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SURFICIAL GEOLOGY

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Loamy sand to gravelly sand—Massive, olive-brown (2.5Y 4/3) where

is the result of sorting of finer-grained sediments in stagnant meltwater

between large ice blocks, such as an ice-walled lake plain. Local sand

and gravel lenses along the edges of Lake Minnetonka indicate deltaic

meltwater flow into the basin. In all other mapped areas, meltwater

locally reworked previously deposited Heiberg Member till, washing

away finer-grained sediment and concentrating coarser-grained sediment.

Loam to clay loam diamict—Unsorted, olive-brown (2.5Y 4/4) where

oxidized, very dark gray (2.5Y 3/1) where unoxidized, diamict. Contains

scattered pebbles and cobbles; boulders are rare. Average lithologic

composition of the very coarse-grained sand fraction is shown in Table

2. The lithologic composition of this unit indicates much more shale

(average 41 percent) than units Qvt and Qtt. The surface expression is

generally rolling and hummocky with numerous ice-walled stagnation

plains and ice-block melt-out depressions indicative of ice stagnation.

Silt loam deposited in ponded water is thin, patchy, and locally present

on the tops of ice-walled stagnation plains. *Heiberg Member till*.

Fine-grained sand to sandy gravel—Fine-grained sand to gravel of

gravel that contains both red felsite and shale in statistically significant

proportions. Therefore, this unit is described as part of the Twin Cities

moraines associated with unit Qti, and along the sides of and within

former meltwater channels in northeast Minneapolis. This unit was

generated in two ways: by sediment sliding down the slopes of push

to very pale brown (10YR 7/4) where oxidized and finer-grained, silty

clay to loamy sand and gravel. Lithologic composition is similar to

unit Qtt. The surface expression is primarily in the form of linear to

concave up-ice moraines, but less linear and more rounded forms also

exist to a lesser extent. The interpretation of these features to be push

moraines is based on multiple soil borings on the tops of the moraines

encountering massive silty clay, silty clay loam, and silt loam (unit Qtl)

underlying 10 to 15 feet (3 to 4.5 meters) of sandy loam to loamy sand

(unit Qtt). Lacustrine sediment at this high elevation compared to the

bulldozing proglacial sediments into a positive land feature. Because

the formation of these ridges is ice-contact in origin, it warrants

inclusions of coarse-grained sand and gravel and diamict were also

found along two road cuts pictured in Figure 4, which show the faulted,

deformed, and complex nature of these deposits. Where more rounded

in shape, the unit is primarily loamy sand that overlies and mixes with

Superior-lobe ice-contact deposits, such as near Minnetonka and the

Bryn Mawr and Lowry Hill neighborhoods of Minneapolis. Where

patterned, unit was excavated to use as aggregate. Twin Cities Member

Silty clay to silt loam—Massive, light yellowish-brown (2.5Y 6/4) to

light olive-brown (2.5Y 5/3) where oxidized, very dark gray (2.5Y 3/1)

where unoxidized, silty clay to silt loam. The composition of the small

percentage of very coarse-grained sand in this unit is indicative of mixed

provenance, similar to unit Qtt (Table 2). Surface expression of this

unit is highly variable. The unit was initially deposited in proglacial

lakes as the Grantsburg sublobe advanced to the northeast. Continued

advance led to deformation of the unit into the aforementioned push

moraines, but this unit can also be found undeformed, especially on

Silty clay loam to sandy loam—Massive, reddish-brown (5YR 4/3)

to brown (7.5YR 4/3 to 10YR 4/3) to olive-brown (2.5Y 4/3) where

oxidized, very dark gray (7.5YR 3/1 to 10YR 3/1 to 2.5Y 3/1)

surrounding topography implies ice-marginal deformation essentially

Heiberg Member stagnation deposits.

Superior-lobe deposits. Villard Member till.

Member outwash.

Twin Cities Member colluvium.

ice-contact deposits.

Cities Member lacustrine deposits.

Qti

INTRODUCTION

This map emphasizes the origin and distribution of the surficial geologic sediments in Hennepin County, Minnesota. It is a revision of the surficial map by Meyer and Hobbs (1989). Updated data include: new well logs from the Minnesota Geological Survey County Well Index, new soil boring data from the Minnesota Department of Transportation, digitized soil maps and data sets (National Resources Conservation Service, 2014), new aerial photographic imagery, digitized lake bathymetry information, and county-wide 3-foot (1-meter) resolution lidar coverage (Fig. 1). Additional information from previous mapping was included in the analysis and interpretation of map units. These existing data were further augmented by fieldwork conducted in 2015 and 2016 that included observations at limited surficial exposures in gravel pits, excavations, construction sites, and road cuts, along with shallow hand auger borings to a depth of 5 feet (1.5 meters). These were supplemented by 150 auger borings using a Giddings soil probe to an average depth of 20 feet (6 meters; see Plate 1, Data-Base Map). A total of 1,038 samples were analyzed for texture, lithology of the very coarse-grained (1-2 millimeter) sand fraction, and Munsell color. All analytical results were digitized and compiled geospatially for mapping. In addition to new data, this map update includes new interpretations about glacial landforms and their associated sediments. Effort was made to account for human development on the landscape, but generally, the map depicts pre-development sediments found at the surface.

GLACIAL HISTORY

The surficial geology throughout Minnesota is complex, reflecting a long history of glacial and post-glacial events during the Pleistocene (2,600,000 to 11,700 years ago) and Holocene (11,700 years ago to present) Epochs. In Hennepin County, the surficial geologic units reflect the events of the last glacial maximum of the Laurentide Ice Sheet, named the Wisconsinan glaciation. The interpretation of these units is facilitated by recognition of distinct ice lobes that each generated a unique assemblage of rocks (Table 1). This unique assemblage is controlled by the bedrock type and sediment in the source area, or provenance, of the ice (Fig. 2).

Dakota County to the west. The St. Croix moraine was buried to the west and north

in Hennepin and Wright Counties by subsequent glacial advances, but it can be seen

at the surface in southeastern Stearns County. The location of the St. Croix moraine

in Hennepin County is therefore unclear. Subsequent subsurface interpretation of

glacial stratigraphy indicates that instead of forming one large moraine, the Superior

lobe formed multiple smaller moraines, implying that this portion of the Superior lobe

ice margin in Wright and Hennepin Counties fluctuated more than it did in adjacent

18,200 cal YBP³ (Clayton and Moran, 1982; Mooers and Lehr, 1997), generating a

wide, patchy network of coarse-grained outwash fan deposits at the mouths of tunnel

valleys as it receded (Mooers, 1989; Patterson, 1994), and contributing proglacial

meltwater to the freshly deglaciated landscape (Fig. 3B). Some of this meltwater

ponded in low spots on the landscape up-ice from recessional Superior-lobe deposits

and formed an early fine-grained sandy phase of glacial Lake Lind. Other meltwater

likely followed existing tunnel-valley paths and eventually coalesced and drained

into the ancestral Mississippi River. The Superior lobe also left behind numerous ice

blocks in and around the recently vacated landscape. These ice blocks likely persisted

throughout the final two glacial advances into Hennepin County, as evidenced by

ice-wedge polygons in the St. Croix moraine in Washington County, indicating an

extended period of very cold, continuous permafrost conditions after the advance of

the Superior lobe (Stanley, 2016). The first of these final advances, known as the

Automba phase, deposited Cromwell Formation till with higher silt and clay content

than older Superior-lobe tills, implying reworking of proglacial Lake Lind sediments

(Meyer, 1998). Automba-phase deposits extend south to north Minneapolis, and have

the final time by ice of the Des Moines lobe. The Des Moines lobe advanced into

northwestern Minnesota from Winnipeg and continued south to Des Moines, Iowa,

carrying rocks characteristic of Riding Mountain provenance (Fig. 2; Table 1).

Its deposits are called the New Ulm Formation, of which there are nine members

distinguished by texture and shale composition (Johnson and others, 2016). After the

advance of the Automba phase of the Superior lobe at 16,500 cal YBP⁴ and before the

formation of glacial Lake Grantsburg between 14,400 to 13,900 cal YBP⁵ (Wright and

Rubin, 1956; Clayton and Moran, 1982), an offshoot of ice from the Des Moines lobe,

called the Grantsburg sublobe, branched to the northeast (Fig. 3C). As it advanced,

the Grantsburg sublobe overrode freshly-deposited Superior-lobe sediments, including

Following the retreat of the Superior lobe, Hennepin County was glaciated for

been dated to be approximately 16,500 cal YBP⁴ (Clayton and Moran, 1982).

The Superior lobe then began to actively retreat to the northeast starting at about

Stearns and Dakota Counties.

Ice margin

Meltwate

win Cities

Glacial Lake Grantsburg deposits

St. Croix moraine

Member deposi

/illard Member

orientation switched from perpendicular to the ice margin to ice marginal. This Qhi parabolic ice margin continued to recede to a final position just east of Lake Minnetonka Fig. 3E). Lake Minnetonka is situated at the vertex/focal point of this parabolic ice margin, and the numerous bays of the lake, together oriented east-northeast in the Former direction of ice-flow, indicate active decay/erosion of Grantsburg-sublobe ice in the form of large ice blocks. It is likely these ice blocks persisted for some time as evidenced by the many peninsulas and isthmuses within the lake basin. These land forms represent former gaps or lows between ice blocks that were subsequently filled Qsh during the melting of the Grantsburg sublobe (unit Qsh), forming what is now a series of interconnected lake bays/basins.

As Grantsburg-sublobe ice continued to stagnate and calve into additional ice blocks, meltwater flowed into the lowland to the northeast in Anoka County to form glacial Lake Anoka (Fig. 3E), which persisted until 13,650 to 13,550 cal YPB⁶ (Meyer, 1998). One meltwater channel in Golden Valley may have flowed to the north into glacial Lake Anoka (unit Qnb), leading to deposition of the deltaic New Brighton Formation (unit Qnd) north of the channel. Eventually, the lake drained through an area of north Minneapolis termed the Camden breach (Fig. 3F; Meyer and Hobbs, 1989; Meyer, 1998), and led to the development of wide river terraces with numerous braided streams that flowed across the flat outwash and lake plains.

Additional meltwater from the drainage of glacial Lake Agassiz in northwestern Minnesota flowed to the southeast, then turned to the northeast toward Hennepin County. This deluge of meltwater, called glacial River Warren (Fig. 3F), carved the large valley of the modern Minnesota River (Wright, 1972). Glacial River Warren was initially the dominant meltwater conduit in the state, with the Mississippi River acting as a tributary. This restricted the Mississippi River to a lower terrace level and caused the formation of large slackwater lacustrine deposits on higher outwash terraces in Minneapolis. As glacial River Warren continued to entrench its valley, it reached a point near downtown St. Paul where it encountered a deeper former river channel/ bedrock valley and formed a waterfall atop Platteville Formation limestone (Wright, 1990). The poorly cemented St. Peter Sandstone below the Platteville Formation

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oxidized, dark gray (2.5Y 4/1) where unoxidized, loamy sand to gravelly Numbers in parentheses correspond to those shown on the Index to Previous Mapping. sand. This unit is lithologically similar to both units Qht and Qvt, but stratigraphically occurs within the Heiberg stagnation sequence. Unit Alley, R.B., Cuffey, K.M., Evenson, E.B., Strasser, J.C., Lawson, D.E., and Larson, probably represents a former ice-margin of the Grantsburg sublobe G.J., 1997, How glaciers entrain and transport basal sediment: Physical constraints: as it actively retreated to its final stagnation position east of Lake Minnetonka. Heiberg Member ice-contact deposits.

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Loam to sandy loam diamict—Unsorted, olive-brown (2.5Y 4/4) Johnson, M.D., and Mooers, H.D., 1998, Ice-margin positions of the Superior lobe where oxidized, very dark gray (2.5 Y 3/1) where unoxidized, diamict luring the late Wisconsinan deglaciation, in Patterson, C.J., and Wright, H.E., Ji Contains scattered pebbles and cobbles; boulders are uncommon. The eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological average lithologic composition of the very coarse-grained sand fraction Survey Report of Investigations RI-49, p. 7-14. is shown in Table 2. Generally contains less shale than unit Qht but Knaeble, A.R., 1998, Superior-lobe glacial thrusting of sediment and bedrock along more than unit Qtt. The surface expression is generally less rolling the St. Croix moraine, Stearns County, Minnesota, in Patterson, C.J., and Wright, and hummocky than unit Qht; ice-walled stagnation plains are rare. H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota This suggests deposition under active-ice conditions. Contains less Geological Survey Report of Investigations RI-49, p. 15-26. than 5 percent red clasts, indicating only slight mixing with underlying

COUNTY ATLAS SERIES ATLAS C-45, PART A **Hennepin County** Plate 3—Surficial Geology

multiple small terminal moraines and patchy recessional tunnel valley kames. Finegrained sand deposits of glacial Lake Lind facilitated the advance of the Grantsburg sublobe by providing an easily deformable substrate. There is also evidence that the Grantsburg sublobe overrode and deformed its own proglacial lacustrine sediments near the terminus at the Pine City moraine (Johnson and Hemstad, 1998), a process that may have occurred throughout the advance of the lobe. Once the flank of the Grantsburg sublobe reached the up-ice side of the St. Croix moraine, it encountered a more continuous and higher relief form of the moraine extending from Dakota County to the northeast through Ramsey and Washington Counties and was unable to advance any further. Grantsburg-sublobe deposits have variable composition, especially in shale content, which in Hennepin County and adjacent areas is the basis for the distinction between the Villard (unit Qvt) and Heiberg (unit Qht) Members of the New Ulm Formation. Evidence collected as part of this project suggests that the variability can be largely accounted for by the degrees of incorporation of substrate beneath the ice, and comminution of material by ice deformation. In this scenario, initial high shale content (greater than 40 percent) of sediment in up-ice areas of the Grantsburg sublobe was decreased by comminution to levels characteristic of the Villard Member as the ice flowed to the northeast. Additional changes in sediment composition occurred as the Grantsburg sublobe, now carrying sediment characteristic of the Villard Member, advanced further northeast through Hennepin County, where it incorporated underlying Superior-lobe deposits, generating the mixed provenance sediment of the Twin Cities Member of the New Ulm Formation (Figs. 4A, D, E; Stone, 1966; Chernicoff, 1980; Meyer and Hobbs, 1989; Meyer, 2007). Till of the Twin Cities Member (unit Qtt) is preferentially distributed along the former margins of the Grantsburg sublobe, where the ice was thinner, flowed radially, and sheared and incorporated underlying Superiorlobe deposits. This process of ice-marginal deformation under high stress gradients and longitudinally compressive flow is a well-documented phenomenon (Alley and others, 1997; Benn and Evans, 2010). The most striking examples of this deformation are the push moraines cored with mixed provenance lake sediment located in Eden Prairie, Edina, and Bloomington (unit Qti; Fig. 4A). The Twin Cities Member was also generated where the Grantsburg sublobe encountered topographically high tunnel valley kames of the Superior lobe located in Greenfield, Minnetonka, Maple Grove, and the Bryn Mawr and Lowry Hill neighborhoods of Minneapolis. The Twin Cities Member is absent or very thin in the subsurface along the former central axis of the Grantsburg sublobe, where the ice was thick and little to no erosion occurred. Instead, the Villard and Heiberg Members are present in this area overlying Superior-lobe deposits (Fig. 4C). The Villard Member was deposited during continued active ice flow, and thus maintained relatively low shale content produced by comminution. In contrast, the Heiberg Member was deposited late in the history of the sublobe, as active ice flow waned. It is associated with numerous ice stagnation features, including ice-walled stagnation plains and ice-block depressions. Comminution of shale was minimal in these conditions; therefore the shale content of the deposits is comparatively high. This interpretation of the content and distribution of the Villard and Heiberg Members is generally consistent with the Des Moines-lobe model of Matsch (1972). It differs from the suggestion of Lusardi and others (2011) that several ice streams with shifting source areas played a more important role in dictating compositional and textural variability. Further research is needed to better understand the relative contribution of these processes. Throughout the advance and active retreat of the Grantsburg sublobe, numerous meltwater channels incised proglacial sediments, eventually opening out to a broad outwash plain covering much of the eastern part of Hennepin County (unit Qts; Figs. 3D, E). The orientation of these channels indicates initial meltwater flow away from or perpendicular to the ice margin during the active recession of the Grantsburg sublobe (Fig. 5). Another meltwater channel perpendicular to this same ice margin flowed into Bde Maka Ska (formerly Lake Calhoun) toward the northeast. Once the margin deposits. retreated, it changed shape from concave to convex up-ice, and meltwater-channel SHERBURNE WRIGH

The first major ice advance into Hennepin County during the late Wisconsinan upstream until the Platteville Formation thinned just west of Fort Snelling State Park. glaciation was during the Emerald phase of the Superior lobe, for which a maximum age This collapse generated a waterfall where the tributary Mississippi River entered the of $32,547 \pm 762$ cal YBP¹ (Meyer and Stefanova, 2009; Meyer, 2010) was determined main river valley. This waterfall, known as St. Anthony Falls, continued to erode from wood underlying Superior-lobe deposits in Chisago County to the northeast. During upstream to the north and deepen the tributary Mississippi River valley to Minneapolis, this time, the Superior lobe advanced from the northeast and deposited sediments of the establishing the modern floodplain (Meyer and Hobbs, 1989; Wright, 1990; Meyer, Cromwell Formation (Johnson and others, 2016). These include reddish lacustrine, till, 1998). Minnehaha Falls in Minneapolis was contemporaneously formed during the outwash, and ice-contact deposits (unit Qsi) composed of sediments incorporated from retreat of St. Anthony Falls as the already established Minnehaha Creek joined with the underlying bedrock over which the lobe passed (Fig. 2; Table 1). An equilibrium the Mississippi River. Following the establishment of these river valleys, the volume position (when ice advances and melts at the same rate) of the Superior lobe during of meltwater decreased as all ice lobes finally vacated Minnesota. the Emerald phase is not evident everywhere in Minnesota because it was buried by In addition to rivers, Hennepin County is marked by a large number of lakes. Each subsequent glaciations, or it has a patchy surface expression, but the ice advance appears lake represents a former ice block or cluster of ice blocks left behind by the Grantsburg to have covered most of Hennepin County (Fig. 3A). It is likely that the Superior sublobe and/or the Superior lobe. Underlying bedrock topography also controls the lobe advanced contemporaneously with the Rainy lobe (also called the Wadena lobe), a north–northeast provenance ice lobe, during this phase (Fig. 3A). The Hewitt and Traverse de Sioux Formations associated with the Rainy lobe occur in Wright County to the west (Knaeble, 2013), but were not found in Hennepin County, indicating that

orientation of lakes, such as the chain of lakes in Minneapolis that overlies a large valley in the bedrock surface. Many of these lakes decreased in surface area throughout the Holocene Epoch, the normal result of a warmer post-glacial climate. In areas where lake levels have decreased, organic material (unit Qp) can be found at the land the boundary between the two ice lobes must have existed somewhere between the surface on top of and interbedded with lake sediment (unit QI). Organic deposits and two counties. The Superior and Rainy lobes eventually both retreated, the timing of slackwater lakes are common within the Minnesota River valley because the modern which is not constrained with radiocarbon age dates, but has been speculated to have river no longer occupies the entire width of the valley formed by glacial River Warren. occurred about 24,000 cal YBP² (Johnson and Mooers, 1998). Later, the Superior lobe It is also likely that eolian (wind) activity altered the landscape, especially on top readvanced into Hennepin County during the St. Croix phase. During the readvance of former ice-walled stagnation plains, but no significant thicknesses of windblown phase, the Superior lobe built the extensive St. Croix moraine (Fig. 3A), of which the sediment (loess) were identified. Further alteration of the landscape post-glacially closest surface expression to Hennepin County is along the northwestern border of resulted from industrialization and establishment of human society.

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DESCRIPTION OF MAP UNITS

Holocene

Qc Loamy sand and gravel—Mapped on steep bluffs along the Minnesota River and its tributary valleys. Unit consists of loose, redeposited sediments from upslope ranging from clay to boulders. Colluvium. Qp **Organic detritus**—Partially decomposed, fine- to coarse-grained plant matter in post-glacial land surface depressions currently or formerly beneath the water table. Only sediment with organic content greater than 50 percent is mapped. It is commonly underlain by organic-rich, Holocene Epoch, lacustrine, fine-grained sand, silt, and clay. Mapping was modified from the Natural Resource Conservation Service (2014).

Organic clayey silt to sand—Fine-grained organic matter (sapropel), may be both massive and laminated, fine-grained sand, silt, and clay in current or former lake basins or other areas of non-flowing water. Brown to black where organic-rich, gray-green-blue where unoxidized. May contain mollusk shells and other macro-organics. Includes wavegenerated shoreline and beach sediments along with human-made beaches. Most, if not all, of these lakes originated as water ponded in former ice-block locations. Where patterned, the lake was drained, excavated, and filled with other material. Unit is especially common in developed areas. Lacustrine deposits.

Silty clay loam to loamy fine-grained sand—Silty clay loam, silt loam, and loamy fine-grained sand that is common in floodplains in the Minnesota River valley. Also present in small, low-flow streams with a sediment load dominated by fine-grained material eroded from surrounding deposits. May be interbedded with peat and contain modern organic material. Fine-grained alluvium.

Qag Sand and gravel—Fine- to coarse-grained sand and gravel occupying modern river channels along the Mississippi and Crow Rivers. Generally coarsens with depth and contains scattered organics. Typically finergrained on higher elevation floodplains and coarser-grained in the modern stream channel. Coarse-grained alluvium.

Late Pleistocene

Qat **Terrace sand and gravel**—Similar to unit Qag in composition but no longer part of the present day channel of the Crow, Mississippi, and Minnesota Rivers. Deposited by formerly fast-flowing, channelized lacial meltwater related to glacial River Warren and the ancestral Crow and Mississippi Rivers. Terrace sediment.

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Figure 2. Location of major provenances and the distribution of ice-lobe materials at the land surface in Minnesota. Distinct assemblages of glacial sediments are derived from the unique suite of bedrock and sediment found in each of the source regions (provenances) shown. Sediments derived from Riding Mountain provenance are shown in green. The surface extent of Rainyand Superior-provenance sediments is shown in brown and pink, respectively. The St. Croix moraine is shown by the dotted line. Arrows indicate primary ice-flow direction.

MAP SYMBOLS

Geologic contact—Approximately located. Esker—A sinuous ridge of cobbles, gravel, and sand deposited in a subglacial tunnel channel/valley or ice-walled channel by flowing water. Arrows indicate interpreted flow direction. Locally reworked by anthropogenic activities.

Tunnel valley—A broad trough in the modern land surface that locally hosts both chains of lakes and eskers. The feature is aligned with a buried valley in the bedrock surface. Hachures point downslope. Interpreted to be a subglacial drainage channel of the Superior lobe. Other channels (not indicated) were filled during subsequent glacial events.

> **Ice margin**—A former equilibrium position of an ice lobe marking either the furthest extent of the lobe or recessional positions during ice retreat. Composed primarily of till with local pockets of sand and gravel. The ice margins in the southwestern portion of the county indicate the multiple, smaller terminal moraines generated by the Superior lobe during the St. Croix phase. All other ice margins represent recessional positions of the Grantsburg sublobe. These include washboard moraines in the northern part of the county. Ticks are on the up-ice side of the line.

Push moraine—Tall (50 to 150 feet [15 to 45 meters] of relief), linear to concave up-ice ridges that represent deformation of proglacial lacustrine sediments and St. Croix-moraine deposits by the Grantsburg sublobe (see Fig. 4A). Generally capped by Twin Cities Member diamict (unit Qtt) and cored by Twin Cities Member ice-contact deposits (unit Qti) with a large amount of variation locally depending on the type of St. Croix-moraine deposit that was reworked (such as sand and gravel, diamict, or lacustrine deposits).

Ice-walled stagnation plain—Broad, relatively level plateaus in areas of hummocky topography. Predominately composed of diamict with patchy caps of or interbedded with silt loam ranging in thickness from 1 to 9 feet (0.3 to 3 meters). Plateau relief ranges from 10 to more than 100 feet (3 to 30 meters) and reflects the former thickness of the stagnant ice.

Meltwater channel—Hachures on the downslope side indicate the flanks of former channelized meltwater flow. These channels were used repeatedly during various diamict-depositing events of the New Ulm Formation

General flow direction of meltwater—Arrows point downstream in the direction that glacial meltwater flowed.



Figure 3. A schematic depiction of the late Wisconsinan glacial history of Hennepin County and surrounding areas.

A. The Superior lobe first advanced into Hennepin County during the Emerald phase from the northeast (Superior provenance) and deposited sediment of the Cromwell Formation (gray). It likely advanced contemporaneously with the Rainy lobe, which flowed into Minnesota from the north-northeast (Rainy provenance) and deposited sediment of the Hewitt Formation (brown; southern ice margin). The position of the dashed line separating the two ice lobes is based on the existence of the Hewitt Formation sediments in adjacent Wright County. The Superior and Rainy lobes then retreated back to the northeast and north, respectively. The Superior lobe readvanced into Hennepin County during the St. Croix phase, including into territory formerly occupied by the Rainy lobe, and deposited the St. Croix moraine (northern ice margin). This readvance ice margin is marked by thrust-block uplifts (hill-hole pairs) identified within the Lake Minnetonka basin, and is interpreted to be contemporaneous to the Powder Ridge Winter Recreation Area ski hill, another thrust-block uplift in Stearns County (Knaeble, 1998). During this phase, it is also likely that the portion of the Minnesota River on the southern border of Hennepin County formed as an ice-marginal meltwater channel.

B. After the St. Croix phase, the Superior lobe retreated back toward the Lake Superior basin. Proglacial meltwater, following the paths of former tunnel valleys, dissected recessional Superior-lobe deposits and eventually coalesced toward the ancestral Mississippi River. Some of the meltwater ponded behind these recessional deposits and formed an early phase of glacial Lake Lind (dashed lines). This ponding was also controlled by the Stacy basin, a bedrock low. Numerous ice blocks (gray) were left behind on the recently ice-free landscape, with a high concentration in Hennepin County. Meanwhile, the Des Moines lobe advanced into Minnesota from the northwest (Riding Mountain provenance) and contributed meltwater to the area. C. As the Des Moines lobe continued to advance into Minnesota, an offshoot branched to the northeast from the central core of the lobe, forming the Grantsburg sublobe. This offshoot of ice flowed radially over the ice-cored, dissected, and patchy terrain of the Superior lobe and as a result incorporated sediments of Superior provenance. Grantsburg-sublobe meltwater in this area followed the existing channels cut by Superior-lobe meltwater and also flowed toward the Mississippi River. This advance generated the Twin Cities Member of the New Ulm Formation, particularly evident along the margins of the Grantsburg sublobe. A central axis core of Villard Member till was also deposited at this time in Hennepin County. Glacial Lake Grantsburg, a proglacial lake to the north, was active at this time.

D. The Grantsburg sublobe actively retreated from its maximum position at the Pine City moraine to the position shown. It continued to flow radially, generating arcuate washboard moraines marking annual recession. Meltwater channels emanated from the ice margin, cutting into recently deposited Twin Cities Member sediments. This recessional position also exposed deposits of the Villard Member of the New Ulm Formation on the southwestern side of the area delineating the St. Croix moraine. Because ice in this area did not cross the moraine, it is not of mixed provenance. Glacial Lake Grantsburg had drained by this time.

E. Active recession of the Grantsburg sublobe ceased and the ice stagnated, exposing more sediments associated with the Villard Member of the New Ulm Formation. Numerous meltwater channels emanated from this last ice margin, progressively dissecting recently deposited material. Some of this meltwater followed existing channels in southeastern Hennepin County, but the rest flowed to the northeast into the Stacy basin, forming glacial Lake Anoka. Within the stagnant ice, ponds of meltwater formed on the ice surface, generating ice-walled stagnation plains.

F. The stagnation of the Grantsburg sublobe generated the extensively ice-cored topography associated with the Heiberg Member of the New Ulm Formation in Hennepin County. Glacial Lake Anoka eventually drained through the Camden breach in north Minneapolis, cutting large terraces and delineating the modern path of the Mississippi River. Glacial Lake Agassiz in northwestern Minnesota also drained, forming the large glacial River Warren valley currently occupied by the Minnesota River. This deluge of meltwater also generated St. Anthony Falls.



Figure 4. Photos of the nature of Twin Cities area deposits. A. A cut along strike of a push moraine in Edina. Note the highly variable nature of the sediments, reflecting mixed pmposition and depositional environment. The Grantsburg ublobe deformed its own proglacial deposits and existing perior-lobe deposits into complex push-moraine assemblages : Twin Cities Member deposits. This road cut no longer ists; shovel for scale.

Another cut along strike of a push moraine in Edina. The wavy bedding of proglacial outwash fine-grained sand and silty fine-grained sand with microfaults emphasizes the deformed nature of these push moraines. This road cut no longer exists; shovel for scale.

C. A sharp contact between the Villard Member of the New Ulm Formation and the Cromwell Formation near St. Anthony. Despite being near the edge of Grantsburg-sublobe deposits, the Twin Cities Member was not generated, indicating that mixing and incorporation of underlying sediments was inconsistent Grain counts of the 1-2 millimeter very coarse-grained sand fraction of samples taken above and below the contact indicated very slight mixing between the two tills at the contact. Samples were taken using a Giddings soil auger, and the contact was at a depth of 17 feet (5.2 meters). **D.** An example of streaky Twin Cities Member till from Edina. The red color represents incorporated Cromwell Formation sediment (Superior provenance) into Grantsburg-sublobe till. The overall brown color of the till reflects mixed provenance, but the streaky nature implies immature and incomplete mixing. E. An example of the Twin Cities Member till from Golden Valley. This version of the Twin Cities Member is mottled, showing immature and incomplete mixing of the two tills. DMT: Des Moines-lobe till; ST: Superior-lobe till.

New Brighton Formation Very fine- to medium-grained sand-Massive, yellowish-brown to gray,

very fine- to medium-grained sand deposited in glacial Lake Anoka. Mixed provenance resulting from incorporation and/or erosion of both Superior-lobe and Grantsburg-sublobe deposits. Local silt lenses with depth, and gravelly near the surface where adjacent to glacial or fluvial sediment. Fine-grained sand facies of glacial Lake Anoka.

Sand and gravel—Massive, yellowish-brown to gray, medium- to coarsegrained sand and gravel with local minor cobbles associated with Grantsburg-sublobe meltwater flow into glacial Lake Anoka. Likely the result of reworking surrounding diamict through wave-washing along with deposition in a deltaic environment. Sand and gravel facies of glacial Lake Anoka.

New Ulm Formation—The units described below are the Heiberg, Villard, and Twin Cities Members of the New Ulm Formation. The youngest member, the Heiberg, contains considerably higher amounts of shale (average 41 percent) compared to the slightly older Villard (average 17 percent) and Twin Cities (average 13 percent) Members (Johnson and others, 2016). The Heiberg Member, on average, also contains more fine-grained material. The Heiberg and Villard Members both represent pure Riding Mountain-provenance deposits, whereas the Twin Cities Member represents both Riding Mountain- and Superior-provenance deposits. Unit Qno cannot be distinguished as either Heiberg or Villard Member sediment and is therefore undifferentiated, and unit Qts was generated by all three New Ulm Formation members and reflects mixed lithologic composition.

Fine-grained sand to sandy gravel—Massive, fine-grained sand to gravel along the Crow River. This unit is texturally similar to unit Qts but differs compositionally in its scarcity of Superior-provenance material (Table 2). It is present where Grantsburg-sublobe meltwater carved what is now the Crow River valley and eroded Villard and Heiberg Member deposits. New Ulm Formation outwash-undifferentiated. Silty clay loam to silt loam—Sorted, massive, olive-brown (2.5Y 4/3) where oxidized, dark gray (2.5Y 4/1) where unoxidized, lake sediment. The very coarse-grained sand fraction is composed primarily of shale, but few grains are present. The unit is mapped near Rogers, where a proglacial lake fronted the Grantsburg sublobe at the ice margin indicated. Locally interbedded with small sandy lenses that indicate small pulses of meltwater into the lake. Heiberg Member lacustrine

Loam to sandy loam diamict—Unsorted, reddish-brown (5YR 4/3) -1990, Geologic history of Minnesota rivers: Minnesota Geological Survey to brown (7.5YR 4/3 to 10YR 4/3) to olive-brown (2.5Y 4/3) where Educational Series 7, 20 p. oxidized, very dark gray (7.5YR 3/1 to 10YR 3/1 to 2.5Y 3/1) where Wright, H.E., Jr., and Rubin, M., 1956, Radiocarbon dates of Mankato drift in Minnesota: unoxidized, diamict. Contains many pebbles and cobbles; boulders are Science, v. 124, p. 625-626. common in places. Unit also includes lenses of sand, silt, and gravel in places. Average lithologic composition of the very coarse-grained

sand fraction is shown in Table 2. This average, however, does not ¹Age is in calendar years before present (cal YBP), recalibrated using CALIB illustrate the complex compositional variability within this unit. When radiocarbon calibration program Calib7.1 (Stuiver and others, 2017) with 2 sigma error the Grantsburg sublobe advanced to the northeast, it deformed and from radiocarbon date $28,580 \pm 220$ ¹⁴C (Meyer and Stefanova, 2009; Meyer, 2010). incorporated existing red Superior-lobe diamict into its own yellow ²Age is in calendar years before present (cal YBP), calibrated using CALIB diamict, generating red and yellow streaked, blended, and distorted radiocarbon calibration program Calib7.1 (Stuiver and others, 2017) with 2 sigma diamict (Fig. 4). Red diamict inclusions can also be found within error from an uncalibrated, speculated age of 20,000 cal YBP (Johnson and Mooers, predominantly yellow diamict. Pervasively mixed red and yellow 1998) till is uncommon in Hennepin County but can be found further to the

³Age is in calendar years before present (cal YBP), recalibrated and averaged northeast, where the Grantsburg sublobe continued to incorporate and using CALIB radiocarbon calibration program Calib7.1 (Stuiver and others, 2017) with deform existing Superior-lobe deposits. Twin Cities Member till. sigma error from radiocarbon dates 16,000 ¹⁴C, 15,500 ¹⁴C, and 15,000 ¹⁴C (Clayton Cromwell Formation—The only sediments of the Cromwell Formation and Moran, 1982; Mooers and Lehr, 1997).

mapped at the surface in Hennepin County are ice-contact deposits. ⁴Age is in calendar years before present (cal YBP), recalibrated and averaged Cromwell Formation diamict was once abundant at the surface but was using CALIB radiocarbon calibration program Calib7.1 (Stuiver and others, 2017) later covered by deposits associated with the Grantsburg sublobe. with 2 sigma error from radiocarbon dates 14,000 ¹⁴C and 12,030 ¹⁴C (Clayton and Loamy sand to sandy gravel—Reddish-brown to brown loamy sand to Moran, 1982).

sandy gravel. The surface expression of this unit is limited because ⁵Ages are in calendar years before present (cal YBP), recalibrated and averaged most deposits were reworked and buried by later glacial events, but it sing CALIB radiocarbon calibration program Calib7.1 (Stuiver and others, 2017) with is typically hummocky. These deposits were generated at the mouths sigma error from radiocarbon dates 12,300 ¹⁴C and 12,030 ¹⁴C (Wright and Rubin, of tunnel valleys, where pressurized subglacial meltwater carrying 1956; Clayton and Moran, 1982).

coarse-grained sediment reached the edge of the Superior lobe and Ages are in calendar years before present (cal YBP), recalibrated and averaged deposited the sediment as large-scale subaerial deltas or alluvial fans. sing CALIB radiocarbon calibration program Calib7.1 (Stuiver and others, 2017) with Consequently, this unit has been extensively mined in the Maple Grove gma error from radiocarbon dates 11,830 ¹⁴C and 11,710 ¹⁴C (Meyer, 1998). area for use as aggregate. Another deposit in Prospect Park marks the highest elevation in the city of Minneapolis. Where patterned, unit was excavated for use as aggregate. Superior-lobe ice-contact deposits.

loamy sand

Absent

Common



Table 1. Physical characteristics of glacial deposits in Hennepin

Table 2. Average values for the texture and composition of till, outwash, and lacustrine units of the New Ulm Formation recognized at the surface in Hennepin County. Matrix texture (less than 2-millimeter grain-size fraction) is expressed as relative proportions of sand, silt, and clay in percent. The lithologic composition of the very coarse-NORTHEAST grained sand fraction (1-2 millimeter) is expressed in percent as relative proportions of crystalline rock, carbonate SUPERIOR

rock, and shale fragments. The crystalline fraction is further subdivided by rock type: light (granite and gneiss), Superior (Cromwell red (rhyolite, felsite, agate, and sandstone), and dark (mafic igneous and metasedimentary/volcanic rocks). These Sandy loam to lithologic distinctions are one of the tools used to distinguish between glacial sediments and identify provenance. MATRIX TEXTURE CLAST TYPE Brown to red-brown Percentage of total grains Percentage of tota Gray to red-gray counted of the 1-2 crvstalline millimeter fraction grains counted Percentage of the Rare to uncommon less than 2 millimete Common to abundant fraction Common to common 88 11 1 Heiberg Member till (unit Qht) 381 4 41 39 40 26 34 116 7 49 34 56 25 19 86 12 2

/illard Member till (unit Qvt) Twin Cities Member till (unit Qtt) 73 7 54 30 16 76 15 9 70 18 12 New Ulm Formation outwash (unit Qno) 8 12 92 5 3 63 28 9 87 11 2 Twin Cities Member outwash (unit Qts) 73 16 91 7 2 82 15 3 74 18 8 Twin Cities Member lacustrine 20 1 23 52 25 73 13 14 72 19 9 deposits (unit Qtl)



Terrace scarp—An abrupt change in elevation (escarpment) marking the banks of former fluvial channels; interpreted to have been incised by fast flowing, high volume glacial rivers. Ticks are on the downslope side of the line. **Outcrop**—Undifferentiated limestone, shale, and sandstone exposed along the Mississippi River of Ordovician age. See Plate 2 for a more detailed description



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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.

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GEOLOGIC ATLAS OF HENNEPIN COUNTY, MINNESOTA