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MINNESOTA GEOLOGICAL SURVEY
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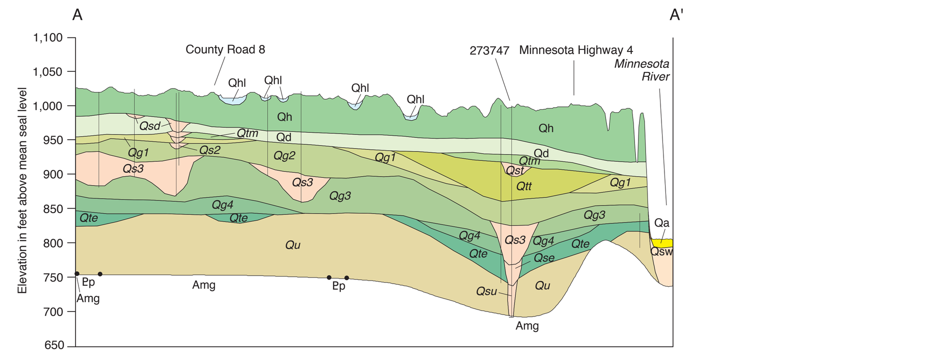
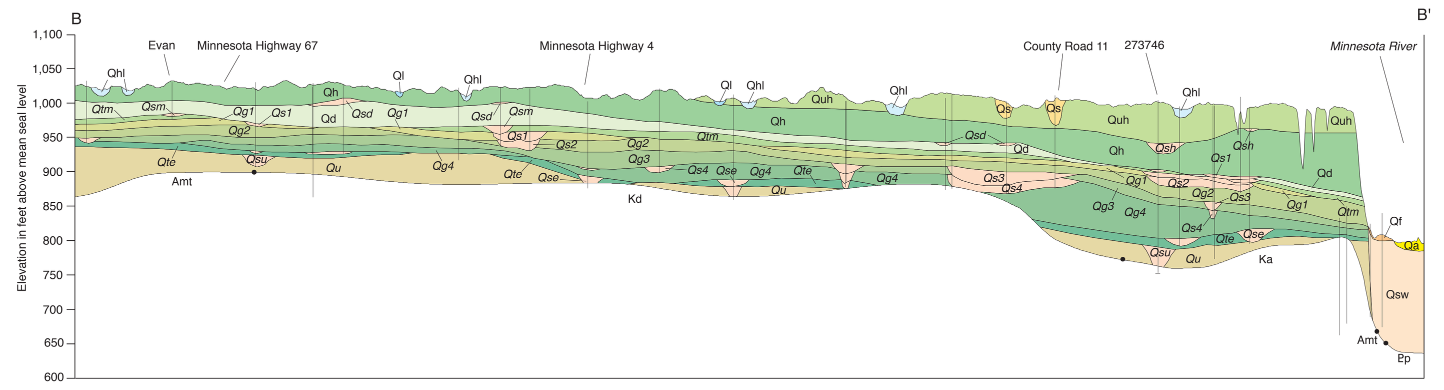
QUATERNARY STRATIGRAPHY

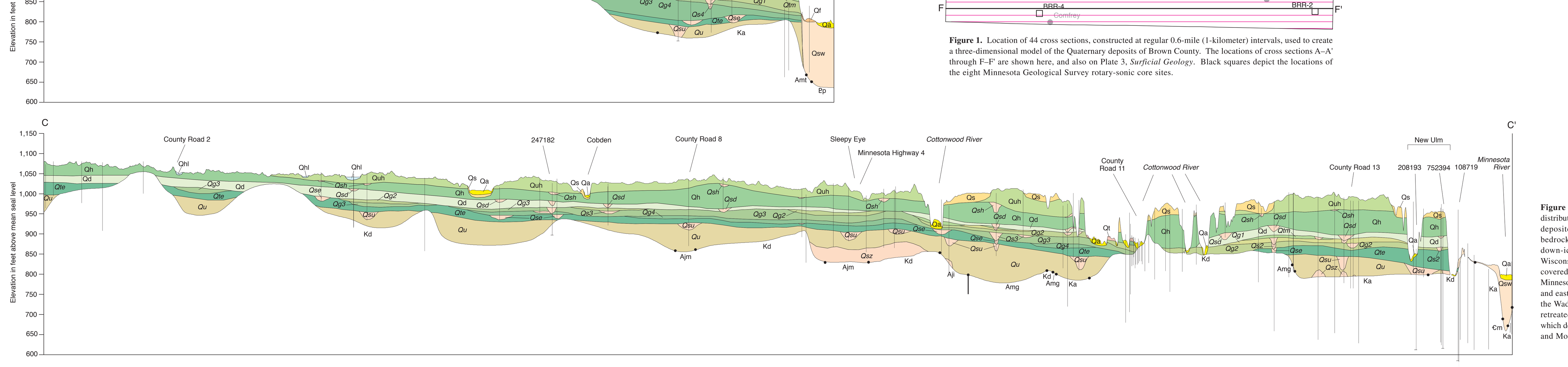
By

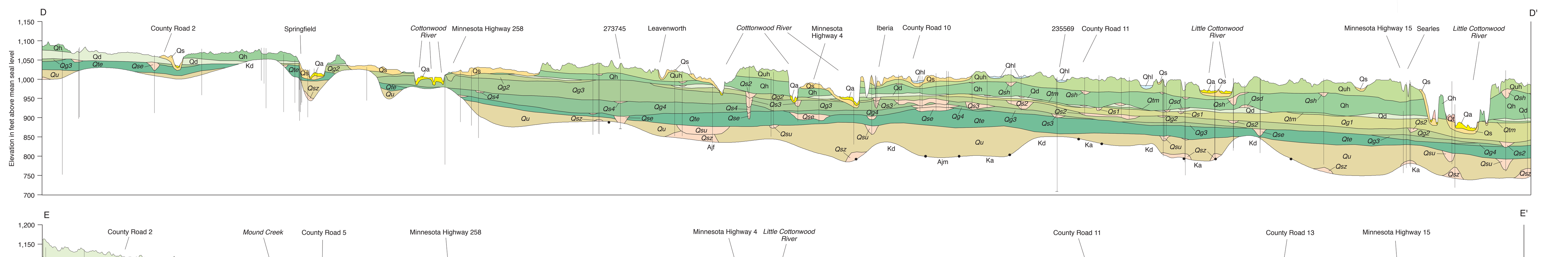
Alan R. Knaeble

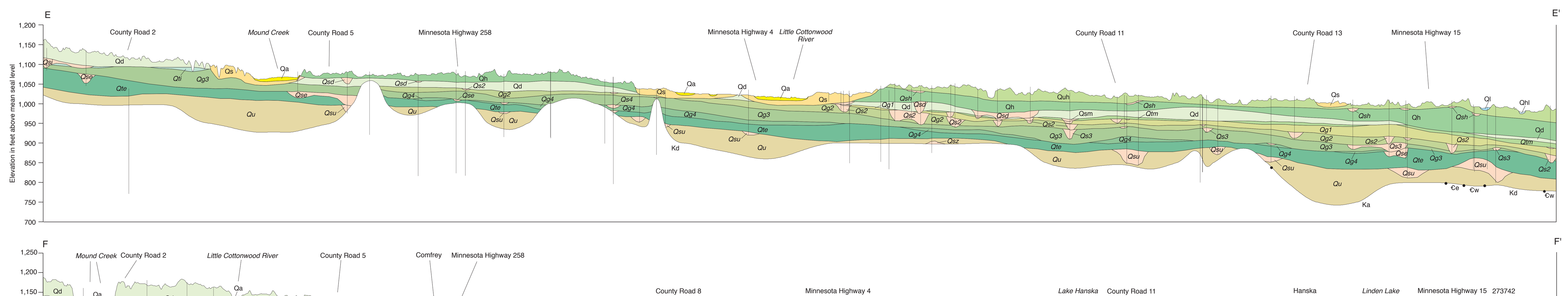
2016

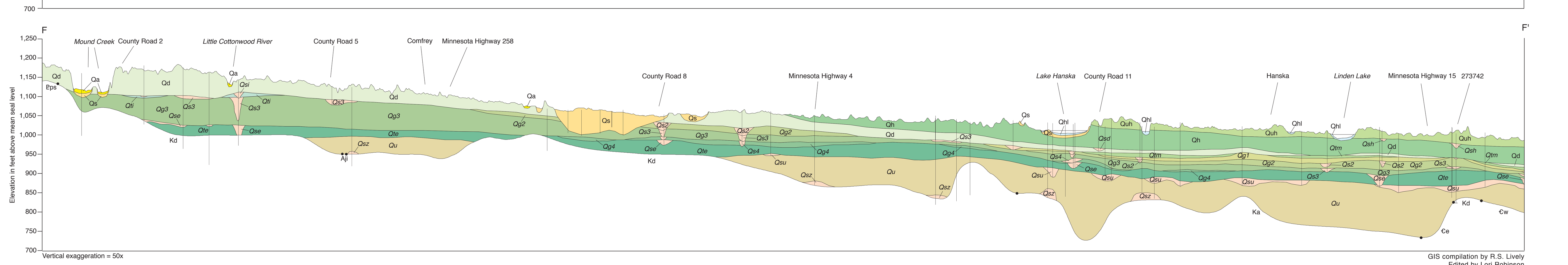












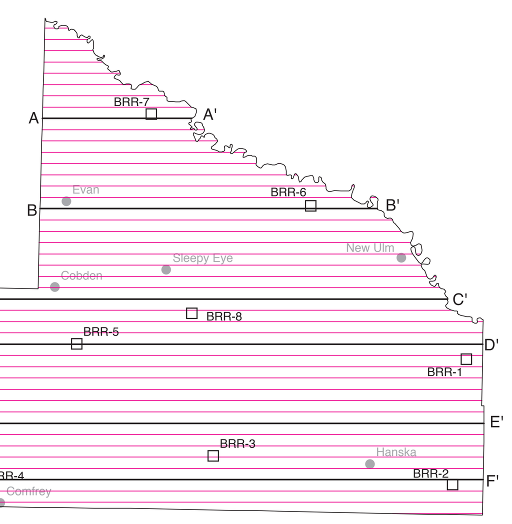


Figure 1. Location of 44 cross sections, constructed at regular 0.6-mile (1-kilometer) intervals, used to create a three-dimensional model of the Quaternary deposits of Brown County. The locations of cross sections A–A' through F–F' are shown here, and also on Plate 3, *Surficial Geology*. Black squares depict the locations of the eight Minnesota Geological Survey rotary-sonic core sites.

CROSS-SECTION SYMBOLS

Geologic contact—Approximate. No-line boundaries occur where data were insufficient to reliably extend units.

Scientific drill hole—Includes cored rotary-sonic drill holes and cuttings-sampled rotary drill holes with their associated unique numbers. See Introduction for details.

Drill hole—Includes water-well drillers' sites. The top of the drill-hole symbol may not coincide with the cross-section surface elevation line because the point is located near (commonly within 0.3 mile [0.5 kilometer]) but not on the cross-section line and therefore may have a slightly different surface elevation.

Fault—Bedrock fault, see Plate 2, *Bedrock Geology.*

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

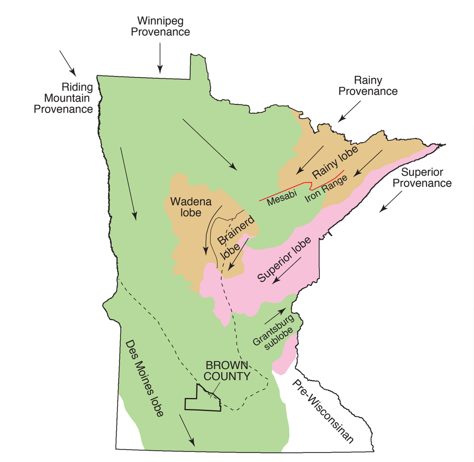


Figure 2. Location of major provenances (source regions) and the distribution of ice-lobe materials at the land surface. Glacial sediments deposited in the county derive their distinct material content from bedrock and sediment found in these regions and along flow paths down-ice from these regions. During the last glaciation, the Late Wisconsinan, ice carrying debris of predominantly Rainy provenance covered portions of northeast (Rainy lobe) and central (Wadena lobe) Minnesota and is discontinuously present in the subsurface slightly south and east of the Minnesota River. The approximate maximum extent of the Wadena lobe is shown by the dashed line. After Wadena-lobe ice retreated, Brown County was covered by ice of the Des Moines lobe, which deposited sediment associated with the Heiberg, Dovray, Ivanhoe, and Moland Members of the New Ulm Formation (Fig. 3).

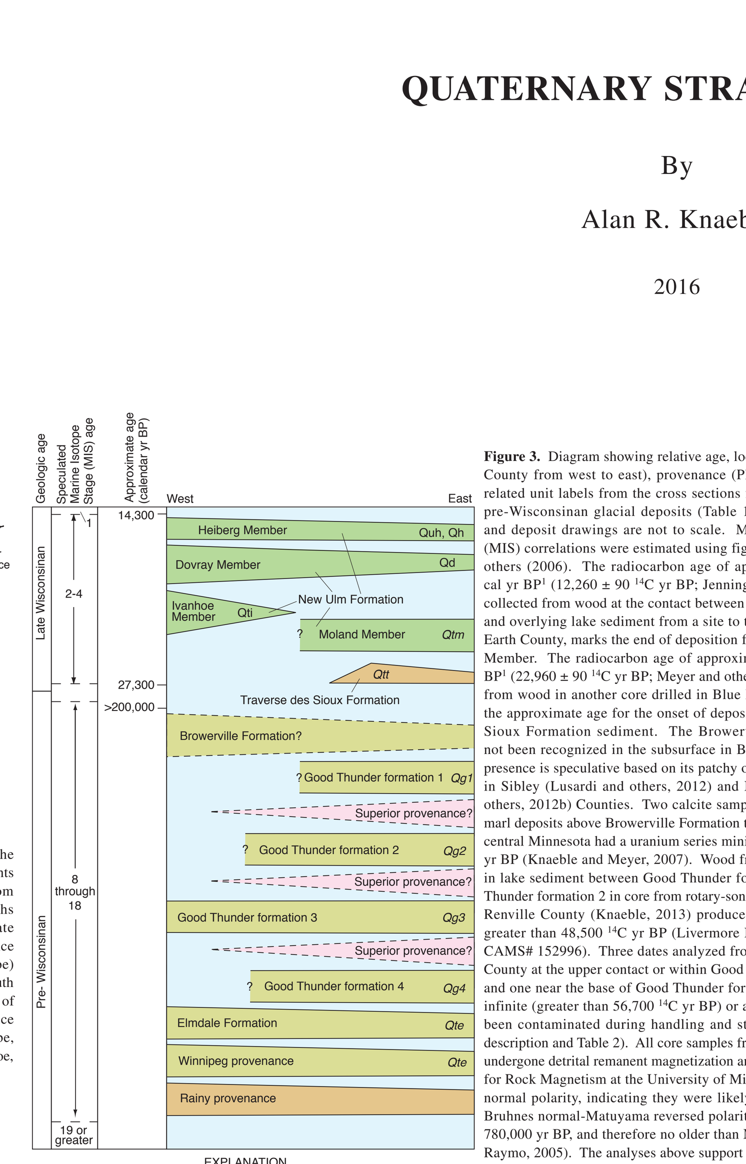


Figure 3. Diagram showing relative age, location (across Brown County from west to east), provenance (Plate 3, Table 1), and related unit labels from the cross sections for Wisconsinan and pre-Wisconsinan deposits (Table 1). The age column and deposit drawings are not to scale. Marine Isotope Stage (MIS) correlations were estimated using figures in Jennings and others (2006). The radiocarbon age of approximately 14,300 cal yr BP* (12,260 ± 90 ^{14}C yr BP; Jennings and others, 2012), collected from wood at the contact between Heiberg Member till and overlying lake sediment from a site to the southeast in Blue Earth County, marks the end of deposition for till of the Heiberg Member. The radiocarbon age of approximately 27,300 cal yr BP (22,960 ± 90 ^{14}C yr BP; Meyer and others, 2012a), collected from wood in another core drilled in Blue Earth County, marks the approximate age for the onset of deposition of Traverse des Sioux Formation sediment. The Browerville Formation has not been recognized in the subsurface in Brown County and its presence is speculative based on its patchy occurrence to the east in Sibley (Lusardi and others, 2012) and Nicollet (Meyer and others, 2012b) Counties. Two calcite samples from interglacial marl deposits above Browerville Formation till in Todd County in central Minnesota had a uranium series minimum age of 200,000 yr BP (Knaeble and Meyer, 2007). Wood from organic deposits in lake sediment between Good Thunder formation 1 and Good Thunder formation 2 in core from rotary-sonic drilling in adjacent Renville County (Knaeble, 2013) produced an infinite date of greater than 48,500 ^{14}C yr BP (Livermore National Laboratory, CAMS# 152996). Three dates analyzed from samples in Brown County at the upper contact or within Good Thunder formation 3 and one near the base of Good Thunder formation 2 were either infinite (greater than 56,700 ^{14}C yr BP) or are suspected to have been contaminated during handling and storage (see unit *Qg3* description and Table 2). All core samples from the area that have undergone detrital remanent magnetization analysis at the Institute for Rock Magnetism at the University of Minnesota have yielded normal polarity, indicating they were likely deposited after the Brunhes normal-Matuyama reversed polarity boundary, dated at 780,000 yr BP and therefore no older than MIS 18 (Lisiecki and Raymo, 2005). The analyses above support a Middle Pleistocene age for Good Thunder formation deposits.

*Ages are in calendar years before present (cal yr BP), recalibrated from published radiocarbon dates using CALIB radiocarbon calibration program, Calib7.0.2 (Stuiver and others, 2014) with 2 sigma error.

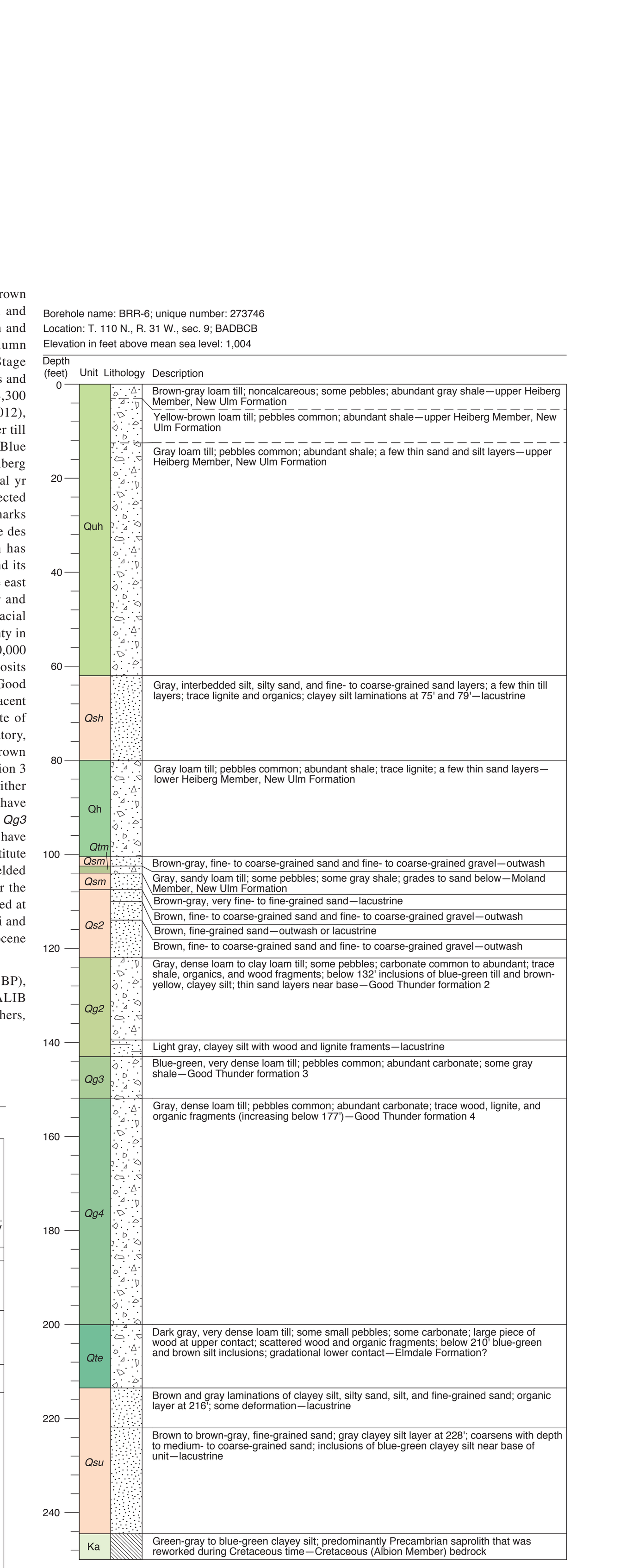


Figure 4. Descriptive log of rotary-sonic core BRR-6 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. One lake sediment sample from beneath the pre-Wisconsinan Elmdale Formation deposits was interpreted to have normal remanent magnetism (Chandler, unpub. data).

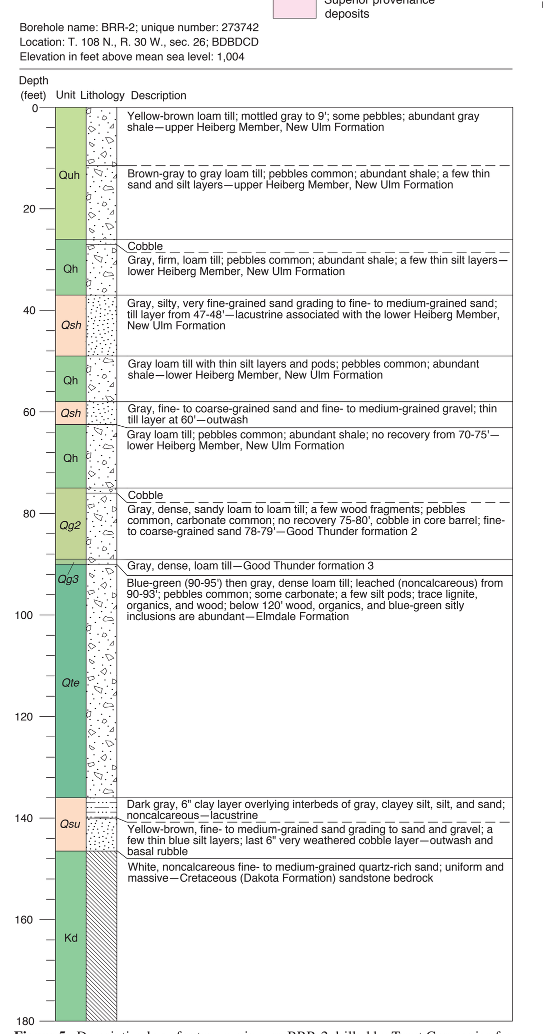


Figure 5. Descriptive log of rotary-sonic core BRR-2 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. Two lake sediment samples from within the pre-Wisconsinan Elmdale Formation deposits were interpreted either to have normal remanent magnetism (Chandler, unpub. data) or inconclusive results.

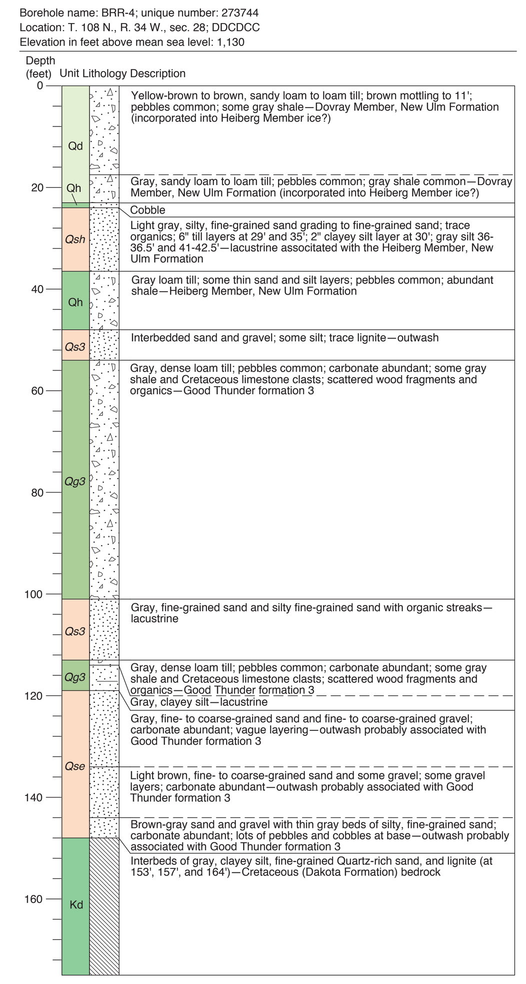


Figure 6. Descriptive log of rotary-sonic core BRR-4 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. Two lake sediment samples from within the pre-Wisconsinan Good Thunder formation 3 member deposits were interpreted either to have normal remanent magnetism (Chandler, unpub. data) or inconclusive results.

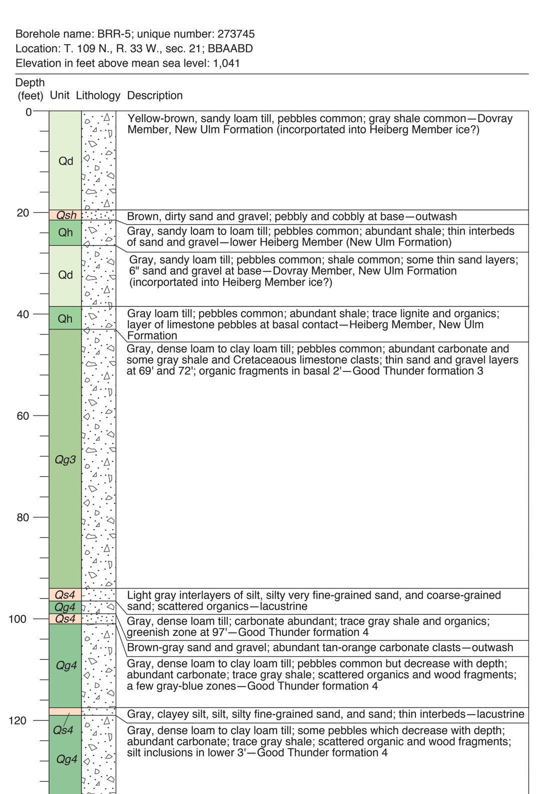


Figure 7. Descriptive log of rotary-sonic core BRR-5 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

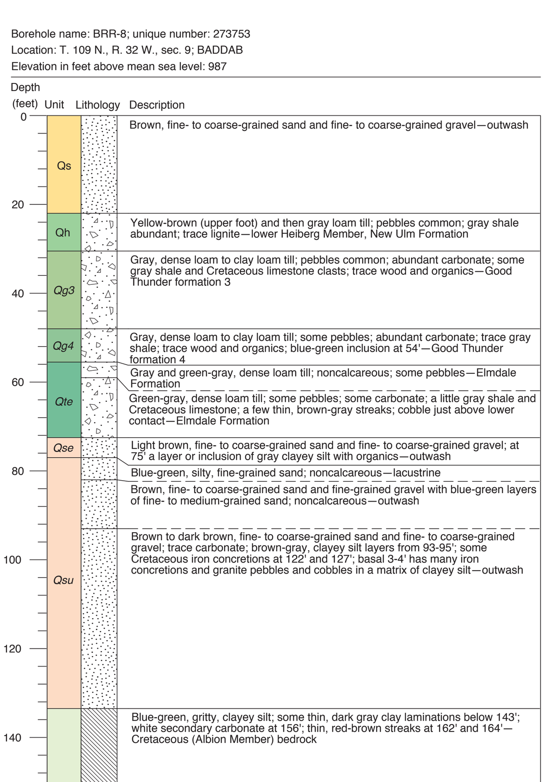


Figure 8. Descriptive log of rotary-sonic core BRR-8 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

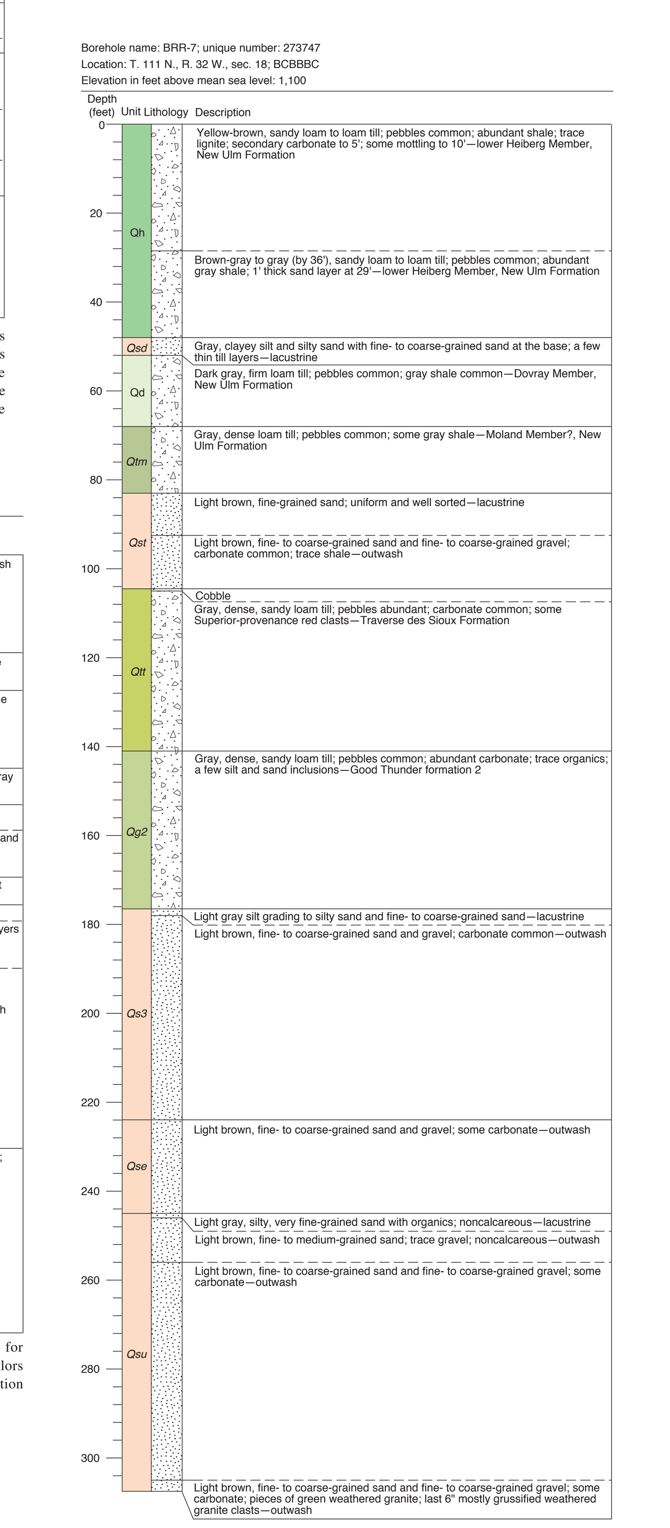


Figure 9. Descriptive log of rotary-sonic core BRR-7 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. Two lake sediment samples from within the pre-Wisconsinan Good Thunder formation 2 member deposits were interpreted either to have normal remanent magnetism (Chandler, unpub. data) or inconclusive results.

INTRODUCTION

The Quaternary Stratigraphy plate shows the unconsolidated materials expected to be encountered between the land and bedrock surfaces in Brown County. Cross sections A–A' through F–F' are representative of 44 cross sections (Fig. 1) that were constructed to create a three-dimensional model of the Quaternary deposits of Brown County. The major sand 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. These include (in order of importance): 111 outcrops along the Cottonwood and Little Cottonwood Rivers and 35 outcrops along the bluffs of the Minnesota River and its tributaries; rotary-sonic drill core from eight drill holes completed by the Minnesota Geological Survey; 14 descriptions of drill cuttings archived in the Minnesota Geological Survey cuttings library; rotary-sonic drill core in adjacent Blue Earth (Meyer and others, 2012a), Nicollet (Meyer and others, 2012b), Redwood (Gowan, 2016), and Renville (Knaeble, 2013) Counties; water-well drillers' logs; 34 shallow (average depth of 18 feet [6 meters]) auger borings along river terraces; 63 shallow auger borings completed by the Minnesota Geological Survey for Plate 3, *Surficial Geology*; Minnesota Department of Transportation bridge boring logs (Minnesota Department of Transportation, 2015); and data from Mn/Model drill hole descriptions and samples (Hudak and others, 2002).

Where the above data are scarce along the cross-section lines, units composed of till and fine-grained lake sediments are generally portrayed (modeled) as continuous, with relatively uniform thicknesses and minimal elevation change, while the less common, thinner sand and gravel units are portrayed as discontinuous. The basis for this portrayal is the fact that abundant fine-grained sediment was present in the ice and was commonly deposited as laterally extensive sheets, whereas stream dissection and sedimentation of sand and gravel typically occurred in discrete channels. In areas of high data density, all units tend to be discontinuous and variable in thickness and elevation over relatively short distances—which reflects more accurately the actual complexity of glacial deposits, especially as older, deeper, and potentially more eroded and dissected units are examined. These factors should be kept in mind while viewing the cross sections.

Cross-section locations are shown on Figure 1 and on Plate 3, *Surficial Geology.* Some units match those on Plate 3, some new units appear only on the cross sections because they are present only in the subsurface or because the area of exposure on the surficial map is too small to be mapped (such as river bluff exposures), and others are a combination of multiple units from Plate 3. Peat and organic deposits (unit Qpo), eolian deposits (pattern), and colluvium (unit Qc) from Plate 3 are too thin to show on the cross sections. Unit modifications were made in order to produce subsurface models of sand and till layer interfaces that could be processed to create the sand-distribution models on Plate 5. A few key stratigraphic control points (rotary-sonic drill holes and drill holes with cutting sets) are shown on the cross sections with an associated unique number (see Cross-Section Symbols). The rotary-sonic drill core and water-well drillers' cuttings samples from adjacent counties that were mentioned above are not shown on the cross sections, but their unique well numbers are included in the digital data file. Drill holes, represented by the vertical lines, may start above or below the land surface elevation because the data are projected onto the cross section from a distance of up to 0.3 mile (0.5 kilometer) from the line of section. Bedrock units taken from Plate 2, *Bedrock Geology*, are labeled at the base of the Quaternary deposits between black dots (unit contact lines). Thick black lines extending below the bedrock surface are recognized bedrock faults.

Figure 2 is a map showing the general up-ice location of major provenances (source regions) and extent of the surficial ice lobes. A schematic illustration showing the relationships between age, provenance, stratigraphic position, and location of the sediments deposited in Brown County primarily during major glacial episodes is shown in Figure 3. A figure correlating Brown County cross-section units with the units in adjacent Blue Earth, Nicollet, Redwood, and Renville Counties appears on Plate 5, *Sand-Distribution Model* (Plate 5, Fig. 1). Logs of six of the eight rotary-sonic cores, which were recovered during drilling for the Minnesota Geological Survey by Traut Companies, are shown in Figures 4 through 9. Analyses of the texture and clast composition of the Quaternary sediment were completed for select geologic units, and are listed in Table 1. Radiocarbon dates of wood and organics collected during field work are shown on Table 2.

ACKNOWLEDGEMENTS

John Knisley, Brown County Water Plan Coordinator, provided background information and logistical assistance for rotary-sonic drilling. Minnesota Geological Survey staff members Stewart Orlowski, Alex Gjorvad, and Bruce Bloomgren provided essential support during rotary-sonic drilling. Valerie Stanley processed samples from rotary-sonic core for paleomagnetic orientation, and she and V.W. Chandler interpreted the paleomagnetic measurements. Vania Stefanova analyzed and interpreted pollen samples from rotary-sonic cores BRR-3, BRR-5, and BRR-6. LacCore staff Jessica Heck, Amy Myrbo, and Anders Noren assisted in processing pollen samples and wood dating, and Amy Myrbo provided interpretation of the ^{14}C dates. Thanks are extended to all landowners who allowed rotary-sonic drilling on their property, and to all gravel pit operators and landowners who gave permission to examine exposures on their property.

DESCRIPTION OF CROSS-SECTION UNITS

Each unit on the cross sections is designated by a letter code, which is described below and placed in one of three categories that designates the origin of the code, as indicated in parentheses after the description: 1. *Surficial Geology* unit—units having an identical description, label, and color as on Plate 3, *Surficial Geology*; see Plate 3 for the detailed descriptions; 2. New unit—unit that appears only on the cross sections that has a unique label and color; and 3. Modified unit—multiple units from Plate 3 that are combined into one unit on the cross sections (for example units Qtd and Qwd are combined into unit Qd). Contact lines that intersect the land surface on cross sections do not match all contact lines shown on the surficial map because some units shown on Plate 3 are too small or thin to be shown on the cross sections.

HOLOCENE

Qa **Sand and pebbly sand with silt and clay—alluvial stream sediment** (modified unit)—Map units Qa and Qrk from Plate 3. May be thin over bedrock or include bedrock in some areas where associated with unit Qrk.

Qf **Loamy sand and gravelly sand—alluvial fan sediment** (*Surficial Geology* unit)—Small, thin areas may not be shown on the cross sections.

Qhl **Silt and clay—modern lake sediment** (*Surficial Geology* unit)—Predominantly silt and clay but may include organics and well-sorted sand. Small, thin areas may not be shown on the cross sections.

HOLOCENE AND PLEISTOCENE

Qsw **Sand and gravelly sand—glacial River Warren fluvial deposits** (*Surficial Geology* unit)—Forms the river terraces along the Minnesota River valley. It also backfills the eroded valley up to the base of the modern river alluvium. Includes significant amounts of aggrading post-glacial alluvium.

Qt **Sand and gravelly sand—terrace deposits** (*Surficial Geology* unit)—These deposits form terraces or thinly cover till strath terraces along the lower reaches of the Cottonwood and Little Cottonwood Rivers.

PLEISTOCENE

Late Wisconsinan glacial deposits

New Ulm Formation (Des Moines-lobe deposits)—The New Ulm Formation (Johnson and others, 2016) is composed of numerous members, which appear to have been deposited by ice streams emanating from ice from the Riding Mountain provenance (see Figs. 2, 3; Plate 3, Figs. 2, 4, and the Glacial History and Description of Map Units sections; Lusardi and others, 2011).

Qs ***Sand, gravelly sand, and cobbly gravel—outwash*** (*Surficial Geology* unit)—Glacial stream deposits undifferentiated as to New Ulm Formation member.

Ql ***Silt and clay—glacial lake sediment*** (*Surficial Geology* unit)—May include well-sorted sand in places. Undifferentiated as to New Ulm Formation member.

Heiberg Member (Johnson and others, 2016)—The youngest glacial material in Brown County (Figs. 2, 3; and Plate 3, Figs. 1, 5, and Description of Map Units section). The Heiberg Member is divided into an upper (unit Quh) and lower (unit Qh) unit (similar to adjacent Blue Earth [Meyer and others, 2012a] and Nicollet [Meyer and others, 2012b] Counties) separated in places by a bed of sand and gravel (unit *Qsh*). The lower Heiberg Member unit includes the Garden City Member of the New Ulm Formation (Johnson and others, 2016) and in places contains slightly more shale than the upper Heiberg Member unit.

Quh ***Upper Heiberg Member till*** (modified unit)—Map units Qth and Qwh from Plate 3. Primarily loam till, which contains abundant clasts of gray, siliceous shale, typically composing 30 to 50 percent of the very coarse-grained sand fraction (Table 1). May include Dovray Member till (unit Qd) within the unit and at the surface, in the west-central and southwest areas of the county, where Dovray Member materials and stagnant ice may have been incorporated into Heiberg Member ice as it advanced over the area. May also include thin lake sediment (similar to unit Ql), debris flows, locally sorted and redeposited material, and inclusions of sand and gravel, particularly near the land surface. This till is at the surface, thickest, and most continuous in northern and eastern Brown County; however, it pinches out to the southwest, where the lower Heiberg and Dovray Members compose the surface sediments.

Qsh ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Glacial stream sediment associated with Heiberg Member meltwater. Found between the upper and lower Heiberg Member units. May be composed of either post-glacial outwash of the lower Heiberg Member or proglacial outwash of the upper Heiberg Member, or a mix of both.

Qh ***Lower Heiberg Member till*** (modified/new unit)—Where at the surface in western Brown County, it includes map units Qth and Qwh from Plate 3. In all other places in the subsurface it is a new unit. Primarily loam till, which contains abundant clasts of gray, siliceous shale, typically composing 30 to 60 percent of the very coarse-grained sand fraction (Table 1). May include Dovray Member till within the unit and at the surface in the west-central and southwest areas of the county, where Dovray Member materials and stagnant ice probably were incorporated into Heiberg Member ice as it advanced over the area. May also include thin lake sediment (similar to unit Ql), debris flows, locally sorted and redeposited material, and inclusions of sand and gravel, particularly near the land surface.

Dovray Member (Johnson and others, 2016)—At the surface in western Brown County, but otherwise found only in the subsurface (Fig. 3), except where it is exposed in places along the river bluffs along the Minnesota, Cottonwood, and Little Cottonwood Rivers. The Dovray Member is widespread but discontinuous in the subsurface.

Qsd ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Glacial stream sediment deposited by meltwater chiefly associated with the Dovray Member, but may include proglacial meltwater deposits of the overlying Heiberg Member.

Qd ***Sandy loam to loam till*** (modified unit)—Map units Qtd and Qwd from Plate 3. Till of this unit commonly contains clasts of gray, siliceous shale, typically composing 15 to 30 percent of the very coarse-grained sand fraction (Table 1). May include lenses and thin layers of outwash sand and gravel, and sand, as well as lacustrine sand, silt, and clay.

Ivanhoe Member (Johnson and others, 2016)—Discontinuous deposits attributed to an early phase of the Des Moines lobe (Figs. 2, 3). Forms the surface unit on the Coteau des Prairie in counties southwest of Brown County (Gowan and Jennings, 2016), but is found only in the subsurface in western Brown County.

Qsi ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Glacial stream sediment deposited by meltwater associated with the Ivanhoe Member. May include proglacial meltwater deposits of the overlying Dovray and Heiberg Members.

Qti ***Sandy loam to loam till deposits*** (new unit)—Till has fewer clasts of gray, siliceous shale than the overlying Dovray and Heiberg Member deposits. Shale content for two samples ranges from 10 to 15 percent of the very coarse-grained sand fraction (Table 1). May include pods, lenses, and thin layers of outwash sand and gravel, and sand, as well as lacustrine sand, silt, and clay.

Moland Member (Johnson and others, 2016)—Discontinuous deposits attributed to the earliest advance of the Des Moines lobe (Figs. 2, 3; Plate 3, Fig. 4). Exposed in places along the river bluffs along the Minnesota, Cottonwood, and Little Cottonwood Rivers, but otherwise found only in the subsurface in northern and eastern Brown County. Possibly correlative to the Verdi Member of the New Ulm Formation (Johnson and others, 2016).

Qsm ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Glacial stream sediment deposited by meltwater associated with the Moland Member. May include proglacial meltwater deposits of the overlying Dovray and Heiberg Members.

Qtm ***Sandy loam till deposits*** (new unit)—Deposits are commonly denser and contain more matrix sand and fewer clasts of gray, siliceous shale than the overlying Dovray and Heiberg Member deposits. Typically, shale content ranges from 3 to 15 percent of the very coarse-grained sand fraction (Table 1). Without laboratory analyses this unit is difficult to distinguish from till of the older Traverse des Sioux Formation (unit *Qtt*), so the thickness and extent of the two units relative to each other as shown in the cross sections is only approximate. May include pods, lenses, and thin layers of outwash sand and gravel, and sand, as well as lacustrine sand, silt, and clay.

Traverse des Sioux Formation (Wadena-lobe deposits)—Evidence from studies (Lusardi and others, 2012; Meyer and others, 2012a, b; Knaeble, 2013) completed along the Minnesota River valley suggested that the Traverse des Sioux Formation (Johnson and others, 2016) is correlative with the Hewitt Formation (Johnson and others, 2016), which was deposited by the north–northeastern (Rainy) provenance Wadena lobe and its meltwater in central Minnesota (Figs. 2, 3).

Qst ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Sediment deposited by glacial meltwater. May include proglacial meltwater deposits of the overlying New Ulm Formation members.

Qtt ***Sandy loam till deposits*** (new unit)—Gray, dense, sandy loam till was recognized in rotary-sonic drill core from BRR-7, where 35 feet (11 meters) of till were encountered (Fig. 9). This site is one of the few confirmed occurrences of this unit in Brown County and provides, along with evidence of its presence along the Minnesota River valley channel near the city of New Ulm in Sibley County (Lusardi and others, 2012), the basis for showing its patchy subsurface distribution on the cross sections in eastern Brown County. Traverse des Sioux Formation till is similar in texture, color, and density to the overlying Moland Member till, but can be distinguished from the Moland Member in the core by its scarcity (trace amounts) of gray shale (Table 1). Yet in the cross sections where differentiation is more difficult the thickness and extent of the two units relative to each other is only approximate. Includes pods, lenses, and thin layers of outwash sand and gravel, and sand.

Pre-Wisconsinan deposits

Good Thunder formation—Light olive-brown to dark gray, bedded sediment and dense, sandy loam to clay loam till of Winnipeg provenance (Fig. 3; Plate 3, Table 1) was recognized and informally named the Good Thunder formation by Johnson and Gramstad (Gramstad, 1997; Gramstad and others, 1997) and described in more detail in Johnson and others (2016). Studies in Blue Earth (Meyer and others, 2012a), Nicollet (Meyer and others, 2012b), Renville (Knaeble, 2013), and Sibley (Lusardi and others, 2012) Counties suggested multiple units (members) compose the formation. The tills typically contain abundant carbonate and some gray shale (Table 1). Rotary-sonic drill core and outcrop exposures along the Minnesota River valley have identified at least four similar yet distinct till members as part of the informally named Good Thunder formation in Brown County (Fig. 3). These units vary in thickness and are typically discontinuous yet widespread throughout the county. These tills are separated, in places, by organic-rich clayey silt with wood, as well as by at least two, and possibly three, separate, scattered, thin, red, Superior-provenance deposits in the above mentioned adjacent counties. Along the Minnesota River valley in and near Brown County there were only three sites where red till was present between Good Thunder formation units. The fact that red deposits separate these units, and that the upper portion of Good Thunder formation units is sometimes oxidized to yellow-brown or oxidized/reduced to green or green-blue, suggests that a significant period (interglacial or interstadial) of exposure and weathering took place between these ice advances. Some of these units probably correlate to the Lake Henry and Eagle Bend Formations of central Minnesota (Johnson and others, 2016), whereas some of the intervening red tills may correlate with the St. Francis Formation (Johnson and others, 2016) of central Minnesota and the Hawk Creek Formation (Matsch, 1971, 1972; Johnson and others, 2016) of southwest Minnesota. Although all Good Thunder formation units are similar in texture and grain content, subtle distinctions can be made, as shown in Table 1 and noted in the unit descriptions. All units may contain pods, lenses, and thin layers of outwash sand and gravel, and sand.

Qs1 ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Chiefly composed of glacial stream sediment derived from unit *Qg1*, but may also include materials from overlying units Qd, *Qtm*, and *Qtt*.

Qg1 ***Loam till*** (new unit)—Contains slightly more gray shale and other Cretaceous rock fragments than Good Thunder formation units *Qg2* and *Qg4* (Table 1), but less than unit *Qg3*. May have a pebble and cobble stone line at the upper contact. In a few places in the lower portion of the unit, it may include pre-Wisconsinan reddish, sandy loam till of Superior provenance. Material from unit *Qg2*, wood fragments, and/or fine-grained lake sediments are also likely included in places. Sediments in the upper portion may be green to greenish-blue in places due to post deposition oxidation caused by a significant period of surface exposure that was followed by reduction as the next ice advance created saturated reducing conditions.

Qs2 ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Commonly composed of glacial stream sediment from unit *Qg2*, but may include some materials derived from overlying units *Qg1*, *Qtm*, *Qtd*, and Superior-provenance deposits.

Qg2 ***Loam till*** (new unit)—In places, slightly sandier than other Good Thunder formation units. Contains trace amounts of gray shale and other Cretaceous rock fragments, similar to unit *Qg4* (Table 1). May include reddish sandy loam till of Superior provenance, fine-grained lake sediment, wood fragments, and organics, as well as material derived from unit *Qg3*. May have a pebble and cobble stone line at the upper contact. Green to greenish-blue (oxidized then reduced) sediment is also present in places beneath the upper contact of this unit.

Qs3 ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Commonly composed of glacial stream sediment derived from unit *Qg3*; may include some materials derived from overlying units Qh, Qd, *Qti*, *Qtm*, *Qg1*, *Qg2*, and Superior-provenance deposits.

Qg3 ***Loam till*** (new unit)—Contains approximately 10 percent gray shale and other Cretaceous rock fragments (Table 1), but may range from 5 to 25 percent, which makes this unit similar to Des Moines-lobe till deposits in outcrops along the Minnesota River valley bluffs. May include reddish sandy loam till of Superior provenance and material from unit *Qg4*, as well as wood fragments, organics, and fine-grained lake sediment. Green to greenish-blue (oxidized then reduced) sediment is also present in a few places beneath the upper contact of this unit. In places an organic soil horizon has developed, commonly in lake sediment, forming the upper contact of this unit. Radiocarbon dating on wood and lignite samples from sediment at the top of or within unit *Qg3* and from within unit *Qg2* from four sites produced ages of 31,060 ± 200, greater than 56,700, 45,500 ± 1,000, and 52,200 ± 2,300 ^{14}C yr BP (see Table 2 for details and Fig. 3). The accuracy of the finite dates is questionable because contamination by younger ^{14}C materials may have taken place during handling and storage of the samples (Amy Myrbo, laboratory manager, LacCore/Limnological Research Center, unpub. data). Therefore all finite dates are suspected to be the result of contamination.

Qs4 ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Commonly composed of glacial stream sediment from unit *Qg4*; may include some materials derived from overlying units *Qg2*, *Qg3*, and Superior-provenance deposits.

Qg4 ***Loam till*** (new unit)—Contains trace amounts of gray shale and other Cretaceous rock fragments, similar to unit *Qg2* (Table 1). May include reddish, sandy loam till of Superior provenance, material from unit *Qte* and older undifferentiated units, as well as wood fragments, organics, and fine-grained lake sediment.

Elmdale Formation—Yellow-brown to dark gray, bedded sediment and dense loam to clay loam till of predominantly Winnipeg provenance (Fig. 3; Plate 3, Table 1) associated with the "W" sequence units of central and north-central Minnesota (Meyer, 1997; Johnson and others, 2016). The till contains small to moderate amounts of carbonate and some gray shale and other Cretaceous clasts (Table 1). The upper contact of this unit, in places, is leached, has an organic horizon, and/or is green to greenish-blue (oxidized then reduced). It varies in thickness, is widespread but patchy, and where present appears to be the basal glacial unit above bedrock. May contain wood fragments, organics, and incorporated saprolite (weathered bedrock) and bedrock. This unit, as depicted, may be comprised of two separate ice advances with slight lithologic differences in the carbonate, shale, and red clast composition. It also includes remnant deposits of older glacial events that are leached in places. Some of these events may have a northeast source area. Therefore, consider this unit a composite that includes similar older units that are too scarce to be shown individually.

Qse ***Sand, gravelly sand, and gravel—outwash*** (new unit)—Commonly composed of glacial stream sediment from unit *Qte*; may include materials from overlying units *Qg2*, *Qg3*, *Qg4*, Superior-provenance deposits, older glacial deposits, and reworked bedrock.

Qte ***Loam till*** (new unit)—Present in four rotary-sonic drill holes and in outcrops along the Minnesota and the Cottonwood Rivers. May include materials from Superior-provenance deposits, older glacial deposits, and possibly some saprolite and bedrock.

Undifferentiated deposits

Qsu **Undifferentiated sand and gravel** (new unit)—May be composed of outwash sediment from units *Qg2*, *Qg3*, *Qg4*, *Qte*, Superior provenance deposits, and older glacial deposits, but is probably composed primarily of materials from the unit (*Qte*) directly above it. In places may include till.

Qu **Undifferentiated sediment** (new unit)—Includes undifferentiated till, sand, gravel, and fine-grained lake sediments. Shown in areas where control data were scarce or absent. Till of this unit may contain Good Thunder and Elmdale formation deposits, other Rainy provenance "W" sequence deposits, and older deposits. Although some water wells extend below the upper boundary of this unit, the data are too few and far between to make meaningful correlations.

Qsz **Undifferentiated basal sand and gravel** (new unit)—Includes primarily sand and gravel directly overlying bedrock, but may include till and other fine-grained lake sediments. Shown in areas where control data were scarce. Although some water wells extend below the upper boundary of this unit, the data are too few and far between to make meaningful correlations.

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Table 1. Average values for the matrix texture and sand composition of tills recognized in Brown County. Matrix texture (the less than 2 millimeter grain-size fraction of the sample) is expressed as relative proportions of sand, silt, and clay in percent. The lithologic composition of the very coarse-grained sand fraction (1-2 millimeters) is expressed in percent as relative proportions of Precambrian crystalline rocks, Paleozoic carbonate rocks, and Cretaceous shale (includes dark, tabular Cretaceous limestone) using the classification system of Hobbs (1998). The Precambrian crystalline 1-2 millimeter fraction is further differentiated by crystalline rock type—light (granite and gneiss), dark (mafic-igneous and other metamorphic rocks), and red (iron-formation, rhyolite, agate, and sandstone). Clear quartz is a further differentiation of the Precambrian crystalline light 1-2 millimeter fraction.

	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	Gravel (percentage of total sample weight)	Sand	Silt	Clay	Total number of samples	Precambrian crystalline	Paleozoic carbonate	Cretaceous shale	Light	Dark	Red	Clear quartz
Deposits of the Des Moines lobe													
New Ulm Formation													
Heiberg Member till (units Qth and Qwh on Plate 3; units Quh and Qh on cross sections)	385	5	38	42	20	378	35	24	41	87	12	1	21
Dovray Member till (units Qtd and Qwd on Plate 3; unit Qd on cross sections)	100	6	45	39	16	98	49	30	21	87	12	1	19
Ivanhoe Member till (unit *Qti* on cross sections)	2	5	38	44	18	2	51	36	13	83	15	2	16
Moland Member till (unit *Qtm* on cross sections)	18	8	53	34	13	18	59	30	11	90	9	1	23
Deposits of the Wadena lobe													
Traverse des Sioux Formation													
Till (unit *Qtt* on cross sections)	14	7	51	33	16	14	73	26	1	86	11	3	24
Pre-Wisconsinan deposits													
Good Thunder formation													
Member 1 till (unit *Qg1* on cross sections)	36	5	37	39	24	36	54	42	4	88	11	1	24
Member 2 till (unit *Qg2* on cross sections)	94	5	40	41	19	94	65	33	2	87	11	2	24
Member 3 till (unit *Qg3* on cross sections)	133	5	35	42	23	133	52	39	9	88	11	1	23
Member 4 till (unit *Qg4* on cross sections)	32	3	27	49	24	32	59	39	2	87	12	1	26
Elmdale Formation													
Till (unit *Qte* on cross sections)	69	3	32	44	24	67	83	14	3	88	10	2	37
					leached	2	99	1	0	97	2	1	40

Table 2. Wood and lignite found in one outcrop and in three Minnesota Geological Survey rotary-sonic cores was sampled for radiocarbon dating. The samples were prepared by LacCore of the University of Minnesota and processed by Lawrence Livermore National Laboratory, Livermore, California. Sample 32844-31.5 was taken from an outcrop along the Cottonwood River south of Sleepy Eye from wood in an organic horizon developed in a thin sand layer at the top of unit *Qg3*. The other three samples were from rotary-sonic core. Sample BRR-3-34 came from a piece of lignite from a disturbed disseminated organic layer associated with a cobble layer at the upper contact of unit *Qg3*. Sample BRR-4-113 is wood from a thin till layer in sandy, silty lake sediment within unit *Qg3*. Sample BRR-6-141 is wood from clayey silt lake sediment beneath a till near the base of unit *Qg2*. See Figure 3 text and the description for unit *Qg3* for discussion of the reliability of finite dates.

CAMS number	Sample name	Minnesota Geological Survey number	Depth	$\delta^{13}C$	Fraction modern	$D^{14}C$	^{14}C age
168831	32844-31.5	32844	31.5	-25	0.0209 ± 0.0005	-979.1 ± 0.5	31,060 ± 200
168832	BRR-3-34	273743	34	-25	0.0000 ± 0.0004	-1,000.4 ± 0.4	>56,700
168833	BRR-4-113	273744	113	-25	0.0035 ± 0.0004	-996.5 ± 0.4	45,500 ± 1,000
168834	BRR-6-141	273746	141	-25	0.0015 ± 0.0004	-998.5 ± 0.4	52,200 ± 2,300