/elevation/lidar.html>) and on a 30-meter digital elevation model (DEM) of the area, which includes bathymetric data for some of the larger lakes (Fig. 2). Unit contact lines, descriptions, and map symbols were determined from observation, description, and sampling by Minnesota Geological Survey (MGS) staff during the 2016, 2017, and 2018 field seasons. This included approximately 400 natural, gravel pit, and construction exposures; 170 Giddings probe auger borings completed by the MGS, which commonly ranged from 10 to 30 feet (3 to 9 meters) deep; and rotary-sonic core from seven MGS-drilled holes ranging from 67 to 280 feet (20 to 85 meters) deep (see Plate 4, *Quaternary Stratigraphy*). Additional description and sampling from three Minnesota Department of Natural Resources (DNR) rotary-sonic holes ranging from 116 to 276 feet (35 to 84 meters; Martin and others, 1989), and 12 rotary-sonic holes ranging from 110 to 249 feet (34 to 76 meters) completed by Kennecott Exploration Company were also used. These sites produced approximately 800 surface samples that were analyzed for texture and composition. Data from bridge boring logs (Minnesota Department of Transportation, 2019), well logs included in the County Well Index (CWI), Waste Management Board (1982) drill holes with split spoon samples, and correlations with soil series map units (Nyberg, 1979; Natural Resources Conservation Service, 2016) were also used. Data from previous mapping (see Index to Previous Mapping) of the county contain approximately 500 site observations and descriptions, including analysis of about 250 samples (Hobbs, 1981) and an aggregate resources map produced by the DNR (Jennings and Kostka, 2014). Previous mapping data in adjacent counties were also used and include MGS projects in Pine (Patterson and Knaeble, 2001), Crow Wing (Knaeble and others, 2004), Itasca (Meyer and others, 2005), Carlton (Knaeble and Hobbs, 2009b), Kanabec (Dengler, 2016b), Cass (Lusardi and Nguyen, 2018), and St. Louis (Wagner and others, 2022) Counties; as well as DNR aggregate mapping in Mille Lacs (Arends, 2008), Carlton (Friedrich, 2009), and Kanabec (Friedrich, 2012) Counties. Using all of the above, the unit contact lines and map symbols were drawn using geographic information system (GIS) software on 1:24,000-scale U.S. Geological Survey topographic maps. Most of the above data are stored at the MGS in an internal database, the Quaternary Data Index (QDI).

All referenced dates are in calibrated years before present and capitalized formation and member names are formal lithostratigraphic units (Johnson and others, 2016), which have been recognized under the North American Stratigraphic Code guidelines (North American Commission on Stratigraphic Nomenclature, 2005). Uncapitalized formation and member names are informally recognized lithostratigraphic units.

GLACIAL HISTORY

Aitkin County was glaciated many times in the last 2.6 million years during the Pleistocene Epoch. Ice lobes emanating from the Laurentide ice sheet advanced into the study area from the northeast, northwest, and east. Evidence of early ice advances (pre-Wisconsinan glaciation) into the mapping area is rarely found at the land surface. Evidence is evident in rotary-sonic drill core (see Plate 4, Introduction) and in previous scientific and exploration drilling in the region (Winter and others, 1973), and in adjacent Pine (Knaeble and others, 2001), Crow Wing (Knaeble and Meyer, 2004), Carlton (Knaeble and Hobbs, 2009a), Kanabec (Dengler, 2016a), Cass (Lusardi and others, 2018), and St. Louis (McDonald and others, 2022) Counties. In Aitkin County, many older deposits were partially or completely eroded by subsequent glaciations.

Late Wisconsinan

Three ice lobes affected the region during late Wisconsinan time (Fig. 3) and their sediment record is more completely preserved than those of earlier ice advances. Each ice lobe deposited sediment containing a unique assemblage of rock fragments eroded from bedrock and sediment in an up-ice source area. This general source area is referred to as the ice lobe's provenance (Fig. 3; Table 1).

The first glacier to enter the region during late Wisconsinan time was the northeast-sourced Rainy lobe (Rainy provenance; Fig. 3), which separated into two ice streams: the Wadena lobe flowing north of the Mesabi Iron Range, and a proto-Brainerd sublobe flowing south of the iron range (Fig. 4A). Ice advanced through Minnesota (Wright, 1972; Meyer, 1986; Mooers, 1988; Knaeble and Meyer, 2007), eventually retreated, and then readvanced to form the northern portion of the St. Croix moraine (Fig. 4B) in Morrison (Lusardi and Adams, 2014) and Cass (Lusardi and Nguyen, 2018) Counties. This readvance was called the Brainerd lobe by Schneider (1961) and later called the Brainerd sublobe (Johnson and others, 2016), as it is referred to here. Its deposits in central Minnesota were informally named the South Long Lake member (Knaeble and Meyer, 2004) and later formally named the South Long Lake Member of the Independence Formation (Johnson and others, 2016; see unit descriptions), and are at the surface only in a few areas, mostly in western Aitkin County near the Cass/Crow Wing County border, where they have not been covered by younger glacial deposits. In the northern three-quarters of Aitkin County, these deposits are in the subsurface, where they are widespread and generally thick (see Plate 4). Their precise extent is uncertain because they are almost completely buried by younger glacial sediment.

At about the same time as Rainy-lobe ice was active in the area, the Superior lobe entered the region from the northeast (Superior provenance) following the Lake Superior basin (Wright, 1972). Its initial phase, called the Emerald phase (Johnson, 1986, 2000), deposited materials as far as the southern edge of the Twin Cities and may have been active while Rainy-lobe ice formed the Alexandria moraine (Fig. 4A). Superior-lobe ice eventually retreated and readvanced during the St. Croix phase, when it was confluent with Brained-sublobe ice to the north. This advance formed the southern portion of the St. Croix moraine while at its maximum extent (Fig. 4B; Wright, 1972; Mooers, 1988; Knaeble and Meyer, 2007). These two initial Superior-lobe ice advances deposited sediment across the southern third of Aitkin County, all of which were subsequently buried by younger deposits of the next phase. The Superior lobe then retreated into the Lake Superior basin east of Carlton County (Fig. 4C). The ice was fronted by small proglacial lakes (Hobbs, 2002) and as ice readvanced during the Automba phase (Wright, 1972), it incorporated fine-grained, proglacial lake sediment and eventually overlaid the Automba drumlin field in eastern Carlton and western Aitkin Counties (Fig. 2; Knaeble and Hobbs, 2009b).

Because the formerly confluent Brained-sublobe ice to the north had also retreated and was slower to readvance, the Automba-phase ice was able to move further west and north into the glacial Lake Aitkin/Upham basins and surrounding regions than St. Croix-phase ice (Knaeble and others, 2005; Knaeble and Hobbs, 2009b), allowing red-brown till and outwash to be deposited over much of the northern half of the county (Fig. 4D). However, most of these deposits were later covered by glacial lake sediment and/or St. Louis-sublobe materials and are only exposed at the surface in isolated areas. The Automba-phase margin in the central portion of the county is constrained (Fig. 4D, dashed ice-margin lines), but appears to have advanced as far south as the northern edge of the Twin Cities (Meyer, 2013; Johnson and others, 2016; Berthold, 2018). When the terminal Mille Lacs moraine (Wright, 1972; Mooers, 1988; Knaeble and others, 2004) was deposited, ice appears to have formed two vaguely separated lobes: one to the north around the west end of the future glacial Lake Aitkin basin, and another to the south around the west side of modern-day Mille Lacs Lake (Figs. 2, 4D). Between the two, a discontinuous interlobate moraine was formed (see unit cmw). Additional vague recessional ice margins are detectable in the eastern half of the county (see **recessional ice margin** in Map Symbols) because ice retreated eastward out of the county into the Lake Superior basin.

As Superior-lobe Automba-phase ice retreated east, its meltwater, along with meltwater draining from Brainerd-sublobe ice that was retreating to the northeast and meltwater from the St. Louis sublobe that was advancing from the northwest, contributed to the formation of proglacial lakes in the basins between the ice lobes that grew to become glacial Lake Aitkin I and glacial Lake Upham I (Figs. 4E, F; Wright and Watts, 1969). Interbedded red, brown, and gray, massive and laminated, generally fine-grained sediment was deposited in these lakes. The exact length of time these lakes existed is unclear, but it appears that glacial Lake Aitkin I existed for more than 350 years based on a count of varve-like laminations in a 25-foot (7.6-meter) interval within a section of glacial Lake Aitkin I drill core, near the center of the lake basin (see Plate 4, Fig. 5). At this site, approximately 40 percent of the laminations were red and 60 percent gray, suggesting that there was significant sediment input from the Superior lobe as well as possibly both the Brainerd and St. Louis sublobes.

Ice of the St. Louis sublobe, an offshoot of the Des Moines and Koochiching lobes (Martin and others, 1989; Meyer and others, 2005), advanced from the northwest into glacial Lakes Aitkin I and Upham I. As it crossed the lake basins, it incorporated the underlying lake sediment and deposited sediment on the uplands around the basins (Fig. 4G). Brown till deposits of the St. Louis sublobe to the west in and around the glacial Lake Aitkin I basin were noted by Winter (1971), informally called Nelson Lake till (Knaeble and Meyer, 2004), and later formally named the Nelson Lake Member of the Aitkin Formation (Johnson and others, 2016). The till color grades from brown to reddish-brown going east across the county. In contrast, St. Louis-sublobe deposits of red till to the east in and around the glacial Lake Upham I basin have been named the Alborn Member of the Aitkin Formation (Baker, 1964; Winter, 1971; Wright, 1972; Knaeble and Hobbs, 2009b; Johnson and others, 2016). The gradation in color from west to east has been attributed to the incorporation of underlying red lake sediment, some from glacial Lake Aitkin I and even more from glacial Lake Upham I (Baker, 1964; Wright, 1972; see Plate 4, Fig. 5, rotary-sonic drill hole AKR-2), as well as from Automba-phase till (see Aitkin Formation, Alborn Member, and unit aat; Knaeble and Hobbs, 2009b; Johnson and others, 2016).

The Prairie Lake Member, hypothesized here to be a slightly younger phase of the St. Louis sublobe (Baker, 1964; Knaeble and others, 2005; Knaeble and Hobbs, 2009b; Johnson and others, 2016), deposited yellow-brown, at least 5-foot (1.5-meter) thick till discontinuously and less extensively than the initial phase of the St. Louis sublobe (Fig. 4G). Where it overlies Alborn and Nelson Lake Member sediments, the Prairie Lake Member till can exhibit varying degrees of mixing with the older underlying fine-grained materials. As a result, it usually takes on a similar lithologic character intermediate to those underlying units, especially in the basal portion of the deposits (Knaeble and Hobbs, 2009b).

As St. Louis-sublobe ice retreated to the northwest, its meltwater ponded to form glacial Lakes Aitkin II and Upham II (Fig. 4H). Field evidence suggests that these younger glacial lakes were slightly less extensive than glacial Lakes Aitkin I and Upham I (Knaeble and others, 2005) and that their fine-grained sediments were predominantly brown and gray with a few thin, red layers (Knaeble and others, 2004). Meltwater streams from retreating ice deposited large sand deltas at the north and northwest ends of the lakes. The glacial lakes had a complex history that included drainage input from glacial Lakes Norwood (Hobbs, 1983; Lehr and Hobbs, 1992) and Koochiching (Martin and others, 1989; Meyer and others, 2005). In addition, they experienced significant lake-level fluctuation and multiple successive drainage outlets, all of which were a result of retreating Superior-lobe, Brainerd-sublobe, and St. Louis-sublobe ice, as well isostatic rebound as the landscape deglaciated (Hobbs, 1983; Marlow, 2004; Marlow and others, 2004). Eventually, glacial Lake Aitkin II drained into the Mississippi River to the west and glacial Lake Upham II drained into the St. Louis River in the southeast.

POSTGLACIAL HISTORY

During the post-glacial Holocene Epoch, organic-rich deposits (units pe, hl, his) accumulated in low-lying areas, including ice-block melt-out depressions and abandoned drainageways. Alluvial sediments (unit al) were deposited as glacial meltwater waned and modern drainage channels were established. After glacial Lakes Aitkin II and Upham II drained (Fig. 4I), eolian dunes (pattern) formed in places from reworking of sandy lake deposits (Marlow, 2004). Dune formation occurred soon after deglaciation, before extensive vegetation had developed, and subsequently during periods when climate warming and moisture conditions allowed sand and silt to remobilize (Marlow and others, 2004).

ACKNOWLEDGEMENTS

Thanks are extended to Brian Goldner of Kennecott Exploration Company, who provided access for logging and sampling glacial sediment from rotary-sonic core drilled near Tamarack; Rich Courtemanche from the Aitkin County Land Department, who assisted with drill site access; Randy Forster, John Menter, Richard Liljenquist, Ernest Darlow, and Allen Oesterich—landowners who allowed rotary-sonic drilling on their property; all field review participants who contributed comments and observations; and Rachel Lindgren and Wes Rutelonis, Minnesota Department of Natural Resources staff, who assisted in logging and collecting core for two rotary-sonic holes.

DESCRIPTION OF MAP UNITS

HOLOCENE AND LATE PLEISTOCENE

Peat and other organic sediment—Partially decomposed plant matter with organic-rich silt and marl (calcareous silt and clay); dark gray to black, soft, and compressible; deposited in bogs and swamps. Typically found in depressions formed from melting buried glacial ice, on lake sediments, particularly the fine-grained deposits (unit alc) that form the glacial Lakes Aitkin II and Upham II basins, in swales between drumlins, and along former glacial stream channels. Includes adjacent narrow deposits of alluvium along streams, beach deposits, and small bodies of open water.

Floodplain alluvium—A dark upper horizon, generally less than 6 feet (1.8 meters) thick, consisting of unbedded or thinly interbedded silt, clay, sand, and organic-rich material, including scattered wood and shell fragments, which may overlie sand, gravelly sand, or gravel. Carbonate is commonly leached. Interpreted to be overbank deposits accumulating on the modern flood plain. It includes many former channel cut-off depressions that have been filled with silty to clayey sediment, particularly along the Mississippi River and its tributaries in the glacial Lake Aitkin II basin, where meandering is prevalent. In places, contacts with other map units are scarps.

Modern sandy shoreline lake sediment—Predominantly fine- to coarse-grained sand with some gravel; forms beach deposits along the shoreline of post-glacial lakes. Shown mostly along the north and east sides of Mille Lacs Lake where Cromwell Formation outwash (unit cmw) was reworked to form significant beach deposits as the lake level dropped following ice retreat (see Map Symbols). In places includes multiple beach ridges, some of which may be preserved, annual, ice-push ridges.

Modern lake sediment—Silt, clay, and sand with some gravel, overlain in places by variable amounts of aquatic and terrestrial organic material. Sediment is typically coarser-grained (ranging from fine-grained sand to gravel) near the shoreline and finer-grained (silt and clay) in the topographically lower basins, where it may be laminated. The extent of exposure depends on the water level of the lake. Deposited in ponded water in post-glacial lakes.

Eolian sand—Very fine- to medium-grained sand with well-sorted, rounded sand grains. Locally includes silt. Forms dunes in places with local relief that rarely exceeds 15 feet (4.6 meters; Marlow, 2004). The pattern shows where dune landforms are identifiable, based on lidar topographic data, on top of glacial Lakes Aitkin II and Upham II sediment (unit alx). Where no pattern is shown, there may be a thin layer of windblown sand covering this unit and adjacent peat throughout the lake basins.

PLEISTOCENE

Late Wisconsinan

Aitkin Formation—Interpreted to be late Wisconsinan glacial sediment associated with the St. Louis sublobe, a two-phased, northwestern-sourced provenance (mixed Riding Mountain and Winnipeg provenances) ice advance, similar to the Des Moines lobe (Knaeble and Hobbs, 2009b; Johnson and others, 2016), deposited over roughly the northern half of the county (Fig. 4G). The formation consists of deposits from five members: the glacial Lakes Aitkin I and Upham I member (informal), the Nelson Lake Member, the Alborn Member, the Prairie Lake Member, and the glacial Lakes Aitkin II and Upham II member (informal). Sediment of the oldest member was deposited by glacial Lakes Aitkin I and Upham I when they occupied the basin and received meltwater from the eastward-retreating Superior lobe and Brainerd sublobe, as well as from St. Louis-sublobe ice as it approached from the northwest (Figs. 4E, F). As St. Louis-sublobe ice filled the lake basins and flowed onto the surrounding uplands, a western branch deposited brown to red-brown Nelson Lake Member till and an eastern branch deposited red-brown to red Alborn Member till (Fig. 4G). A later pulse of St. Louis-sublobe ice deposited yellow-brown to brown, shale-bearing till of the Prairie Lake Member discontinuously over older sediments in and around the lake basins (Fig. 4G). Finally, as ice retreated, glacial Lakes Aitkin II and Upham II formed in the basins (Fig. 4H). Intermixing of varying degrees at member contacts is common. Early interpretations hypothesized that all the till members were deposited by one ice advance (Baker, 1964; Wright, 1972). It was suggested that as St. Louis-sublobe ice advanced into glacial Lakes Aitkin I and Upham I, basal incorporation of the lake sediments into the ice gave the deposited sediments a stratified appearance, the upper unaffected layer being the yellow-brown Prairie Lake Member till with shale, and the lower layer—influenced by incorporated lake sediment—the brown Nelson Lake Member till or red Alborn Member till. In contrast, the interpretation put forth by subsequent mapping (Knaeble and Hobbs, 2009b) and on this map suggests that the Prairie Lake Member was a separate, later ice advance. Supporting evidence includes: stratigraphic position—as seen in MGS rotary-sonic drill core, cutting sets, Giddings auger borings, and outcrops; separate, lithologically distinct, adjacent terminal moraines (Culver moraines) in adjacent St. Louis County (Wagner and others, 2022); and the presence in Itasca County of three distinct depositional phases of Keewatin-sublobe material (the up-ice parent lobe of the St. Louis sublobe), where proglacial lake sediments separate deposits of each phase (Martin and others, 1989, 1991).

Glacial Lakes Aitkin II and Upham II member—As the final phase of St. Louis-sublobe ice wasted and retreated to the northwest, two large, interconnected glacial lakes, glacial Lake Aitkin II in the southwest and glacial Lake Upham II in the northeast, formed and deposited sediment in the basins they occupied (Fig. 4H).

Sand and gravel shoreline and deltaic deposits—Interbedded gray silt, brown fine- to coarse-grained sand, and fine- to coarse-grained gravel deposited locally along the shoreline of both glacial lakes (Marlow, 2004). Generally, the coarsest-grained material is located at the top of the shoreline. Depending on the location within the basin, the deposits record the maximum lake level, as well as later, lower lake levels. Generally occurs along the top of wave-washed till (units apw, anw, aaw). This unit is also used to represent deltaic deposits in the northwest portion of the county where meltwater in the Willow River channel flowed southeast and entered glacial Lake Aitkin II (Fig. 2).

Sand and silt near-shore or shallow-water deposits—Interbedded silt and fine- to medium-grained, well-sorted sand. May contain minor amounts of organic material, fine-grained gravel, and clayey silt in places. Carbonate leaching depth varies from 5 to 18 feet (1.5 to 5.5 meters). Present in the northeast part of the county, where meltwater streams flowing from the retreating St. Louis-sublobe ice deposited sand into the lake basins. Later, when the lakes drained, the sand was remobilized by the prevailing northwest wind to form dunes (eolian sand; Marlow, 2004).

Fine-grained silt and clay lake sediment—Laminated, varved, and massive silt and clay. Layers and lenses of fine-grained sand and organic material are present in places. Carbonate leaching depth varies from 3 to 12 feet (0.9 to 3 meters). Fine-grained sand with some clayey silt and gravelly sand. May include some debris-flow deposits. Generally, finer-grained sediment occurs toward the middle and deeper parts of the deposit, while coarse-grained sand and gravel may be present along unit boundaries. Except for the large proglacial lake deposit north of Mille Lacs Lake that formed as ice retreated, this map unit represents primarily ice-walled lake plains.

Outwash deposits—Fine- to coarse-grained sand and fine- to coarse-grained gravel; poorly to moderately well-sorted; generally stratified. Carbonate typically is leached to a depth of greater than 10 feet (3 meters). Deposited by meltwater from Automba-phase ice. Commonly found along meltwater streams and near recessional ice margins. Channelization within a broad outwash plain, sourced from the large esker/fan complex that is present west of Rice Lake (Fig. 2), extends as far south as Mille Lacs Lake and can be followed in the bathymetry of the northwestern part of the lake.

Ice-contact deposits—Sand, gravelly sand, and cobbly gravel. Contains boulders. May be capped by or include interbeds of till. Deformation features such as collapsed and faulted bedding may be evident. Associated with esker and kame deposits of the Automba phase. In eastern Aitkin County, just south of the border with Carlton and St. Louis Counties, a long esker complex originates in Carlton County and runs west for approximately 4 miles (6 kilometers), terminating at an ice marginal fan. The esker here is draped by Alborn Member till of the St. Louis sublobe. Two other large esker/fan complexes are described below in unit cmm.

Till deposits—Chiefly unsorted sediment having a sandy loam matrix texture, although in places along and within the glacial Lake Aitkin II basin where this unit was encountered at or near the surface, it also could have loam and clay loam textures due to incorporation of underlying lake sediment (Plate 4, Fig. 3, Table 1). Pebbles, cobbles, and boulders are less common in the lake basin but abundant in most parts of the county. The matrix color is reddish-brown (7.5YR 4/4 to 5YR 4/3 to 4/4) where oxidized and dark reddish-gray (5YR 4/2 to 4/1) where unoxidized (Table 1). In places, unit may include bedded sediment at or near the surface. Carbonate leaching ranges from 3 to 15 feet (1 to 4.6 meters), but typically at least 7 feet (2.1 meters). In most places, there is a thin layer of silty, pale reddish-white eluviated layer beneath the topsoil where the clay has been translocated downward to an underlying redder, clayey zone. This till is commonly rocky and dense in the southeastern part of the county, where ice drumlinized the landscape to varying degrees as it formed the western extent of the Automba drumlin field (Figs. 2, 4D). Large peat areas may be underlain by undifferentiated lake sediment as well as till.

Interlobate-recessional moraine complex—Commonly composed of red-brown till of unit cmt, but also may include sand and gravel ice-contact (unit *cmv*) and outwash deposits (unit *cmo*). A ridge starts at an indent in the Mille Lacs moraine beyond the western edge of the county (about 5 miles [8 kilometers] southeast of the town of Aitkin) and runs discontinuously eastward to northwest of Rice Lake, forming what appears to be an interlobate moraine (Figs. 2, 4D). Two large, south-trending, Superior-lobe eskers terminate at the ridge, their meltwater fans extending south, which suggests that ice that deposited the Mille Lacs Member retreated faster on the higher ground in the southern half of the county than it did in the glacial Lake Aitkin basin to the north.

Independence Formation—Late Wisconsinan glacial sediment of mixed Rainy and Superior provenances (northeast-sourced) deposited by the Brainerd sublobe of the Rainy lobe. In central Minnesota, its deposits formed the northern portion of the St. Croix moraine and were named the South Long Lake Member (Johnson and others, 2016). Includes related deposits reworked by meltwater, gravity, and wind. Deposits are characteristically sandy and pebbly with many cobbles and boulders.

South Long Lake Member—The South Long Lake Member was informally recognized in Crow Wing County (Knaeble and others, 2004) and later formalized in Johnson and others (2016). Deposits are exposed at the surface mostly in western Aitkin County, but also in a few other places, where they are generally mapped as kames or recessional moraine ice-contact deposits. These sediments, where not at the surface, are buried beneath younger materials of the Superior-lobe Automba phase, as well as some or all of the formal or informal members attributed to the St. Louis sublobe.

Lake sand and silt; ice-walled lake plain—Primarily interbedded silt, sandy silt, and fine- to medium-grained sand with some clayey silt and gravelly sand. May include some debris-flow deposits. Generally, finer-grained sediment occurs toward the middle and deeper parts of the deposit, while coarse-grained sand and gravel may be present along unit boundaries. Interpreted to be an ice-walled lake plain, where sediment is deposited in an ice-walled depression created during the early stages of glacial stagnation. Later, when ice melted, the sediment remained as a positive relief feature.

Outwash deposits—Fine- to coarse-grained sand and gravel; poorly to moderately well-sorted; generally stratified. Deposited in meltwater streams and may form a thin cover over Nelson Lake Member till (unit ant) or locally over glacial Lake Aitkin I, Alborn Member, Cromwell Formation, and Independence Formation materials. May include some Alborn Member outwash (unit aao) along the eastern border of the county, where ice of the Nelson Lake and Alborn Members was contributing meltwater near the ice margins (Knaeble and Hobbs, 2009b).

Ice-contact deposits—Sand, gravelly sand, and cobbly gravel. Locally capped by or includes interbeds of till. Locally contains boulders. Deformation features such as collapsed and faulted bedding may be evident. Associated with esker and fan deposits.

Till deposits—Unsorted sediment commonly having a loam to clay loam matrix texture. The matrix color grades from yellowish-brown (10YR 5/4) and brown (10YR 5/3 and 7.5YR 5/4) from west to east across the county where oxidized, and gray (10YR 5/1) to dark gray (10YR 4/1) where unoxidized (Table 1). Pebbles, cobbles, and boulders vary from rare to common but typically are present in small amounts. There are some carbonate clasts below the leached zone, the depth of which varies, but is generally less than 6 feet (1.8 meters). Gray shale is absent or rare, yet is present in trace amounts in a few places, possibly as part of a mixing zone with overlying Prairie Lake Member deposits. Dark and red clast content varies from some to uncommon, thereby falling intermediate between the underlying Superior-lobe deposits (unit cmt) and the overlying Prairie Lake Member till (unit apt; Plate 4, Fig. 3, Table 1). In places, it includes small amounts of lacustrine and bedded sediment. Ice that deposited the Alborn Member incorporated underlying fine-grained lake sediment of glacial Lake Upham I as it advanced south and southeasterly across the lake basin, and as a result, the matrix texture became red and finer-grained (Baker, 1964). This till may be thin and patchy along the eastern border of the county (Fig. 4G), where it overlies Superior-lobe Automba-phase deposits of the Mille Lacs Member of the Cromwell Formation.

Wave-washed till deposits—Similar to unit aat except that the till has a smooth, low-relief surface expression due to wave action erosion from glacial Lake Upham II. May be mantled by thin silt, sand, or gravelly sand beach deposits, particularly at the top of the washed till section.

Cromwell Formation—Late Wisconsinan glacial sediment of Superior provenance (northeast-sourced) deposited by the Superior lobe (Figs. 3, 4A). Includes related deposits reworked by meltwater, gravity, and wind. This formation is comprised of deposits related to three phases of the Superior lobe: the Emerald, St. Croix, and Automba (see Glacial History and Figs. 4A, B, D for the location of ice margins).

Mille Lacs Member—The Cromwell Formation materials at the surface on this map are considered to be deposits of the Automba phase and have been formally assigned to the Mille Lacs Member (Johnson and others, 2016). The textural and lithologic similarity of the materials deposited during the three phases makes it difficult to differentiate them in the field. Clast types in Cromwell formation tills and their associated outwash that define the characteristics of this formation are composed predominantly of gray metasedimentary rocks (slate and graywacke), North Shore volcanic rocks (reddish rhyolite and basalt), dark red sandstone, and dark gabbro. Less common are reddish granophyre and granite. Trace amounts of carbonate are present. There is no shale. See Table 1 for physical characteristics, and Plate 4, Figure 3 and Table 1 for detailed lithologic analyses.

Lake sand and silt—Primarily interbedded silt, sandy silt, and fine- to medium-grained sand with some clayey silt and gravelly sand. May include some debris-flow deposits. Generally, finer-grained sediment occurs toward the middle and deeper parts of the deposit, while coarse-grained sand and gravel may be present along unit boundaries. Interpreted to be an ice-walled lake plain, where sediment is deposited in an ice-walled depression created during the early stages of glacial stagnation. Later, when ice melted, the sediment remained as a positive relief feature. Mapped in only one large area in the northwest quadrant along the western border, where larger peat areas may be underlain by undifferentiated lake sediment as well as till.

Till deposits—Chiefly unsorted sediment having a loam to clay loam matrix texture. The matrix color is yellow-brown to brown (2.5Y 5/4 to 10YR 5/4) where oxidized and brown-gray (10YR 4/2) where partially oxidized (Table 1). Pebbles, cobbles, and boulders vary from rare to uncommon, but typically are present in small amounts (Table 1; see Plate 4, Fig. 3, Table 1 for detailed analysis of clast characteristics). Carbonate clasts vary from few to common, gray shale varies from some to abundant, and there are few red and dark mafic rocks. Carbonate leaching depth is generally less than 3 feet (0.9 meter). Till deposits are commonly less than 10 feet (3 meters) thick, but in a few places can be up to 20 feet (6.1 meters) thick.

Wave-washed till deposits—Similar to unit apt except that the till has a smooth, low-relief surface expression due to wave action erosion from glacial Lakes Aitkin II and Upham II. May be mantled by thin silt, sand, or gravelly sand beach deposits, particularly at the top of the washed till section.

Nelson Lake Member—Glacial sediment deposited by the western branch of the St. Louis sublobe (Fig. 4G; Baker, 1964; Wright, 1972; Knaeble and others, 2004; Johnson and others, 2016) during its initial advance south of the Mesabi Iron Range and into the region surrounding glacial Lake Aitkin I. In places, includes clay, silt, and fine-grained sand related to underlying glacial Lake Aitkin I and overlying glacial Lake Aitkin II sediment. May include areas where younger Prairie Lake Member ice has incorporated and mixed with Nelson Lake Member sediment, producing an intermediate color and texture. Deposited at the same time as the Alborn Member, which formed the eastern branch of the St. Louis sublobe around glacial Lake Upham I (Knaeble and Hobbs, 2009b).

Lake sand and silt; ice-walled lake plain—Primarily interbedded silt, sandy silt, and fine- to medium-grained sand with some clayey silt and gravelly sand. May include some debris-flow deposits. Generally, finer-grained sediment occurs toward the middle and deeper parts of the deposit, while coarse-grained sand and gravel may be present along unit boundaries. Interpreted to be an ice-walled lake plain, where sediment is deposited in an ice-walled depression created during the early stages of glacial stagnation. Later, when ice melted, the sediment remained as a positive relief feature.

Ice-contact deposits—Sand, gravelly sand, and cobbly gravel. Locally capped by or includes interbeds of till. Contains boulders. Deformation features such as collapsed and faulted bedding may be evident. Quadna Mountain near Hill City in the northern part of Aitkin County