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

COUNTY ATLAS SERIES
ATLAS C-46, PART A
Kandiyohi County
Plate 4—Quaternary Stratigraphy

QUATERNARY STRATIGRAPHY

By

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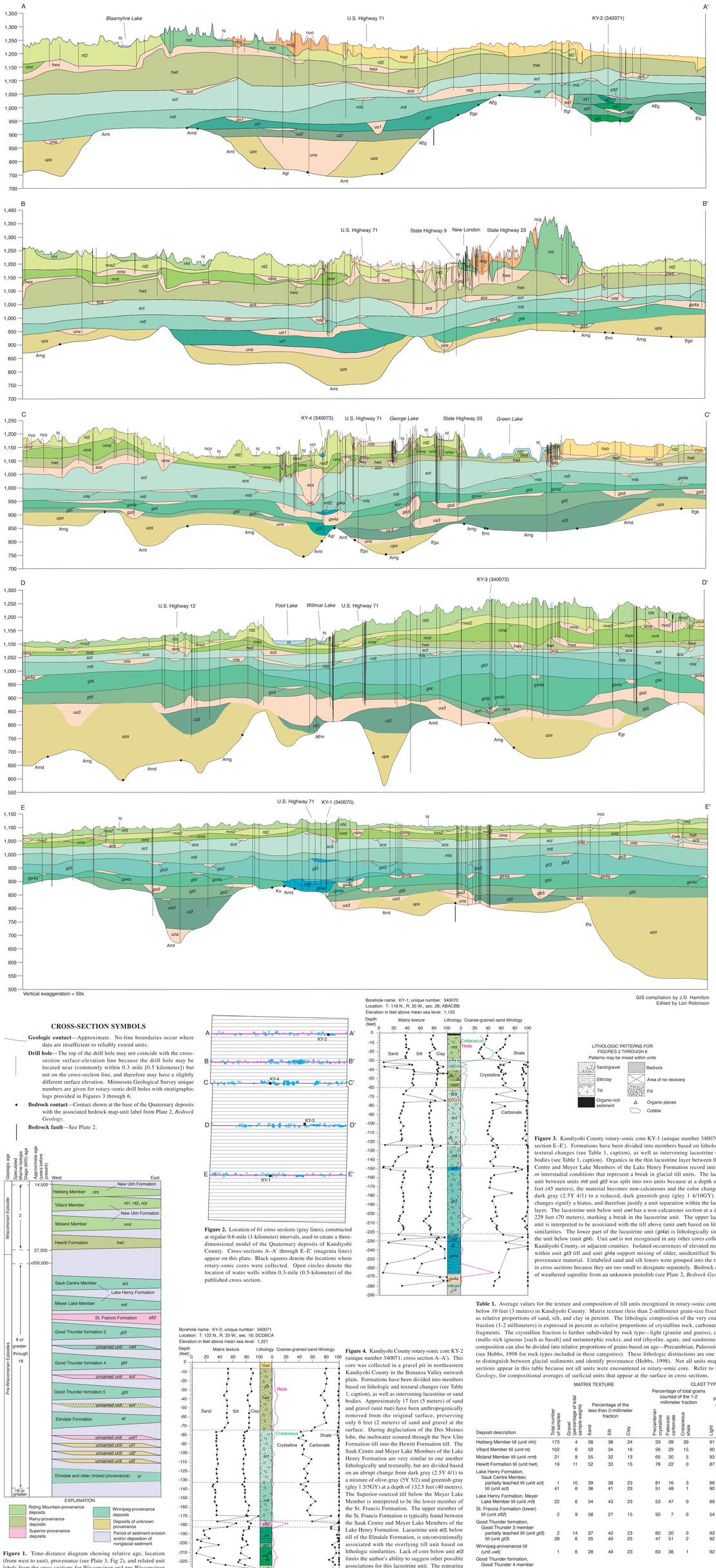
2019



GIS compilation by J.D. Hamilton
Edited by Lori Robinson

LOCATION DIAGRAM

INTRODUCTION

This *Quaternary Stratigraphy* plate shows the unconsolidated materials expected to be encountered between the land surface and bedrock surface in Kandiyohi County (Fig. 1). Cross sections A–A' through E–E' are representative of 61 cross sections (Fig. 2) at 0.6-mile (1-kilometer) spacing that were constructed to create a three-dimensional model of the Quaternary deposits of Kandiyohi County. 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 digital files of the Minnesota Geological Survey. The Quaternary geologic units shown on the cross sections were defined from interpretation of new data collected for this study and from existing data from previous investigations (see Index to Previous Mapping on Plate 3, *Surficial Geology,* for references to adjacent mapping projects). These include rotary-sonic core from four drill holes completed by the Minnesota Geological Survey for this project (KY-1 though KY-4; Figs. 3-6), water-well drillers' logs, cuttings set descriptions, bridge boring logs (Minnesota Department of Transportation, 2015), exposures, and auger samples (Plate 1, *Database Map*).

On the cross sections, drill holes are represented by vertical lines. Rotary-sonic drill holes are labelled with their borehole name and associated unique number (in parentheses). Interpreted logs of the four rotary-sonic cores are shown in Figures 3 through 6 and their locations are shown in Figure 2. Water-well drillers' logs and previous rotary-sonic cores collected by the Minnesota Geological Survey in adjacent counties were used for interpretation and provided significant detailed stratigraphic control. Vertical lines representing 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), where surface elevations could differ. Vertical exaggeration is 50x for all cross sections.

The variability of data is partially responsible for the spatial extent and complexity of the subsurface units shown on the cross sections. Units are generally portrayed (modeled) as continuous, with relatively uniform thicknesses and minimal elevation change where the data are scarce. Where there are more data, units appear more discontinuous and variable in thickness and elevation over relatively short distances, which reflects more accurately the complexity of glacial deposits. Fewer data exist for the older, deeper units, but they are more likely to be portrayed as discontinuous and variable because they are more eroded and dissected. These factors should be kept in mind when viewing the cross sections. 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 till units 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 in future drill holes at the approximate depth of till contacts shown (such as the western half of cross-section A–A', where wells mostly end in a shallow aquifer and there are scarce data for deeper stratigraphy).

The scarcity of deep water-well data makes it difficult to interpret and delineate the extent of older till units and associated sand layers. Rotary-sonic drill cores provide data for identifying these units; however, the extent of those units is highly uncertain only a short distance beyond the immediate vicinity of the core location. Based on the established stratigraphy for the region (Fig. 1), interpretations have been made using limited information provided by the records of isolated, deeper water wells. Where there are no data available at depth, the general regional stratigraphy has been extended in a schematic fashion in order to illustrate the potential presence of glacial units identified elsewhere. Units not separated by black contact lines indicate areas where the regional interpretation is especially speculative. Identification of unit boundaries and sand bodies in these areas is highly speculative.

For convenience, the surficial units that appear in the cross sections are equivalent to those mapped and described on the Surficial Geology map (Plate 3), and have the same label. An exception is unit nt; it is broken into two units on the cross sections: units nt1 and nt2, separated by a sand body within the mapped till unit. Peat (unit pe on Plate 3) is too thin to show on the cross sections and is combined with the surrounding surficial units. Subsurface units appear only on the cross sections and are labeled in italics.

By convention, the name designations of depicted sand and gravel bodies are associated with their underlying till, except for those at the land surface and those that intersect the lowermost unknown units. However, sand and till units are likely an admixture of material derived from immediately above or below the named unit. For example, sand unit *scs* is composed chiefly of outwash sediment laid down as the glacier depositing the Sauk Centre Member of the Lake Henry Formation (unit *sct*) retreated. However, it may also include proglacial meltwater deposits from the advance of ice that deposited the overlying Hewitt Formation in the northern part of Kandiyohi County (unit *hwt*), or the Moland Member of the New Ulm Formation in the southern half of the county (unit *nmt*). Where a particular stratigraphic unit is absent from the section, the units immediately above and below that missing unit likely include eroded remnants that are not shown. Where data from rotary-sonic core samples indicate that an interval of sand is lithologically associated with the overlying unit, it is labelled to reflect that formation name (for example, on Fig. 5A, unit *gs4b* is associated with the overlying Good Thunder formation and not the underlying unnamed Superior-sourced till [unit *sut1*]).

Table 1 and Appendix Figure 1 (located in the digital files that accompany this atlas) summarize the texture and composition of the subsurface units found in Kandiyohi County. Radiocarbon dates of organic material collected from rotary-sonic core appear in Table 2 and are discussed in unit-formation descriptions. Table 1 on Plate 5 shows the correlation of units mapped in Kandiyohi County with those mapped in adjacent Meeker (Meyer, 2015) and Renville Counties (Knaeble, 2013), where correlations can be made.

TILL GEOCHEMICAL ANALYSES

Till geochemical analyses conducted during this project support the unit separations based on core descriptions, intervening lacustrine and sand bodies, and textural and lithologic variations. Geochemical analysis was conducted on one rotary-sonic core (KY-3) as part of a broader program of analyses (Thorleifson, in press). In a manner consistent with methods used by Thorleifson and others (2007), the less than 63 micron fraction of till samples was analyzed by ICP-Mass Spectrometry following a four-acid, near-total dissolution. Analysis of the data indicated that several elements appear to correlate with provenances that are characterized by shale, carbonate, crystalline, and Superior-provenance sediments. Elements appearing to correlate with shale (such as Riding Mountain-provenance units *nht*, *nt*, and *nmt*) include arsenic, vanadium, thallium, antimony, nickel, molybdenum, cadmium, bismuth, zinc, and cesium (Fig. 5B). Elements appearing to correlate with carbonate (such as Winnipeg-provenance units *gt3* and *gt4*) include calcium and magnesium (Fig. 5C). Elements appearing to correlate with crystalline-derived debris (such as Rainy-provenance unit *hwt*) include sodium and strontium (Fig. 5D). Elements appearing to correlate with Superior-provenance sediment (such as Superior-provenance unit *sut*) include iron, titanium, copper, yttrium, and zirconium (Fig. 5E). In addition, some elements like sulfur and uranium appear to respond to multiple controlling factors, such as aeration after deposition and the interaction of groundwater at unit boundaries (Fig. 5F). Other elements may correlate with provenances or hydrologic controls, but the qualitative analysis is weaker and therefore not included in this atlas. Future analysis on these units, and units elsewhere in Minnesota, will allow for comparisons over larger spatial distances.

ACKNOWLEDGEMENTS

Rotary-sonic drilling was conducted by Trust Drilling. Minnesota Geological Survey staff members Anik Regan, Sonia Ellison, Shawn Scott, and Emily Bauer provided essential support during rotary-sonic drilling. Vania Stefanova analyzed and interpreted pollen samples in rotary-sonic cores KY-2 and KY-3. Kristina Brady from LacCore assisted in the logistics of obtaining wood dates for rotary-sonic cores KY-1 and KY-2. Thanks are extended to all landowners who allowed drilling on their property.

DESCRIPTION OF CROSS-SECTION UNITS

Surface units from Plate 3 are labeled as such in the descriptions. Subsurface units are indicated by italicized unit labels in the description. Unit labels and descriptions in gray text represent units that have been identified in adjacent Meeker County (units *wra*, *wrt*, *vs*, *vt*; Meyer, 2015) but have not been identified in any of the rotary-sonic cores in Kandiyohi County. These units are included here because they extend into Kandiyohi County cross sections in an effort to edge-match units. They appear only on the cross sections in the digital files accompanying this atlas. These units are shown with dashed outlines in Figure 1. Note that peat is not included in the cross sections because the unit is too thin. Refer to Plate 3 for more information on the peat unit.

HOLOCENE

al — **Fine-grained sand and gravel** (*Surficial Geology* unit)—Unit only appears in the digital files. *Alluvium.*

hl — **Silt and clay** (*Surficial Geology* unit)—*Lacustrine sediment.*

PLEISTOCENE

Late Wisconsinan

New Ulm Formation (Johnson and others, 2016)—Sediment deposited by ice of the Riding Mountain provenance Des Moines lobe (Plate 3, Fig. 2). Stratigraphic data from rotary-sonic cores collected in Kandiyohi County and water-well records indicate that there are at least three till members with associated bedded sediments that are attributed to the New Ulm Formation (Fig. 5A). Units are easily identified using textural and lithologic distinctions in rotary-sonic cores (Table 1) and further separated in water-well records where thin sand or silt and clay layers separate till layers. Average lithologic composition of the very coarse-grained sand fraction (Table 1) differs from averages calculated for Plate 3, Table 2 within this formation, in part because averages from Plate 3 include only samples to a depth of 10 feet (3 meters) and averages for this plate only include samples collected in core and in auger samples below 10 feet (3 meters). See Plate 3 for additional information regarding surface-unit sample collection and more discussion on surface units *nht* and *nt*. Also refer to Plate 3 for average unit composition of the complex deposits (*nct*, *ncg*, *nct*), associated with the Villard Member of the New Ulm Formation, because they were only encountered in surface samples and not in rotary-sonic core. The Moland Member of the New Ulm Formation is considered to have been deposited by an earlier phase of the Des Moines lobe and could correlate to the Sheldon Creek Formation of Iowa, attributed to two glacial advances at approximately 26,000 to 40,000 ^{14}C yr BP (about 31,000 to 43,700 cal yr BP; Johnson and others, 2016). These dates are older than the dates associated with the Hewitt Formation (see formation description below), which was deposited before the Des Moines-lobe advance. Therefore, these dates are likely a maximum age for the Moland Member in Kandiyohi County, or the Moland Member might correlate to a younger unit than the Sheldon Creek Formation in Iowa. Wood pieces collected from the Moland Member till at a depth of 47.25 feet (14.5 meters) in rotary-sonic core KY-1 (Fig. 3) were radiocarbon dated. Results indicate that the age of the wood pieces are beyond the standard range of calibration curves (greater than 51,300 radiocarbon years) used to calibrate radiocarbon ages to calendar years before present (Table 2; Walker, 2005; Reimer, 2012). The organics are interpreted to be from older units that were incorporated from underlying strata and included in the Moland Member till.

Undifferentiated New Ulm Formation sediment

nls — **Silt and clay** (*Surficial Geology* unit)—Unit only appears in the digital files. *Glaciolacustrine sediment of glacial Lake Benson.*

nuo — **Sand to loamy sand and gravel** (*Surficial Geology* unit)—*Glaciofluvial sediment.*

nco — **Sand to loamy sand and gravel** (*Surficial Geology* unit)—*Collapsed glaciofluvial sediment.*

Heiberg Member

nht — **Loam to clay-loam diamicton** (*Surficial Geology* unit)—Average composition of the very coarse-grained sand fraction (Table 1) indicates a higher percentage of gray shale fragments (39 percent) in the subsurface material than the average surface-sample composition (31 percent). Encountered in rotary-sonic cores KY-1 (Fig. 3) and KY-3 (Fig. 5A). *Glacial till.*

Villard Member

ncl — **Silt and clay** (*Surficial Geology* unit)—Unit only appears in the digital files. *Glaciolacustrine complex deposit.*

ncg — **Sand to loamy sand and gravel** (*Surficial Geology* unit)—*Glaciofluvial complex deposits.*

nct — **Sandy loam to loam diamicton** (*Surficial Geology* unit)—*Villard Member complex deposits.*

nvl2 — **Silty loam**—Dark gray, unoxidized color where encountered in rotary-sonic core KY-4 (Fig 6). *Glaciolacustrine sediment.*

nvs2 — **Sand to sandy loam**—*Glaciofluvial sediment.*

nt — **Sandy loam to loam diamicton** (*Surficial Geology* unit)—Includes both till units nt1 and nt2. Average composition of the very coarse-grained sand fraction (Table 1) is characterized by a moderate percentage of gray shale fragments (15 percent). Typically preserved as a thinner unit than older, pre-Wisconsinan formations, especially in the southern half of the county, and is likely not as continuous as portrayed in cross sections. Encountered in rotary-sonic cores KY-3 (Fig. 5A) and KY-4 (Fig. 6). *Glacial till.*

Moland Member

nms — **Sand to gravely sand**—*Glaciofluvial sediment.*

nmt — **Sandy loam to loam diamicton**—Pebbly, unsorted; light olive-brown (2.5Y 5/3) where oxidized and dark gray (2.5Y 4/1) where unoxidized. More sandy and gravelly in the northern half of the county, likely due to mixing with the sandier underlying Hewitt Formation till (unit *hwt*), as well as glaciofluvial sand and gravel associated with the Hewitt Formation (unit *hws*). Typically preserved as a thinner unit than older, pre-Wisconsinan formations, especially in the southern half of the county, and is likely less continuous than portrayed in cross sections. Average composition of the very coarse-grained sand fraction (Table 1) is characterized by a low percentage of gray shale fragments (5 percent). Encountered in rotary-sonic cores KY-1 (Fig. 3), KY-3 (Fig. 5A), and KY-4 (Fig. 6). *Glacial till.*

Hewitt Formation (Johnson and others, 2016)—Sediment deposited by the Rainy provenance Wadena lobe (Plate 3, Fig. 2). A radiocarbon date of 22,960 ± 90 ^{14}C yr BP (27,294 ± 209 cal yr BP[1]) was extracted from silt below a sand and gravel layer in Blue Earth County to the southeast and is interpreted to represent the timing of the advancing Wadena lobe (Meyer and others, 2012). Wood pieces collected in the Hewitt Formation till at a depth of 26 feet (8 meters) in rotary-sonic core KY-2 (Fig. 4) were radiocarbon dated. Results indicate that the age of the wood pieces are beyond the standard range of calibration curves (greater than 49,500 radiocarbon years) used to calibrate radiocarbon ages to calendar years before present (Table 2; Walker, 2005; Reimer, 2012). The organics are interpreted to be from older units that were incorporated from underlying strata and included in the Hewitt Formation till. Alternatively, the Wadena lobe may have advanced earlier than originally thought, beyond the datable age limit of radiocarbon. The modern expression of the Alexandria moraine has conventionally been interpreted to represent a palimpsest Wadena-lobe arcuate moraine feature, consisting of a thick sequence of Hewitt Formation till (Johnson and others, 2016). Comparison of the thicknesses of the New Ulm Formation and the Hewitt Formation (Appendix Fig. 2 [located in the digital files]) show that thick New Ulm Formation covers much of the Alexandria moraine, and the Hewitt Formation thins in the south–southeastern portion of the moraine. The thin to absent Hewitt Formation challenges the conventional interpretation of the Alexandria moraine that the core of the moraine is dominantly Hewitt Formation, capped by thin New Ulm Formation material. The author suggests a compromise in moraine genesis, whereby a once-massive moraine complex was created during the advancing and stagnation of the Wadena lobe into south-central Minnesota (Plate 3, Fig. 3A); when the Des Moines lobe later advanced into south-central Minnesota, it encountered hummocky topography with ice blocks and unoccupied tunnel valleys. Ice overtopped the moraine (Plate 3, Figs. 3B, C), but was thin in some places, and able to scour along the southern side of the moraine, preserving thinner Hewitt Formation material and depositing thicker New Ulm Formation material in the tunnel-valley lows. Thin to absent Hewitt Formation till in eastern adjacent counties, such as Wright County (Knaeble, 2003), also support the interpretation that the thicker Des Moines-lobe ice was able to scour and incorporate the Hewitt Formation material along the flanks of the lobe.

hws — **Sand to gravelly sand**—*Glaciofluvial sediment.*

hwt — **Loam to sandy loam diamicton** (*Surficial Geology* unit)—Unit only encountered in auger holes and rotary-sonic core (KY-2 [Fig. 4] and KY-3 [Fig. 5A]) on and north of the Alexandria moraine in Kandiyohi County. The Hewitt Formation is interpreted to have been scoured and incorporated into the New Ulm Formation units during the advance of the Des Moines lobe, causing the patchy distribution of the unit. The unit is mapped in cross sections south of the moraine in order to line-match with adjacent Meeker County, but is thought to be less preserved south of the moraine. *Glacial till.*

Pre-Wisconsinan

Lake Henry Formation (Johnson and others, 2016)—Sediment deposited by ice of Winnipeg provenance (Plate 3, Fig. 2). The Lake Henry Formation is regionally extensive and continuous into surrounding counties. Two members are encountered in all cores in Kandiyohi County, the Sauk Centre and Meyer Lake. The Cretaceous clasts of the 1-2 millimeter sand fraction are notably higher (approximately 3 to 9 percent; Fig. 3), especially for the Sauk Centre Member, which resembles the Good Thunder 1 and 2 members of the informal Good Thunder formation (Knaeble, 2013). This suggests that the Good Thunder 1 and 2 members are stratigraphically and chronologically equivalent to the Sauk Centre and Meyer Lake Members of the Lake Henry Formation, respectively, and therefore they are assigned here to the Lake Henry Formation. The Lake Henry Formation was similarly correlated to the upper units of the Good Thunder formation in Meeker County (Meyer, 2015). Spatial variation in ice dynamics during sediment deposition likely accounts for the differences in abundance of Cretaceous grains. The Sauk Centre Member commonly has more carbonate clasts than the Meyer Lake Member (Fig. 5A), but in other cores in Kandiyohi County, the carbonate content was similar (Figs. 3, 4, 6), and the members were separated based on color changes or intervening bedded sediment.

Sauk Centre Member

scs — **Sand to gravelly sand**—*Glaciofluvial sediment.*

sct — **Loam to clay-loam diamicton**—Pebbly; unsorted; commonly a reduced greenish-gray (gley 1 5/10Y) at the upper contact and dark gray (2.5Y 4/1) where unoxidized. Unit is partially leached at the upper contact in rotary-sonic cores KY-1 (Fig. 3) and KY-2 (Fig. 4). Correlated to the informal Good Thunder 1 member of the Good Thunder formation (Knaeble, 2013; Meyer, 2015). *Glacial till.*

Meyer Lake Member

mls — **Sand to gravelly sand**—*Glaciofluvial sediment.*

mlt — **Loam to silt or clay-loam diamicton**—Pebbly; unsorted; commonly a reduced greenish-gray (gley 1 5/10Y) at the upper contact, olive-gray (5Y 5/2) where oxidized, and dark gray (5Y 4/1) where unoxidized. Correlated to the informal Good Thunder 2 member of the Good Thunder formation (Knaeble, 2013; Meyer, 2015). *Glacial till.*

mlt2 — **Silty clay loam to silt loam**—Very dark gray, unoxidized where encountered in rotary-sonic core KY-4 (Fig. 6). *Glaciolacustrine sediment.*

St. Francis Formation, lower unit (Johnson and others, 2016)—Sediment deposited by Superior-sourced ice. Commonly interfingers with the members of the Lake Henry Formation, but only the lower member is encountered in Kandiyohi County (Fig. 4) below the Meyer Lake Member. Unit is typically thin and discontinuous, especially in south-central Minnesota.

sfs2 — **Sand to gravelly sand**—Unit only appears in the digital files. *Glaciofluvial sediment.*

sft2 — **Sandy loam to loam diamicton**—Pebbly; unsorted; gray, reduced with a pink hue (7.5YR 6/1) in rotary-sonic core. *Glacial till.*

Good Thunder formation (Knaeble, 2013)—Sediment deposited by ice of Winnipeg provenance (Plate 3, Fig. 2). Informal unit first defined in Renville County (Knaeble, 2013) and exposed along the Minnesota River valley. The formation has a high percentage of carbonate clasts and a moderately high amount of Cretaceous grains (Table 1). Older Superior-sourced units locally interfinger with the formation in places (such as unit *sut* in Fig. 5A). There is limited understanding of the timing of deposition for the formation, its spatial extent, and how it varies lithologically and texturally over wide distances. It may correlate in part to the formal Eagle Bend Formation of central Minnesota, or other older units. A thin layer (0.5 foot [0.1 meter]) of laminated clay collected from rotary-sonic core KY-3 (Fig. 5A), interpreted to be part of the Good Thunder 4 member of the Good Thunder formation at a depth of 291 feet (89 meters) was analyzed for pollen content. Macrofossil content from the sample "… indicates most probably glacial conditions." (Stefanova, unpub. data), suggesting that a period of warming did not occur between the advance of the Good Thunder 4 and Good Thunder 3 members. Alternatively, the sediment deposited during a warming period was eroded and not preserved in this section.

Good Thunder 3 member

gt3 — **Silty clay loam to silt loam**—Dark greenish-gray (gley 1 4/10GY) in rotary-sonic core KY-1 (Fig. 3). *Glaciolacustrine sediment.*

gs3 — **Sand to gravelly sand**—Only encountered in water-well logs as noted in the County Well Index. *Glaciofluvial sediment.*

gt3 — **Loam to clay-loam diamicton**—Pebbly; unsorted; a reduced greenish-gray (gley 1 5/10Y) at the upper contact, and dark gray (2.5Y 4/1) to very dark gray (2.5Y 3/1) where unoxidized. Encountered in rotary-sonic cores KY-1 (Fig. 3) and KY-3 (Fig. 5A). *Glacial till.*

Unnamed formation of Winnipeg provenance—Sediment deposited by Winnipeg-sourced ice (Plate 3, Fig. 2). Unit is only present in rotary-sonic boring KY-1 (Fig. 3), and therefore the spatial extent of this unit is unknown. It is only mapped in the southern part of Kandiyohi County.

uwt — **Loam diamicton**—Pebbly, unsorted; very dark gray (2.5Y 3/1) to dark gray (2.5Y 4/1) where reduced. Averages 36 percent carbonate clasts (Table 1). *Glacial till.*

uwl — **Loamy sand to silt loam**—*Glaciolacustrine sediment.*

Good Thunder formation (Knaeble, 2013)—See above description.

Good Thunder 4 member

gl4a — **Silty clay loam to silt loam**—Predominantly silt clay loam to silt loam, but includes sections of sand and sandy loam. Very dark gray (5Y 3/1) in rotary-sonic cores KY-1 (Fig. 3) and KY-4 (Fig. 6). *Glaciolacustrine sediment.*

gs4a — **Sand to gravelly sand**—*Glaciofluvial sediment.*

gt4 — **Loam to clay-loam diamicton**—Pebbly, unsorted; commonly a reduced dark gray (gley 1 4/10Y) at the upper contact, and dark gray (2.5Y 4/1) to gray (2.5Y 5/1) where reduced. Encountered in rotary-sonic cores KY-1 (Fig. 3) and KY-3 (Fig. 5A). *Glacial till.*

gl4b — **Silt loam to silty clay loam**—Light olive-brown (2.5Y 5/3) in rotary-sonic core KY-3 (Fig. 5A). *Glaciolacustrine sediment.*

gs4b — **Sand to gravelly sand**—*Glaciofluvial sediment.*

Unnamed formation of Superior provenance 1—Sediment deposited by Superior-sourced ice (Plate 3, Fig. 2). Unit is only present in rotary-sonic boring KY-3 (Fig. 5A), and therefore the unit is mapped only immediately surrounding this core.

sus — **Sand to gravelly sand**—*Glaciofluvial sediment.*

sut — **Sandy loam diamicton**—Pebbly; unsorted; olive-brown (2.5Y 4/4) where partially oxidized and brown (7.5YR 4/2) where oxidized. *Glacial till.*

Good Thunder formation (Knaeble, 2013)—See above description.

Good Thunder 5 member

gl5 — **Silt to silt loam**—Grayish-brown (2.5Y 5/2) where oxidized and dark gray (2.5Y 4/1) where unoxidized. Encountered in rotary-sonic core KY-4 (Fig. 6). *Glaciolacustrine sediment.*

gs5 — **Sand to gravelly sand**—*Glaciofluvial sediment.*

gt5 — **Sandy loam diamicton**—Pebbly, unsorted; brown (7.5YR 4/2) in rotary-sonic core KY-3 (Fig. 5A). Much sandier than other Good Thunder formation members, possibly due to mixing of older, underlying units. *Glacial till.*

Unnamed formation of Rainy provenance (Meyer, 2015)—Sediment deposited by Rainy-provenance ice (Plate 3, Fig. 2). Encountered in rotary-sonic cores MS-1, MS-2, MS-5, and MS-6 in Meeker County.

wrs — **Sand and gravel**—*Glaciofluvial sediment.*

wrt — **Loam diamicton**—*Glacial till.*

Elmdale Formation (Johnson and others, 2016)—Sediment deposited by ice of Winnipeg provenance (Plate 3, Fig. 2). Unit contains red clasts in till and sand and lacustrine sediment, locally indicating possible incorporation of older, Superior-sourced sediment. Only encountered in rotary-sonic core KY-2 (Fig. 4), but extended to match units *wte* and *wse* of Meeker County (Meyer, 2015). No direct age date is associated with the Elmdale Formation, but ambiguous detrital remanent magnetism analyzed on a diamicton similar in stratigraphic position to the Elmdale Formation suggested it was deposited at or prior to the Brunhes-Matuyama magnetic-reversal boundary (780,000 yr BP; Johnson and others, 2016). The subsurface extent of this unit is not well defined. It is roughly correlated to the Wirt Formation of northern Minnesota and the Pierce Formation of western Wisconsin (Johnson and others, 2016). Unlabeled sand and silt lenses were grouped into the till units in cross sections because they are too small to designate separately. Clay and silt (lacustrine) situated between two layers of Elmdale Formation till collected from rotary-sonic core KY-2 (Fig. 4) at a depth of 211 feet (64 meters) was analyzed for pollen content. Microfossil analysis from the sample "… indicates most probably glacial conditions." (Stefanova, unpub. data), and suggests that there was no warming between the deposition of the two Elmdale Formation till layers. Alternatively, sediment deposited during a warming period may have been eroded, but it is more likely that there was no warming between deposition of the tills of the same formation.

el1 — **Silt loam to loam**—Greenish-gray (gley 1 5/5GY) where reduced and very dark gray (2.5Y 3/1) where unoxidized. *Glaciolacustrine sediment.*

es — **Sand to gravelly sand**—Includes two sand units, numbered 1 and 2. *Glaciofluvial sediment.*

el — **Loam to clay or silt-loam diamicton**—Unsorted; dominantly loam, but includes sections of silt loam or clay loam. Dark gray (gley 1 4/N) where reduced and dark gray (5Y 4/1) where unoxidized. Includes two till units, numbered 1 and 2. Encountered only in rotary-sonic core KY-2 (Fig. 4). *Glacial till.*

el2 — **Clay loam to silt loam**—Very dark gray (2.5Y 3/1) where unoxidized in rotary-sonic core KY-2 (Fig. 4). *Glaciolacustrine sediment.*

el3 — **Clay loam to silty clay loam**—Very dark gray (2.5Y 3/1) to black (5Y 2.5/1) where unoxidized in rotary-sonic core KY-2 (Fig. 4). *Glaciolacustrine sediment.*

Unnamed formation of Superior provenance 2—Sediment deposited by Superior-sourced ice (Plate 3, Fig. 2). Unit known only from water-well drilling descriptions, described as "red clay" or similar phrasing. Information is insufficient to assign it to any units defined elsewhere. May include glaciofluvial or lacustrine deposits. The spatial extent is unknown and it is mapped only immediately surrounding the well locations in which the material was noted. Superior-provenance material is commonly thin and patchy in south-central Minnesota and therefore this unit is unlikely to be extensive.

ust1 — **Diamicton**—Unit only appears in the digital files. May include glaciofluvial or lacustrine deposits. *Glacial till.*

The units below have been identified in water-well logs and have been named as described therein, but information about them is insufficient to be certain of material content. The author has mapped these units stratigraphically below the Good Thunder and Elmdale formations for convenience, but they could potentially correlate to any of the lower members of the Good Thunder formation, or the Elmdale Formation.

Unnamed formation 1

us1 — **Sand and/or gravel**—Described in water-well records. May include till or lacustrine deposits. *Glaciofluvial sediment.*

ut1 — **Clay**—Described in water-well records. May include outwash or lacustrine deposits. *Glacial till.*

Unnamed formation 2

us2 — **Sand and/or gravel**—Described in water-well records. May include till or lacustrine deposits. *Glaciofluvial sediment.*

ut2 — **Clay**—Described in water-well records. May include outwash or lacustrine deposits. *Glacial till.*

Unnamed formation 3

us3 — **Sand and/or gravel**—Described in water-well records. May include till or lacustrine in places. *Glaciofluvial sediment.*

ut3 — **Clay**—Described in water-well records. May include outwash or lacustrine deposits in places. *Glacial till.*

Elmdale Formation and Unit V (Meyer, 2015)—Mostly sediment deposited by Winnipeg-provenance ice, but also includes sediment of Superior and Rainy-provenance ice (Plate 3, Fig. 2). Encountered in rotary-sonic core MS-6 in Meeker County.

vs — **Sand and gravel**—*Glaciofluvial sediment.*

vt — **Loam to silty diamicton**—*Glacial till.*

uns — **Undifferentiated Quaternary sand to gravelly sand**—Identified in water-well records; overlies unit *ups*.

ups — **Undifferentiated Pleistocene sediment**—This unit includes all sediment (till, sand and gravel, and lacustrine silt and clay) below the lowermost identified till units, and may include units identified elsewhere in the county. Although some water-well logs extend below this boundary, the data are too sparse to make meaningful correlations.

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[1]Ages are in calendar years before present (cal YBP), recalibrated and averaged using CALIB radiocarbon calibration program Calib7.1 (Stuiver and others, 2016) with 2 sigma error.

CROSS-SECTION SYMBOLS

- **Geologic contact**—Approximate. No-line boundaries occur where data are insufficient to reliably extend units.
- **Drill hole**—The top of the drill hole may not coincide with the cross-section surface-elevation line because the drill hole may be locatar (commonly within 0.3 mile [0.5 kilometer]) but not on the cross-section line, and therefore may have a slightly different surface elevation. Minnesota Geological Survey unique numbers are given for rotary-sonic drill holes with stratigraphic logs provided in Figures 3 through 6.
- **Bedrock contact**—Contact shown at the base of the Quaternary deposits with the associated bedrock map-unit label from Plate 2, *Bedrock Geology*.
- **Bedrock fault**—See Plate 2.

Figure 1. Time-distance diagram showing relative age, location (from west to east), provenance (see Plate 3, Fig 2), and related unit labels from the cross sections for Wisconsinan and pre-Wisconsinan glacial deposits modified from Meyer (2015). The age column and deposit drawings are schematic and not to scale. Dashed lines indicate units in the regional stratigraphy but not encountered in drill holes in Kandiyohi County. Marine Isotope Stage (MIS) correlations were estimated using figures in Jennings and others (2006). See Meyer (2015) for age constraints on units.

Figure 2. Location of 61 cross sections (gray lines), constructed at regular 0.6-mile (1-kilometer) intervals, used to create a