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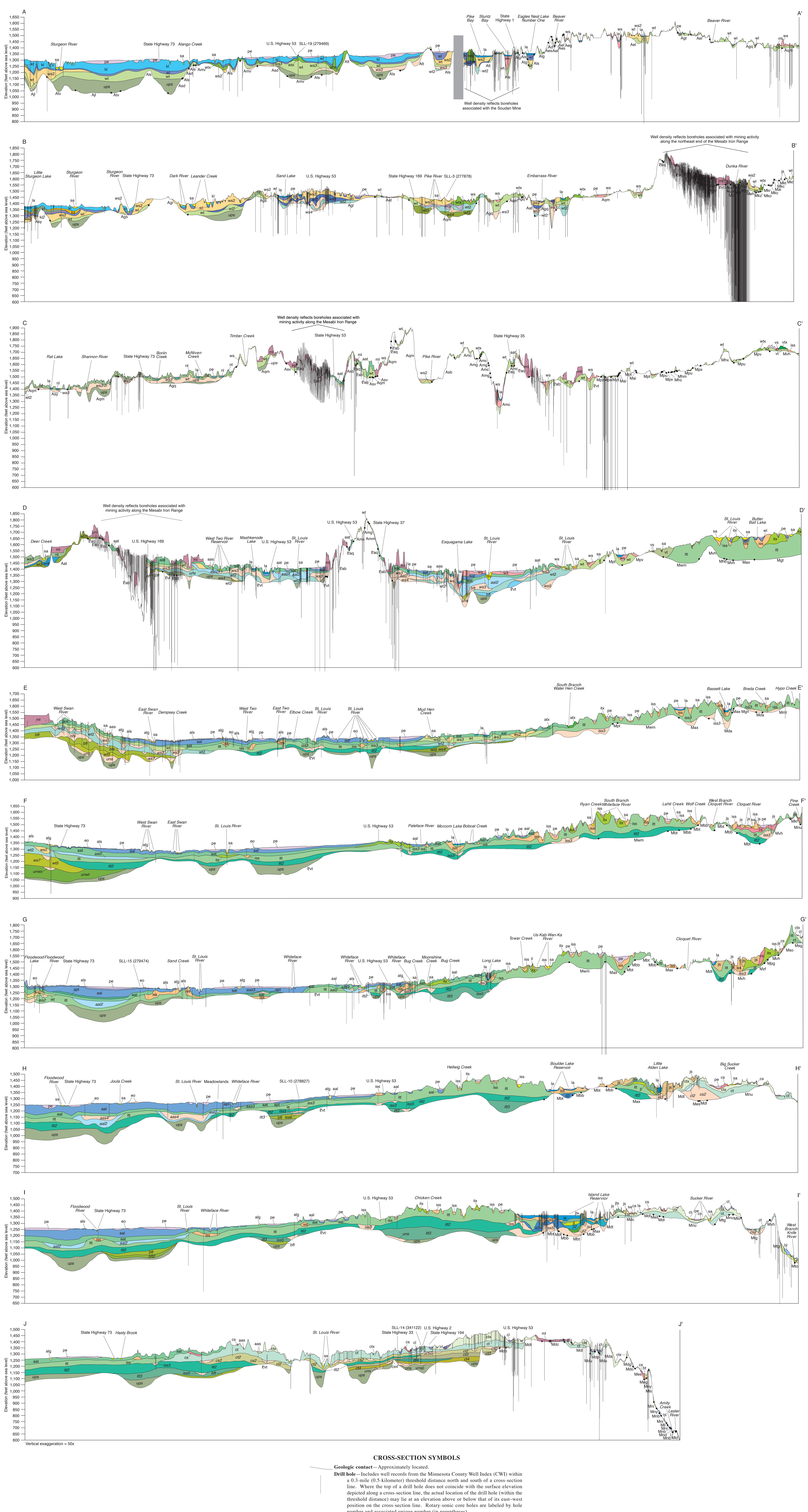

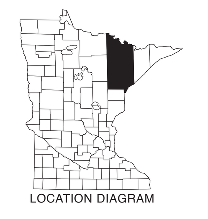

QUATERNARY STRATIGRAPHY

By

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INTRODUCTION

See the Appendix for additional figures.

The Quaternary Stratigraphy plate shows the unconsolidated materials expected to be encountered between the land surface and bedrock surface in St. Louis County. One hundred eighty-one west–east oriented cross sections with 0.6-mile (1 kilometer) north–south spacing (Fig. 1) were constructed to create a three-dimensional model of the Quaternary deposits in St. Louis County. Cross sections A–A' through J–J' are representative of the 181 cross sections. The relative age, location (from west to east), and provenance of units depicted on the cross sections are shown in Figure 2. The formations encompassing these units are linked, spatially and temporally, to ice lobe and depositional phase in Figure 3. Correlations between stratigraphic units depicted on cross sections in St. Louis County with those from nearby and adjacent mapping areas, including Lake County (McDonald and others, 2022), the preliminary Arrowhead products released in Jirsa (2016), the central Mesabi Iron Range area (Jirsa and Meyer, 2007, Plates 4A, 6), and Carlton County (Knaeble and Hobbs, 2009b) are depicted in Figure 4. The major sand and gravel bodies from this model are depicted on Plate 5, *Sand-Distribution Model*; the full model, and all the cross sections used to develop it, can be accessed through the supplementary digital files that accompany this plate.

Quaternary geologic units (Fig. 3) shown on the cross sections were defined using various data sources. These primarily include the Minnesota County Well Index (CWI), which contains water-well drillers' logs and records from exploratory boreholes. CWI data were used in conjunction with data from cuttings sets and from the 17 rotary-sonic drill holes completed by the Minnesota Geological Survey for this project (Fig. 1). Rotary-sonic drill holes (Appendix Figs. 1-17), combined with descriptions of mine-pit exposures from previous studies (Winter, 1971; Jennings and Reynolds, 2005; Jirsa and Meyer, 2007), are the key stratigraphic control points in the study area. Core associated with these drill holes was collected, logged, sampled, and interpreted by the Minnesota Geological Survey. Stratigraphic changes within these cores were described according to color, texture, and composition, and sediments were sampled for textural and lithologic analyses. The average matrix texture and average lithologic composition of the very coarse-grained (1-2 millimeters) sand fraction in till sampled from these rotary-sonic cores are presented in Appendix Figures 18 through 20.

On cross-sections A–A' through J–J', drill holes are represented by vertical lines. Rotary-sonic drill holes are labelled with their borehole names and associated unique number (in parentheses). Interpreted logs of the rotary-sonic cores are shown in Appendix Figures 1 through 17; their locations are shown on Figure 1. Drill holes may start above or below the land surface because the data are projected onto the cross section from a distance of up to 0.3 mile (0.5 kilometer). Vertical exaggeration is 50x for all cross sections, scale is 1:200,000.

The complexity of subsurface units shown on the cross sections is partly a function of the amount of data available. Where the data are scarce (Fig. 1 and Plate 1, *Database Map*), the cross-section units are generally portrayed (modeled) as continuous, with relatively uniform thickness and minimal elevation change. Where there are more data, units tend to be discontinuous and variable in thickness, and their elevations diverge over relatively short distances, which reflects more accurately the complexity of glacial deposits, especially those that are older, more deeply buried, and more eroded and dissected. It is important to consider the interpretive nature of the cross sections, especially for deeper units that are less frequently encountered during drilling, and are thus defined on the basis of less data. Commonly, in areas with little or no data at depth, units are continued from adjacent cross sections. Because subsurface data are sparse across much of the study area, regional surficial geology (Plate 3, *Surficial Geology*) was utilized to develop a conceptual stratigraphic model. In areas of low data density with appreciably thick Quaternary deposits (as determined by remote passive seismic and gravitational methods [Chandler and Lively, 2014]), a conceptual model informed by current understandings of glacial sedimentation and erosion mechanisms, and each individual mapper's experience, was used to portray the order and thickness of discrete sediment packages in the subsurface. Particularly in these areas, illustrated stratigraphic complexity likely underrepresents actual complexity, and more confidence should be placed on the stratigraphic order, rather than the thickness, of any particular unit(s).

Diamicton units, interpreted to be glacial till, are extended across areas where there are little to no data but where it seems reasonable that the tills are continuous. Although sand bodies are not drawn in all of these areas, sand and gravel commonly occur at till boundaries and may be encountered at the approximate depth of till contacts shown. Peat (unit pe) is shown on the cross sections where it is significantly thick (generally greater than 8 feet) or laterally extensive. Where thin or localized, unit pe is incorporated into the underlying unit, as specified in its description.

Depth to bedrock (the thickness of unconsolidated Quaternary deposits) in St. Louis County is highly variable, with values ranging from zero to approximately 350 feet (107 meters). Quaternary deposits are generally thickest across the Toimi drumlin field and glacial Lake Upham basin, shallowing towards the north, and in the Boundary Waters Canoe Area Wilderness, where they are generally less than 15 feet (4.6 meters; see Plate 3 and Plate 6, *Depth to Bedrock*). Aside from those associated with constructional landforms (such as eskers, select drumlins, moraines), most appreciably thick deposits tend to occupy basins or channels mirroring the bedrock surface, and their stratigraphy varies depending on depositional source, paleo-ice and meltwater flow directions, and the (time-transgressive) position of an ice margin during deposition within a basin or channel, with respect to continental drainage divides (see Plate 3, Appendix B, Fig. 6). The cross sections on this plate were selected to illustrate this variability.

Laboratory analyses of the texture (grain size) and lithologic analyses of the 1-2 millimeter (very coarse-grained sand) fraction of till (Table 1) and associated sediment samples under low magnification indicate that unconsolidated materials in St. Louis County derive from several source regions with distinctive composition. These source areas define four unique provenances: Rainy (north–northeast), Superior (east–northeast), Riding Mountain (north–northwest), and Winnipeg (northwest). Sediments with the composition of a distinctive provenance are identified on the basis of matrix texture, color, geochemistry, density/level of consolidation, clast-abundance, and the lithologic makeup of the 1-2 millimeter sample fraction, including carbonate and shale content. Several units of mixed provenance are also mapped in St. Louis County, specifically those of mixed Rainy and Superior (units il, iss, itt, itx, jl, jt, js, jtx, vt, vs, vtx) and mixed Riding Mountain and Winnipeg provenance with local Superior-provenance influence (units alg, aas, als, aal, apt, atx, aat). By convention, the name designations of sand and gravel bodies are associated with the underlying till; however, the upper- and lowermost portions of individual sand and till bodies are likely an admixture of material from immediately above or below the depicted contacts.

All units named here are ascribed to formation and member designations as defined in Johnson and others (2016) on the basis of color, lithologic composition of the 1-2 millimeter (very coarse-grained sand) fraction, texture, and stratigraphic position. Associations were made using information from Johnson and others (2016), and from the Quaternary Database Index (QDI), an internal working database of the Minnesota Geological Survey. It is important to note, however, that laterally extensive till sheets are characterized by some degree of textural and compositional heterogeneity, and as such, certain properties of units presented here may differ from those of their type sections recognized in Johnson and others (2016).

PRE-LATE WISCONSINAN STRATIGRAPHY OF ST. LOUIS COUNTY

St. Louis County was glaciated multiple times during the Quaternary Period (Fig. 2). Sediments attributable to the Wisconsinan, the most recent glacial episode, are described on Plate 3. Glacial deposits older than the Wisconsinan Episode are also present in northeastern Minnesota, but are irregularly distributed throughout the subsurface and have received relatively little study. These earlier glaciations removed and incorporated most of the thick saprolite that was once present, particularly over those areas where the silicate-rich rocks of the Precambrian shield are exposed at or near the land surface. Rotary-sonic drilling completed by the Minnesota Geological Survey in support of the St. Louis and Lake County Geologic Atlases has in part been motivated by attempts to intersect this lowermost portion of the stratigraphic package. Results from targeted drilling show that the late Wisconsinan Laurentide Ice Sheet removed most preexisting glacial deposits across the region, although several holes did intersect pre-late Wisconsinan tills.

The youngest pre-late Wisconsinan sediments in St. Louis County were probably deposited by the Superior lobe at some time prior to the St. Croix phase. This is implied by a ^{14}C age of 48,169 cal yr BP (45,100 ± 1,400 ^{14}C yr BP), obtained during the course of this study, from wood within a thin sequence of glaciolacustrine sediment in rotary-sonic core SLL-14 (Appendix Fig. 12) that is bracketed by an overlying Cromwell Formation till and an older, unnamed diamicton of Superior provenance (unit *unsp*). This date, along with the other radiocarbon dates presented here, were calibrated to cal yr BP using the Calib 7.1 radiocarbon calibration program (Stuiver and others, 2020). The significance of this age is that it imparts both a maximum age for the Cromwell Formation during the Emerald phase of the Superior lobe, and a pre-late Wisconsinan minimum-limiting age for the underlying unit *unsp*. During the Emerald phase, the Superior lobe reached as far south as the southern edge of the Twin Cities (Johnson, 1986; Berthold, 2018). Age dates reported here corroborate those obtained from organic material sampled from similar stratigraphic settings in rotary-sonic cores from Ramsey and Chisago Counties, which when combined with a cooling trend in the pollen record, suggest that the Emerald phase was initiated by at least 32,900 cal yr BP (Meyer and Stefanova, 2009). More robust chronologic constraints on the Emerald phase from across the state remain lacking. Whereas in central to southern Minnesota, Alexandria- and Emerald-phase materials are sharply overlain by younger north- and northwest-sourced (Winnipeg and Riding Mountain provenance) deposits, in northeastern Minnesota, as displayed in rotary-sonic core SLL-14 (Appendix Fig. 12), these grade continuously into overlying sediments emplaced by the Rainy, Brainerd, and Superior lobes, without obvious contacts in most places.

New age constraints are also reported here for a pre-late Wisconsinan Winnipeg-provenance deposit—in the form of an infinite ^{14}C age obtained from wood sampled at the base of a unit of calcareous sandy loam diamicton (core SLL-11; Appendix Fig. 9). Based on stratigraphic position, as well as its textural and lithologic composition, this unit is assigned to the Bigfork Formation (Meyer, 1993; Johnson and others, 2016) and is recognized as correlative with the "basal till" described by Winter (1971, 1973; Winter and others, 1973) from exposures in open-pit mines along the Mesabi Iron Range. This is the first time that such correlations have been established between the lowermost stratigraphy of the Giants Range and buried deposits in the glacial Lake Aitkin/Upham basin. Spruce or tamarack wood in glaciofluvial sediment overlying the "basal till" at the Duncan-Douglas mine near Hibbing, sampled by Winter (1971), also yielded an infinite (pre-late Wisconsinan) ^{14}C age. Below the Bigfork Formation till in rotary-sonic core SLL-11 (Appendix Fig. 9), bedded glaciolacustrine sediments separate that unit from a basal Winnipeg-provenance diamicton (unit *unwt*). The stratigraphic position of this basal till implies an even older pre-Wisconsinan ice advance entered St. Louis County from the north-central part of the state. This unit is possibly equivalent to the Wirt Formation, mapped in adjacent Itasca County by Meyer (1997) and formally defined in Johnson and others (2016).

Rainy-provenance sediments deposited prior to the Last Glacial Maximum (here assigned to an unnamed Rainy-provenance formation) are commonly difficult to distinguish from those belonging to the late Wisconsinan Boundary Waters Formation. Without further study or the collection of suitable material for geochronologic analyses, these sediments cannot be conclusively dated, but it is conceivable that the basal tills intersected in rotary-sonic cores SLL-2 (Appendix Fig. 1) and SLL-16 (Appendix Fig. 14) may correlate to presumed pre-Wisconsinan Rainy-provenance tills described in central and western St. Louis County by Stark (1977) and Meyer (1997), respectively. Stark (1977) documented a coarse-grained, highly cemented, calcareous till beneath younger Rainy-provenance sediments at the base of a mine-pit exposure near Babbitt, which he informally termed the "Dunka till." This deposit occurred in a single location, directly atop bedrock, and had a dark brown to greenish-brown color and predominance of greenstone and metasedimentary clasts typical of local Rainy-provenance tills. It remains ambiguous as to provenance, however, in that it was logged 20 miles (32 kilometers) northwest of the easternmost known occurrence of the (Winnipeg provenance) Bigfork Formation—Winter's "basal till" (Winter, 1971, 1973; Winter and others, 1973)—and thus may correlate with the latter, given a texture and composition that is non-specific to source area.

In two rotary-sonic holes drilled in western St. Louis County as part of a previous investigation, Meyer (1997) described basal Rainy-provenance tills that were oxidized to a pale brown to yellow-brown immediately overlying bedrock and beneath unoxidized Rainy-provenance sediments. These were attributed to the Saum Formation, the youngest pre-Wisconsinan Rainy-provenance till recognized in north-central Minnesota, and later formalized in Johnson and others (2016). Elsewhere, in counties to the west of the mapping area, older Rainy-provenance tills were distinguished by the presence of carbonate, overconsolidation, and increased clay content in their matrix relative to the superjacent Rainy-provenance tills that are recognized here as belonging to the Boundary Waters Formation. Similar deposits—referred to as the "old sandy till" in Jirsa and Meyer (2007)—have been previously documented from deep exposures along the western half of the Mesabi Iron Range. These may be equivalent to the pre-Wisconsinan Shooks Formation, recognized in deep rotary-sonic drill cores in neighboring Itasca and Koochiching Counties by Meyer (1997) and later formally defined in Johnson and others (2016).

Although Rainy-provenance tills in cores SLL-2 and SLL-16 do not contain any macroscopic carbonate, the basal till in core SLL-2 does have a calcareous matrix, and the lowermost till in core SLL-16 is highly consolidated relative to overlying till units. Lacking more extensive regional subsurface data, however, it was not practical to extend these interpretations across large portions of the mapping area, and hence the distribution of pre-late Wisconsinan Rainy-lobe sediments is depicted here as relatively discontinuous on the basis of well-log reports, and the previous investigations of open-pit mine exposures described above.

TILL GEOCHEMICAL ANALYSES

In St. Louis County, downhole geochemical assay values were obtained from rotary-sonic cores SLL-10 (Appendix Fig. 8), SLL-11 (Appendix Fig. 9), SLL-13 (Appendix Fig. 11), SLL-14 (Appendix Fig. 12), SLL-15 (Appendix Fig. 13), SLL-17 (Appendix Fig. 15), and SLL-18 (Appendix Fig. 16) as part of a broader program of analyses (Thorleifson and others, 2019). In a manner consistent with methods described in Thorleifson and others (2007), the less than 63-micron fraction of till samples was analyzed by inductively coupled plasma mass spectrometry (ICP-MS) following a four-acid, near-total dissolution utilizing hydrochloric, perchloric, nitric, and hydrofluoric acids.

More intricate interpretations of the geochemical data from these cores are currently being developed (Wittkop and others, 2020), but initial results indicated that elevated concentrations of certain elements may exhibit some correlation to tills of recognized lithostratigraphic units as follows (numbers in parentheses indicate percentage deviation from the mean of all samples): cadmium in the Prairie Lake Member of the Aitkin Formation (+118%); antimony in the Alborn Member of the Aitkin Formation (+57%); copper in the Cromwell Formation (+49%); chromium in the Independence Formation(+12%); bismuth in the Mesabi member of the Boundary Waters Formation (+1,237%); and arsenic in the Bigfork Formation (+103%; Appendix Table 1).

These initial interpretations suggest that till geochemical analysis can aid in the interpretation of provenance and lithostratigraphic unit separation, in conjunction with core descriptions that include systematic documentation of intervening bedded sediments, and textural and lithologic changes. In addition to the observations noted above, interpretations developed in this study generally support the preliminary generalizations reported in Staley (2019), which indicated elevated concentrations of sodium in tills bearing a preferential shield provenance, and elevated iron in tills sourced from the Superior basin. Sulfur concentrations in till appear to demonstrate some degree of correlation to a northwest source area (Appendix Table 1).

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DESCRIPTION OF CROSS-SECTION UNITS

Each unit description on the cross sections is placed in one of four categories, as indicated in parentheses after the description: 1. *Surficial Geology* unit—unit having an identical description (with the incorporation of peat), label, and color as on Plate 3, *Surficial Geology*; 2. Subsurface unit—unit that is depicted only in the subsurface that has a unique label and color (the subsurface sand and gravel units have the same color to emphasize their status as potential aquifers); 3. Modified surficial unit—multiple units from Plate 3 combined into a single modified unit on the cross sections; 4. Modified subsurface unit—one unit from Plate 3 divided into two or more units on the cross sections, most commonly appearing in the subsurface. It should be noted that all surficial geology units may include thin peat deposits (unit pe) because in the cross sections, peat is only depicted as a separate unit where it is significantly thick (generally greater than 8 feet [2.4 meters]) or laterally extensive. Where thin or localized, unit pe is incorporated into the underlying unit, as specified in its description. See Plate 3 for detailed descriptions. Units in gray do not appear on the printed cross sections, but are represented on unprinted cross sections in the digital files accompanying this plate.

HOLOCENE

- **sa** — **Sand, gravel, cobbles, boulders, and sandy loam to silt loam** (*Surficial Geology* unit).
- **ml** — **Disturbed lands** (modified surficial unit)—Includes surficial units mlp, mlm, mlr, mlo, mf.
- **pe** — **Organic debris, clay, silt, and fine-grained sand** (*Surficial Geology* unit).
- **la** — **Silt, clay, and loamy sand with partially decomposed organic debris** (modified surficial unit)—Includes surficial units la, las, pe.
- **eo** — **Sand** (*Surficial Geology* unit).

PLEISTOCENE

Blackduck Formation—Dark grayish-brown (2.5YR 4/2) to brown (10YR 4/3) to dark yellowish-brown (10YR 4/4), calcareous, clay-loam-textured till and bedded glaciofluvial and glaciolacustrine sediment of Winnipeg provenance.

- **kl** — **Undifferentiated glaciolacustrine sediment** (modified surficial unit)—Includes surficial units kl, kle, kld, kls, klw, pe.
- **ks** — **Fine- to gravelly very coarse-grained sand** (*Surficial Geology* unit).
- **kt** — **Clay-loam diamicton** (modified surficial unit)—Includes surficial units kt, kts, pe.
- *ks2* — Sand and gravel (modified subsurface unit)—Described in unit ks on Plate 3.
- *kl2* — **Undifferentiated glaciolacustrine sediment** (modified subsurface unit)—Described in unit kl on Plate 3.

Barnum Formation—Reddish-brown (2.5YR 4/4 to 5YR 4/4) to dark gray (5YR 4/2 to 7.5YR 4/1), calcareous, clay to silt loam-textured till and bedded glaciofluvial and glaciolacustrine sediment of Superior provenance. The four informal members (Lakewood/Mahtowa, Moose Lake, Wrenshall, and Knife River) recognized by Knaeble and Hobbs (2009b) are not differentiated here.

- **bl** — **Undifferentiated glaciolacustrine sediment** (modified surficial unit)—Includes surficial units bl, bls, bli, pe.
- *bss* — Sand and gravel (subsurface unit)—Reddish-brown (2.5YR 4/4 to 5YR 4/4), bedded glaciofluvial sediment of Superior provenance.
- **bt** — **Loam diamicton** (*Surficial Geology* unit).

Aitkin Formation—Reddish-brown (5YR 4/4) to reddish-gray (5YR 4/1 to 5YR 4/2) to brown (7.5YR 4/4) to grayish-brown (2.5Y 4/3) clay to loam-textured till and bedded glaciofluvial and glaciolacustrine sediment of mixed Rainy, Riding Mountain, Winnipeg, and Superior provenances.

Unnamed member—Reddish-gray (5YR 4/1) to brown (7.5YR 4/4) to grayish-brown (2.5Y 4/3), massive to bedded sediment of mixed Rainy, Riding Mountain, Winnipeg, and Superior provenances.

- **alg** — **Sand and gravelly sand** (*Surficial Geology* unit).
- **aas** — **Sand and gravel** (modified surficial unit)—Includes surficial units asd, ans, ask, pe.
- **als** — **Sand and silt** (*Surficial Geology* unit).
- **aal** — **Undifferentiated glaciolacustrine sediment** (modified surficial unit)—Includes surficial units aal, alc, ali, anl, pe.
- *aas2* — Sand and gravel (modified subsurface unit)—Described in unit aas on Plate 3.
- *aas3* — **Sand and gravel** (modified subsurface unit)—Described in unit aas on Plate 3.
- *aas4* — **Sand and gravel** (modified subsurface unit)—Described in unit aas on Plate 3.
- *aal2* — **Undifferentiated glaciolacustrine sediment** (subsurface unit)—Predominantly silty clay to clay varying to clayey silt in places. Dark gray (5Y 4/1) at depth and rhythmically laminated. Unit was deposited in glacial Lake Upham I and is gradational with other lacustrine units.
- *aal3* — Undifferentiated glaciolacustrine sediment (subsurface unit)—Predominantly silty clay to clay varying to clayey silt in places. Dark gray (5Y 4/1) at depth and rhythmically laminated. Unit was deposited in glacial Lake Upham I or in older, unnamed glacial lakes within the glacial Lake Upham basin, and is gradational with other lacustrine units.

Prairie Lake Member—Light yellowish-brown (10YR 6/4) to dark gray (2.5Y 4/1), loam-textured till of mixed Riding Mountain and Winnipeg provenances.

- **apt** — **Loam diamicton** (modified surficial unit)—Includes surficial units apt, apw, pe.

Alborn Member—Clay to clay-loam-textured till and bedded sediments of mixed Rainy, Riding Mountain, Winnipeg, and Superior provenances.

- **atx** — **Sand and gravel/diamicton/glaciolacustrine complex** (modified surficial unit)—Includes surficial units atx, ali, pe.
- **aat** — **Clay to clay-loam diamicton** (modified surficial unit)—Includes surficial units aat, ats, aaw, pe.

Boundary Waters Formation—Olive-brown (2.5Y 5/3) to yellowish-brown (10YR 5/6) to dark gray (5Y 4/1), sandy loam-textured till and bedded glaciofluvial and glaciolacustrine sediments of Rainy provenance.

Nashwauk member—Olive-brown (2.5Y 5/3) to dark yellowish-brown (10YR 4/4), clay-loam to loam-textured till and bedded glaciofluvial and glaciolacustrine sediments of Rainy provenance.

- **nl** — **Clay, silt, and fine- to medium-grained sand** (*Surficial Geology* unit).
- **ns** — **Sand, cobbly gravel, and gravelly sand** (*Surficial Geology* unit).
- **nt** — **Clay-loam diamicton** (modified surficial unit)—Includes surficial units nt, nts, pe.

Mesabi member—Yellowish-brown (10YR 5/6) and brown (10YR 4/3) to gray-brown (2.5Y 4/2) to dark gray (5Y 4/1), sandy loam-textured till and bedded glaciofluvial and glaciolacustrine sediments of Rainy provenance.

- **ws** — **Sand and gravel** (modified surficial unit)—Includes surficial units ws, wsi, wsk, wsd, pe.
- **wl** — **Undifferentiated glaciolacustrine sediment** (modified surficial unit)—Includes surficial units wl, wli, wls, pe.
- **ws2** — **Sand and gravel** (modified surficial unit)—Described in unit ws on Plate 3.
- **wtx** — **Sand and gravel/diamicton/glaciolacustrine complex** (modified surficial unit)—Includes surficial units wtx, wli, pe.
- *wl2* — **Undifferentiated glaciolacustrine sediment** (modified subsurface unit)—Described in unit wl on Plate 3.
- **wt** — **Sandy loam diamicton** (modified surficial unit)—Includes surficial units wt, pe. In places, incorporation of lacustrine sediment and saprolite near the base of this unit contributes to a denser loam matrix texture with a relative enrichment of fine-grained silt and clay.
- *wl3* — **Undifferentiated glaciolacustrine sediment** (modified subsurface unit)—Described in unit wl on Plate 3.
- *ws3* — **Sand and gravel** (modified subsurface unit)—Described in unit ws on Plate 3.
- *wtx2* — Sand and gravel/diamicton/glaciolacustrine complex (modified subsurface unit)—Described in unit wtx on Plate 3.
- *wt2* — **Sandy loam diamicton** (modified subsurface unit)—Described in unit wt on Plate 3.
- *wl4* — **Undifferentiated glaciolacustrine sediment** (modified subsurface unit)—Described in unit wl on Plate 3.
- *ws4* — **Sand and gravel** (modified subsurface unit)—Described in unit ws on Plate 3.
- *wt3* — **Sandy loam diamicton** (modified subsurface unit)—Described in unit wt on Plate 3.
- *wl5* — Undifferentiated glaciolacustrine sediment (modified subsurface unit)—Described in unit wl on Plate 3.
- *ws5* — **Sand and gravel** (modified subsurface unit)—Described in unit ws on Plate 3.

Mixed Independence and Cromwell Formations—Includes sediments deposited by mixed meltwater sources issuing from the Superior and Brainerd lobes.

- *jl* — **Undifferentiated glaciolacustrine sediment** (subsurface unit)—Includes undifferentiated glaciolacustrine sediments deposited by mixed meltwater sources issuing from the Superior and Brainerd lobes.
- **js** — **Sand and gravel** (modified surficial unit)—Includes surficial units js, jsi, jsd, jsk, pe.
- **jtx** — **Diamicton, silt, clay, sand, and gravel** (*Surficial Geology* unit).
- **jt** — **Loam to sandy loam diamicton** (*Surficial Geology* unit).
- *js2* — Sand and gravel (modified subsurface unit)—Described in unit js on Plate 3.
- *jl2* — **Undifferentiated glaciolacustrine sediment** (subsurface unit)—Includes undifferentiated glaciolacustrine sediments deposited by mixed meltwater sources issuing from the Superior and Brainerd lobes.
- *js3* — **Sand and gravel** (modified subsurface unit)—Described in unit js on Plate 3.
- *jt2* — **Sandy loam diamicton** (modified subsurface unit)—Described in unit jt on Plate 3.
- *js4* — **Sand and gravel** (modified subsurface unit)—Described in unit js on Plate 3.
- *js5* — Sand and gravel (modified subsurface unit)—Described in unit js on Plate 3.
- *jt3* — Sandy loam diamicton (modified subsurface unit)—Described in unit jt on Plate 3.

Independence Formation—Brown (10YR 4/3) to dark grayish-brown (2.5Y 4/2), sandy loam-textured till and bedded glaciofluvial and glaciolacustrine sediments of mixed Superior and Rainy provenances; deposited by the Brainerd lobe.

- **il** — **Undifferentiated glaciolacustrine sediment** (modified surficial unit)—Includes surficial units il, ili, pe.
- **iss** — **Sand and gravel** (modified surficial unit)—Includes surficial units iss, isi, isk, isd, pe.
- **itx** — **Sand and gravel/diamicton/glaciolacustrine complex** (modified surficial unit)—Includes surficial units itx, ili, pe.
- *iss2* — **Sand and gravel** (modified subsurface unit)—Described in unit iss on Plate 3.
- **itt** — **Sandy loam diamicton** (*Surficial Geology* unit).
- *il2* — **Undifferentiated glaciolacustrine sediment** (modified subsurface unit)—Described in unit il on Plate 3.
- *iss3* — **Sand and gravel** (modified subsurface unit)—Described in unit iss on Plate 3.
- *iss4* — Sand and gravel (modified subsurface unit)—Described in unit iss on Plate 3.
- *itt2* — **Sandy loam diamicton** (modified subsurface unit)—Described in unit itt on Plate 3.
- *iss5* — **Sand and gravel** (modified subsurface unit)—Described in unit iss on Plate 3.
- *itt3* — **Sandy loam diamicton** (modified subsurface unit)—Described in unit itt on Plate 3.
- *iss6* — **Sand and gravel** (modified subsurface unit)—Described in unit iss on Plate 3.
- *itt4* — **Sandy loam diamicton** (modified subsurface unit)—Described in unit itt on Plate 3.
- *il3* — Undifferentiated glaciolacustrine sediment (modified subsurface unit)—Described in unit il on Plate 3.

Cromwell Formation—Includes all deposits associated with the northeast-sourced (Superior provenance) Superior lobe. Dark reddish-brown (5YR 3/2) to brown (7.5YR 3/3), loam-textured till and bedded glaciofluvial and glaciolacustrine sediments of Superior provenance. Includes primarily (undifferentiated) materials of the successive Automba and St. Croix phases; however, in places, units *ct3*, *cs4*, *ct4*, *cl4*, and *cs5* may include Superior-lobe deposits associated with the older Emerald phase.

- **cl** — **Undifferentiated glaciolacustrine sediment** (modified surficial unit)—Includes surficial units cl, cli, pe.
- **cs** — **Sand and gravel** (modified surficial unit)—Includes surficial units cs, csd, csk, pe.
- **ctx** — **Sand and gravel/diamicton/glaciolacustrine complex** (modified surficial unit)—Includes surficial units ctx, cli, pe.
- **ct** — **Loam diamicton** (modified surficial unit)—Includes surficial units ct, cts, ctw, pe.
- *cl2* — **Undifferentiated glaciolacustrine sediment** (modified subsurface unit)—Described in unit cl on Plate 3.
- *cs2* — **Sand and gravel** (modified subsurface unit)—Described in unit cs on Plate 3.
- *ct2* — **Loam diamicton** (modified subsurface unit)— Described in unit ct on Plate 3.
- *cs3* — Sand and gravel (modified subsurface unit)—Described in unit cs on Plate 3.
- *ct3* — **Loam diamicton** (modified subsurface unit)—Described in unit ct on Plate 3.
- *cs4* — **Sand and gravel** (modified subsurface unit)—Described in unit cs on Plate 3.
- *ct4* — **Loam diamicton** (modified subsurface unit)—Described in unit ct on Plate 3.
- *cl4* — Undifferentiated glaciolacustrine sediment (modified subsurface unit)—Described in unit cl on Plate 3.
- *cs5* — Sand and gravel (modified subsurface unit)—Described in unit cs on Plate 3.

Mixed Boundary Waters and Independence Formations—Dark grayish-brown (10YR 4/2), sandy loam till and bedded glaciofluvial sediments of mixed Rainy and Superior provenances.

- **vtx** — **Sand and gravel/ diamicton/glaciolacustrine complex** (modified surficial unit)—Includes surficial units vtx, pe.
- **vs** — **Sand and gravel** (modified surficial unit)—Includes surficial units vs, vst, vsk, pe.
- **vt** — **Sandy loam to loamy sand diamicton** (*Surficial Geology* unit).

Pre-late Wisconsinan Episode

Unnamed formation of Superior provenance—Gray (10YR 3/1) to dark gray-brown (10YR 3/3), clay-loam till deposited by Superior-provenance ice. This unit was only encountered in rotary-sonic core SLL-14 (Appendix Fig. 12). Because this stratigraphic layer has not been recognized in adjacent counties, it is only mapped on cross sections within the immediate vicinity of the core.

- *unsp* — **Clay-loam diamicton** (subsurface unit)—Massive, matrix-supported, clay-loam-textured, unsorted sediments with pebbles, cobbles, and scattered boulders. Red volcanic grains commonly comprise a significant proportion of the very coarse-grained sand fraction, generally between 12 and 22 percent.

Bigfork Formation—Dark gray (5Y 4/1) to olive-gray (5Y 5/2), clay-loam-textured till and bedded glaciofluvial and glaciolacustrine sediments of Winnipeg provenance.

- *bfl* — **Undifferentiated glaciolacustrine sediment** (subsurface unit)—Rhythmically bedded, though locally massive, clay and silt with minor very fine- to fine-grained sand. Identified locally in water-well logs.
- *bfs* — **Sand and gravel** (subsurface unit)—Fine- to coarse-grained sand and fine- to coarse-grained gravel. Deposited by meltwater associated with pre-late Wisconsinan ice advances of Winnipeg provenance. Identified locally in water-well logs.
- *bft* — **Clay-loam diamicton** (subsurface unit)—Massive, matrix-supported, clay-loam-textured, unsorted sediments with pebbles, cobbles, and scattered boulders. Ranges from dark gray (5Y 4/1) to olive-gray (5Y 5/2). Paleozoic carbonate commonly comprises a low to moderate proportion of the very coarse-grained sand fraction, generally between 5 and 20 percent.
- *bfs2* — Sand and gravel (subsurface unit)—Fine- to coarse-grained sand and fine- to coarse-grained gravel. Deposited by meltwater associated with pre-late Wisconsinan ice advances of Winnipeg provenance. Identified locally in water-well logs.
- *bft2* — **Clay-loam diamicton** (subsurface unit)—Massive, matrix-supported, clay-loam-textured, unsorted sediments with pebbles, cobbles, and scattered boulders. Ranges from dark gray (5Y 4/1) to olive-gray (5Y 5/2). Paleozoic carbonate commonly comprises a low to moderate proportion of the very coarse-grained sand fraction, generally between 5 and 20 percent.

Unnamed formation of Rainy provenance—Dark brown (10YR 3/3) to greenish-brown (2.5Y 4/3), sandy loam-textured till and bedded glaciofluvial sediments of Rainy provenance. Distribution of pre-late Wisconsinan Rainy-lobe sediments was mapped primarily using information from well logs and previous investigations of open-pit mine exposures (Winter, 1971, 1973; Winter and others, 1973; Stark, 1977; Jennings and Reynolds, 2005; Jirsa and Meyer, 2007).

- *ws6* — Sand and gravel (subsurface unit)—Fine- to coarse-grained sand and fine- to coarse-grained gravel. Deposited by meltwater associated with pre-late Wisconsinan ice advances of Rainy provenance. Identified locally in water-well logs.
- *wt4* — Sandy loam diamicton (subsurface unit)—Massive, matrix-supported, sandy loam-textured, unsorted sediments with pebbles, cobbles, and scattered boulders. Highly cemented and contains a predominance of greenstone and metasedimentary clasts.
- *ws7* — **Sand and gravel** (subsurface unit)—Fine- to coarse-grained sand and fine- to coarse-grained gravel. Deposited by meltwater associated with pre-late Wisconsinan ice advances of Rainy provenance. Identified locally in water-well logs.
- *wt5* — **Sandy loam diamicton** (subsurface unit)—Massive, matrix-supported, sandy loam-textured, unsorted sediments with pebbles, cobbles, and scattered boulders. Highly cemented and contains a predominance of greenstone and metasedimentary clasts.

Unnamed formation of Winnipeg provenance—Brownish-yellow (10YR 7/2), loam-textured till and bedded glaciofluvial and glaciolacustrine sediments of Winnipeg provenance. This stratigraphic layer was recognized in few exposures within mine pits along the Mesabi Iron Range (Winter, 1971) and in rotary-sonic core SLL-11 (Appendix Fig. 9).

- *unws* — **Sand and gravel** (subsurface unit)—Fine- to coarse-grained sand and fine- to coarse-grained gravel. Deposited by meltwater associated with pre-late Wisconsinan ice advances, prior to the Winnipeg-provenance advance associated with the Bigfork Formation.
- *unwt* — **Clay-loam diamicton** (subsurface unit)—Calcareous, massive, matrix-supported, loam-textured, unsorted sediments with pebbles, cobbles, and scattered boulders. Paleozoic carbonate commonly comprises a low to moderate proportion of the very coarse-grained sand fraction, generally between 5 and 15 percent.

Undifferentiated Pleistocene deposits

- *uns* — **Sand to gravelly sand** (subsurface unit)—Identified in water-well logs; overlies unit *ups*.
- *ups* — **Undifferentiated Pleistocene sediment** (subsurface unit)—This unit includes all sediment (diamicton, sand and gravel, and silt and clay) below the lowermost identified till units. Although some water wells extend below this boundary, the data are too sparse to make meaningful interpretations.

Vertical exaggeration = 50x

CROSS-SECTION SYMBOLS

Geologic contact—Approximately located.

Drill hole—Includes well records from the Minnesota County Well Index (CWI) within a 0.3-mile (0.5-kilometer) threshold distance north and south of a cross-section line. Where the top of a drill hole does not coincide with the surface elevation depicted along a cross-section line, the actual location of the drill hole (within the threshold distance) may lie at an elevation above or below that of its east–west position on the cross-section line. Rotary-sonic core holes are labeled by hole number and associated unique number (in parentheses).

Bedrock contact—Contact point shown at the base of the Quaternary deposits with the associated bedrock map unit label from Plate 2, *Bedrock Geology*.

Unmapped tribal land—In accordance with the wishes of the tribal government, the lands of the Bois Forte Band of Chippewa are not included in this publication.

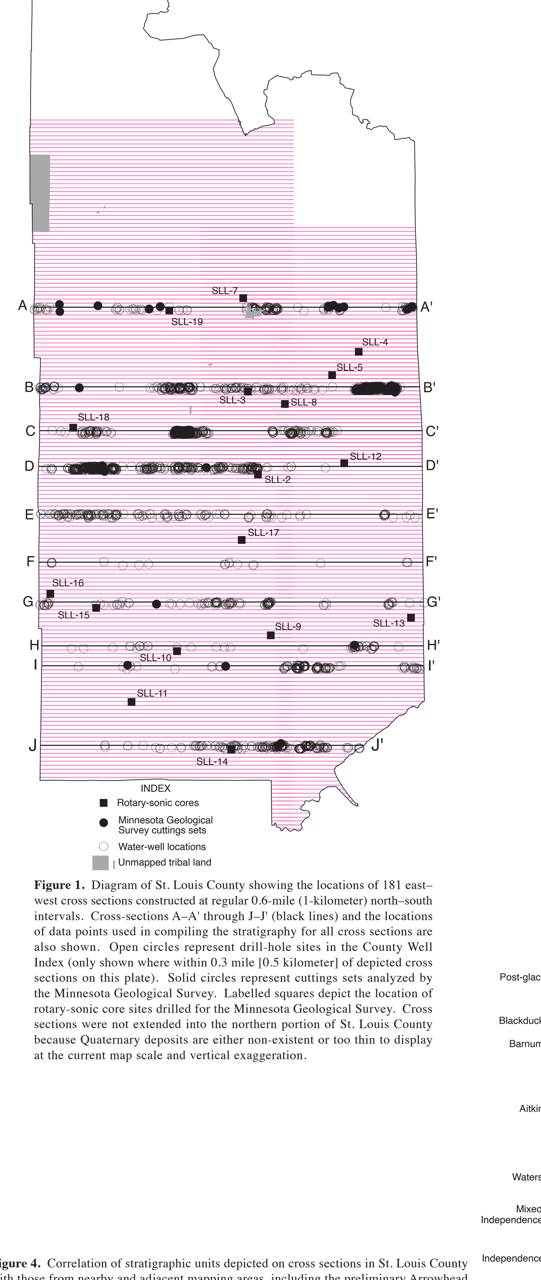

Figure 1. Diagram of St. Louis County showing the locations of 181 east–west cross sections constructed at regular 0.6-mile (1-kilometer) north–south intervals. Cross-sections A–A' through J–J' (black lines) and the locations of data points used in compiling the stratigraphy for all cross sections are also shown. Open circles represent drill-hole sites in the County Well Index (only shown where within 0.3 mile [0.5 kilometer] of depicted cross sections on this plate). Solid circles represent cuttings sets analyzed by the Minnesota Geological Survey. Labelled squares depict the location of rotary-sonic core sites drilled for the Minnesota Geological Survey. Cross sections were not extended into the northern portion of St. Louis County because Quaternary deposits are either non-existent or too thin to display at the current map scale and vertical exaggeration.

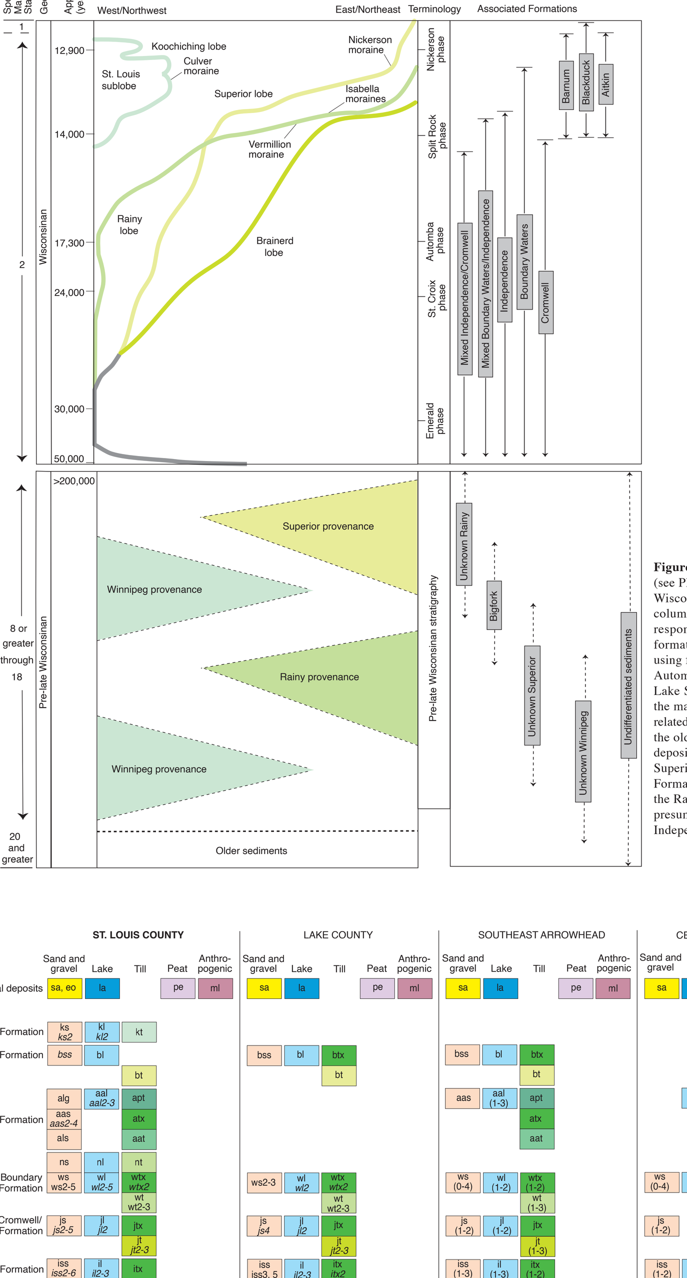

Figure 2. Diagram showing relative age, location (from west to east), provenance (see Plate 3, Fig. 2), and related lithostratigraphic unit from the cross sections for late Wisconsinan and pre-late Wisconsinan glacial deposits in St. Louis County. The age column and deposit drawings are schematic and not to scale. Multiple ice advances responsible for generating a series of lithostratigraphic units within an individual formation are not shown. Marine Isotope Stage (MIS) correlations were estimated using figures in Jennings and others (2006). The Barnum Formation includes all post-Automba-phase deposits of the Superior lobe and extends from the North Shore of Lake Superior west across the southern part of the county. Within St. Louis County, the majority of the Cromwell Formation deposits represent Superior-sourced material related to the Automba and St. Croix phases of the Superior lobe, although material from the older Emerald phase may be present locally. The northeast-sourced Superior lobe deposited sediments contemporaneously with the northeast-sourced (mixed Rainy and Superior provenances) Brainerd lobe. The mixed Boundary Waters and Independence Formations were emplaced along a former interlobate ice-marginal position between the Rainy and Brainerd lobes, where north and east of the Isabella moraines, this was presumably concurrent with or postdated deposition of the adjacent mixed Cromwell/Independence Formations. See Plate 3 for more description.

Table 1. Average values for the composition and matrix texture of till samples obtained from rotary-sonic cores within St. Louis County, collected and processed by the Minnesota Geological Survey for this project. See Plate 3, Table 1 for more values from samples obtained near the land surface. Matrix texture (the less than 2-millimeter grain-size fraction) is expressed as relative proportions of sand, silt, and clay, in percent. Gravel (the greater than 2-millimeter grain-size fraction) is reported as percentage by mass of each bulk 50-gram sample. The lithologic composition of the very coarse-grained sand component (the 1-2 millimeter fraction of the till matrix) is expressed in percent as relative proportions by grain-type. The crystalline category is further subdivided into light (granite, gneiss, monomineralic quartz), dark (mafic-rich igneous and metamorphic), and red (reddish basalt, rhyolite, arkose, iron formation) grain types.

		MATRIX TEXTURE				CLAST TYPE								
		Percentage of the less than 2 millimeter sand fraction				Percentage of total grains counted of the 1-2 millimeter fraction						Percentage of total crystalline grains counted		
Deposit description and geologic units shown on cross sections and Plate 3	Total number of samples	Sand	Silt	Clay	Gravel (percentage of total sample weight)	Crystalline	Carbonate	Shale	Precambrian	Paleozoic	Cretaceous	Light	Dark	Red
Aitkin Formation, Prairie Lake Member (unit apt)	8	41	38	21	6	86	9	5	85	8	7	78	19	3
Aitkin Formation, Alborn Member (unit aat)	11	36	34	30	7	98	1	1	98	1	1	61	36	3
Cromwell Formation (units ct, ct2-5)	14	48	47	5	20	100	0	0	100	0	0	26	54	20
Independence Formation (units itt, itt2-4)	40	58	35	7	24	100	0	0	100	0	0	30	44	26
Boundary Waters Formation, Nashwauk member (unit nt)	2	34	39	27	3	99	1	0	99	1	0	84	16	0
Boundary Waters Formation, Mesabi member (units wt, wt2-3)	39	52	37	11	19	100	0	0	100	0	0	63	34	3
Bigfork Formation (units bft, bft2)	11	32	38	30	7	90	10	0	90	10	0	78	12	10
Pre-late Wisconsinan unnamed Superior-provenance diamicton (unit unsp)	4	25	44	31	2	97	3	0	97	3	0	60	25	15
Pre-late Wisconsinan unnamed Winnipeg-provenance diamicton (unit unwt)	3	21	42	37	25	92	8	0	46	54	0	88	10	2

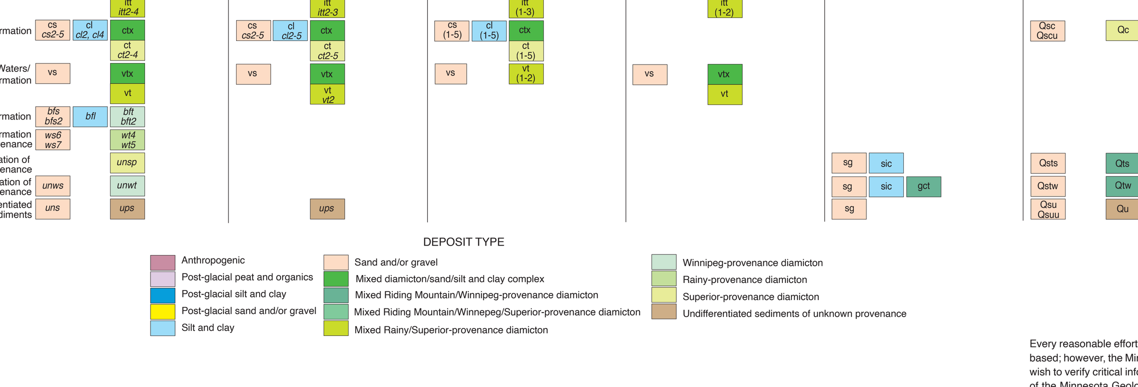

Figure 4. Correlation of stratigraphic units depicted on cross sections in St. Louis County with those from nearby and adjacent mapping areas, including the preliminary Arrowhead products released in Jirsa (2016) and the central Mesabi Iron Range area (Jirsa and Meyer, 2007, Plates 4A, 6). The Cromwell and Independence Formations are commonly interlayered without a consistent stratigraphic age relationship in St. Louis County, where they are interpreted to have been deposited near-contemporaneously. In Johnson and others (2016), the Barnum Formation was divided into multiple individual members based primarily on mapping further south and west in Carlton County. This mapping (Knaeble and Hobbs, 2009a) recognized that deposits of the Independence Formation are commonly mantled by the younger (Automba phase) Mille Lacs Member of the Cromwell Formation. In St. Louis County, the Superior-lobe ice margin did not extend west of the Highland moraine into that portion of the county previously covered by the Brainerd lobe. Also in Carlton County, deposits of the Barnum Formation are shown to bracket those of the Aitkin Formation; this is due to the presence of the Mahtowa (previously named Lakewood) member of the Barnum Formation in that area, which is recognized as slightly older than, or contemporaneous with, the Aitkin Formation. Individual members of the Barnum Formation were not recognized or mapped in St. Louis County.

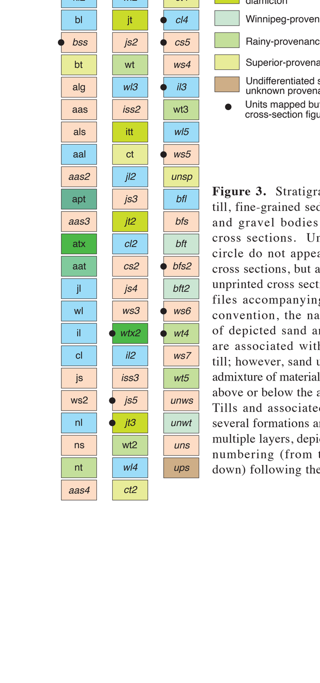

Figure 3. Stratigraphic position of till, fine-grained sediments, and sand and gravel bodies depicted in the cross sections. Units with a black circle do not appear on the printed cross sections, but are represented on unprinted cross sections in the digital files accompanying this plate. By convention, the name designations of depicted sand and gravel bodies are associated with the underlying till; however, sand units are likely an admixture of material from immediately above or below the actual named unit. Tills and associated sand bodies of several formations are subdivided into multiple layers, depicted by sequential numbering (from the land surface down) following the unit codes.

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Every reasonable effort has been made to ensure the accuracy of the factual data on which this map interpretation is based; however, the Minnesota Geological Survey does not warrant or guarantee that there are no errors. Users may wish to verify critical information; sources include both the references listed here and information on file at the offices of the Minnesota Geological Survey in St. Paul. In addition, effort has been made to ensure that the interpretation conforms to sound geologic and cartographic principles. No claim is made that the interpretation shown is rigorously correct, however, and it should not be used to guide engineering-scale decisions without site-specific verification.