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QUATERNARY STRATIGRAPHY

By
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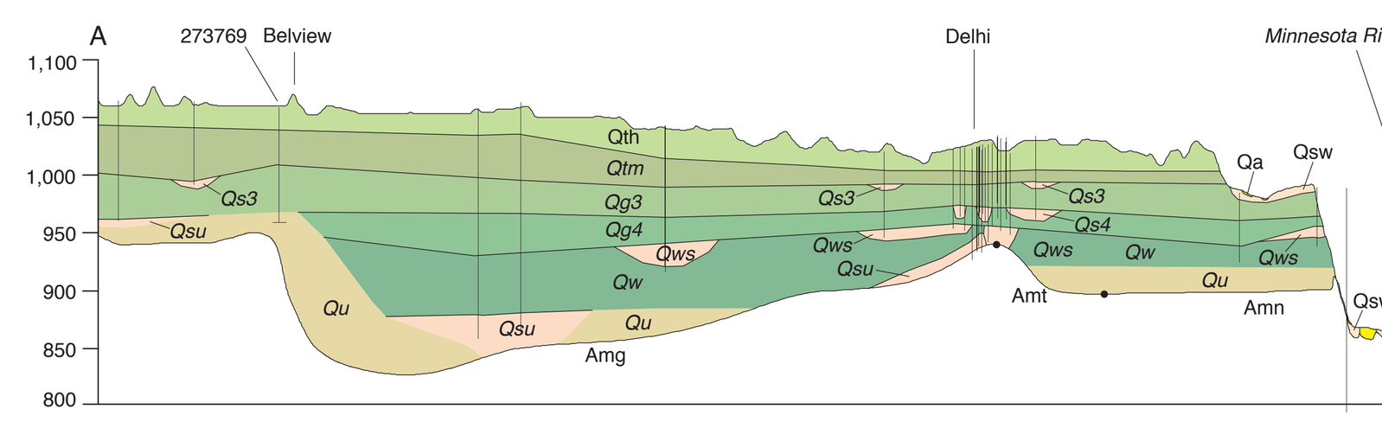
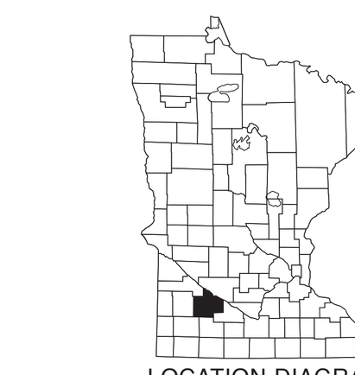
2016





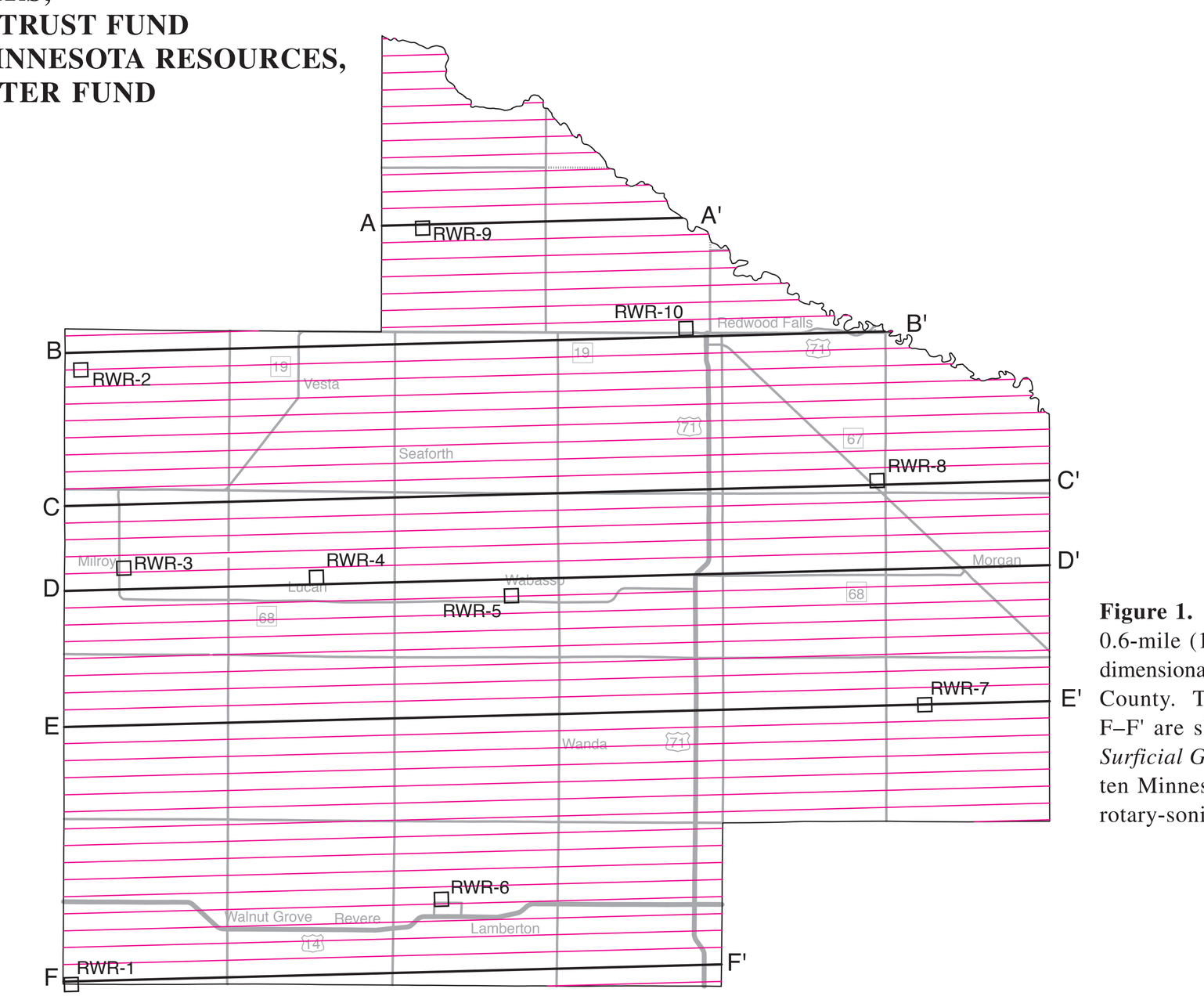
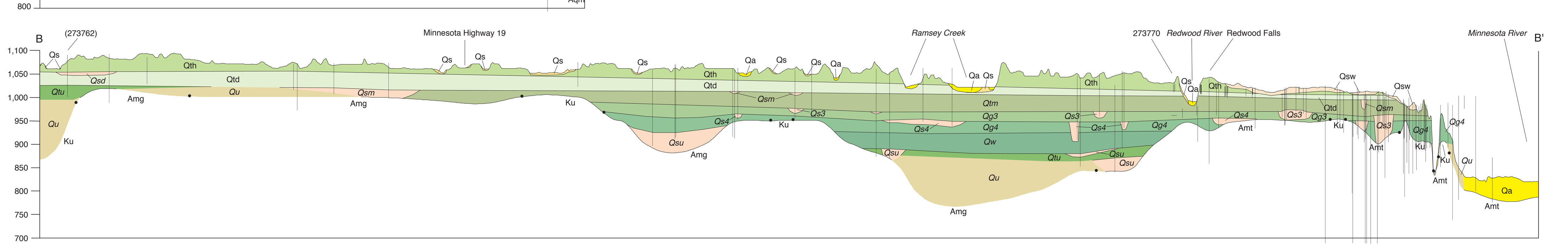
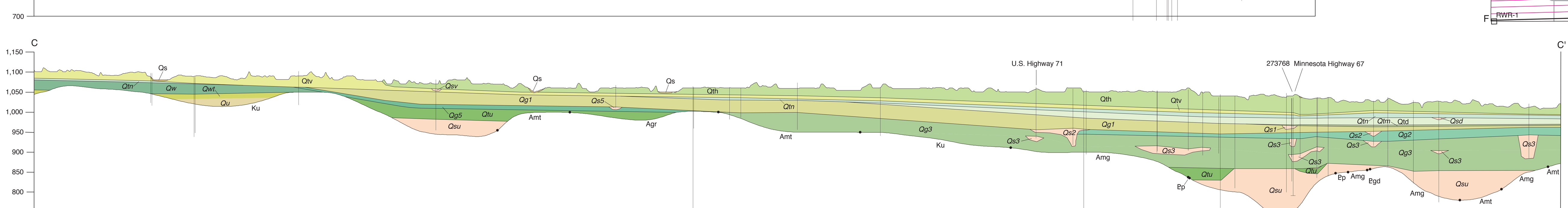
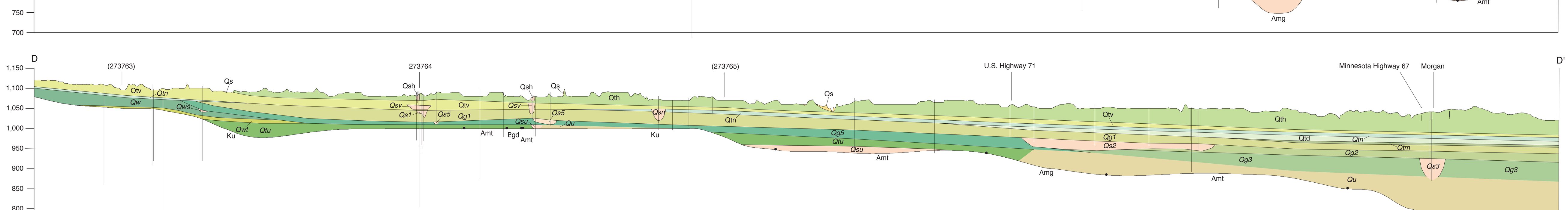
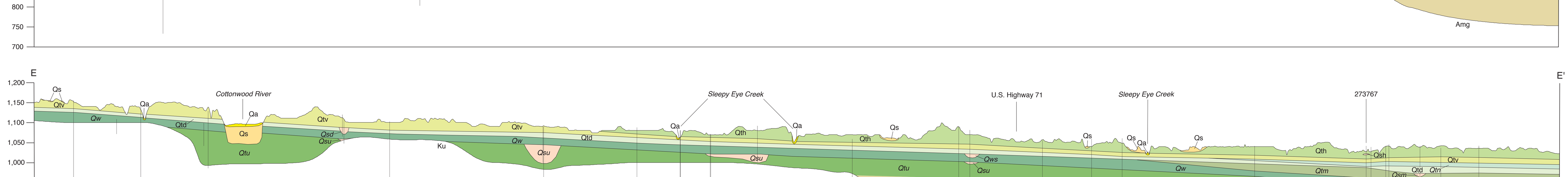


Figure 1. Location of 57 cross sections, constructed at 0.6-mile (1-kilometer) intervals, used to create a three-dimensional model of the Quaternary deposits of Redwood County. The locations of cross sections A–A' through F–F' are shown here, and are also shown on Plate 3, *Surficial Geology*. Black squares depict the locations of ten Minnesota Geological Survey (RWR-1 to RWR-10) rotary-sonic core sites.









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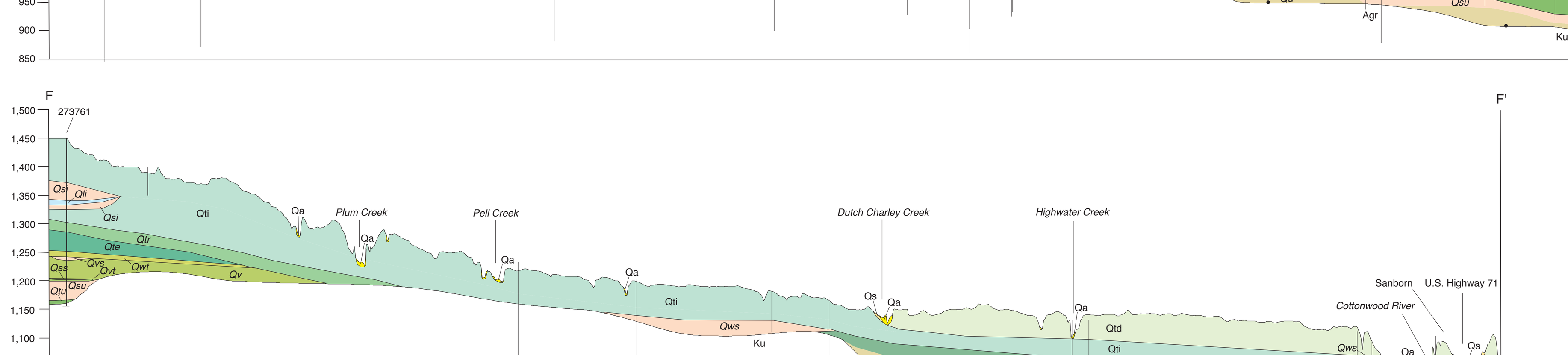

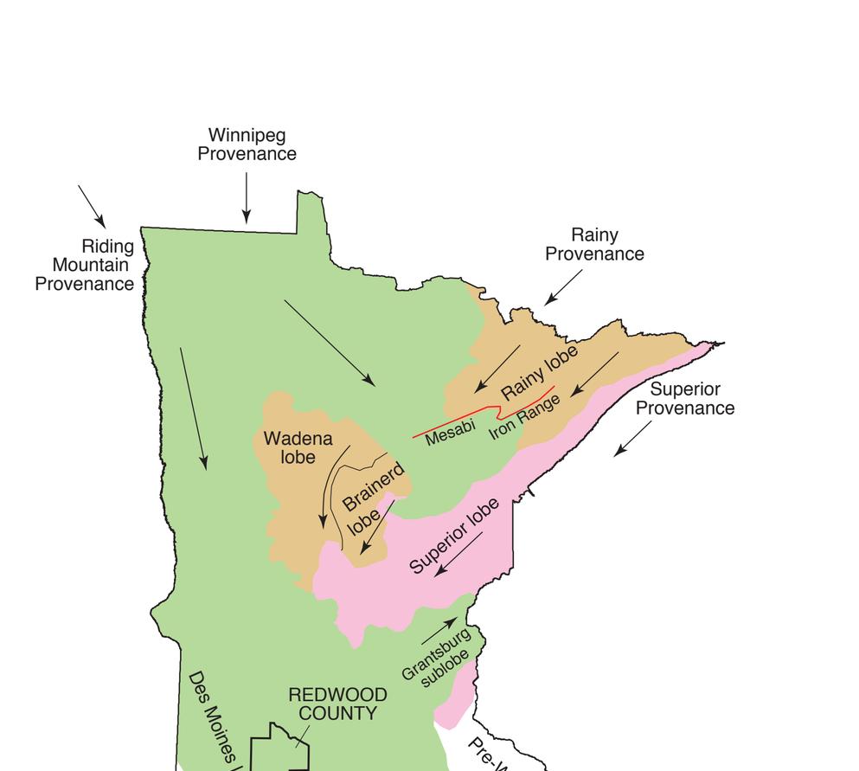

Figure 2. Location of major provenances (source regions) and the distribution of ice-lobe materials at the land surface. Glacial sediments deposited in Redwood County derive their distinct material content from bedrock and sediment found in the region of these provenances. During the last glaciation, the late Wisconsinan, ice carrying debris of predominantly Rainy provenance (brown) covered portions of northeast (Rainy lobe) and central (Wadena and Brainerd lobes) Minnesota and the debris is discontinuously present in the subsurface as far south and west as the Minnesota River. After Wadena-lobe ice melted, Redwood County was completely covered by deposits of at least five advances of the northwestern-source Des Moines lobe (green).

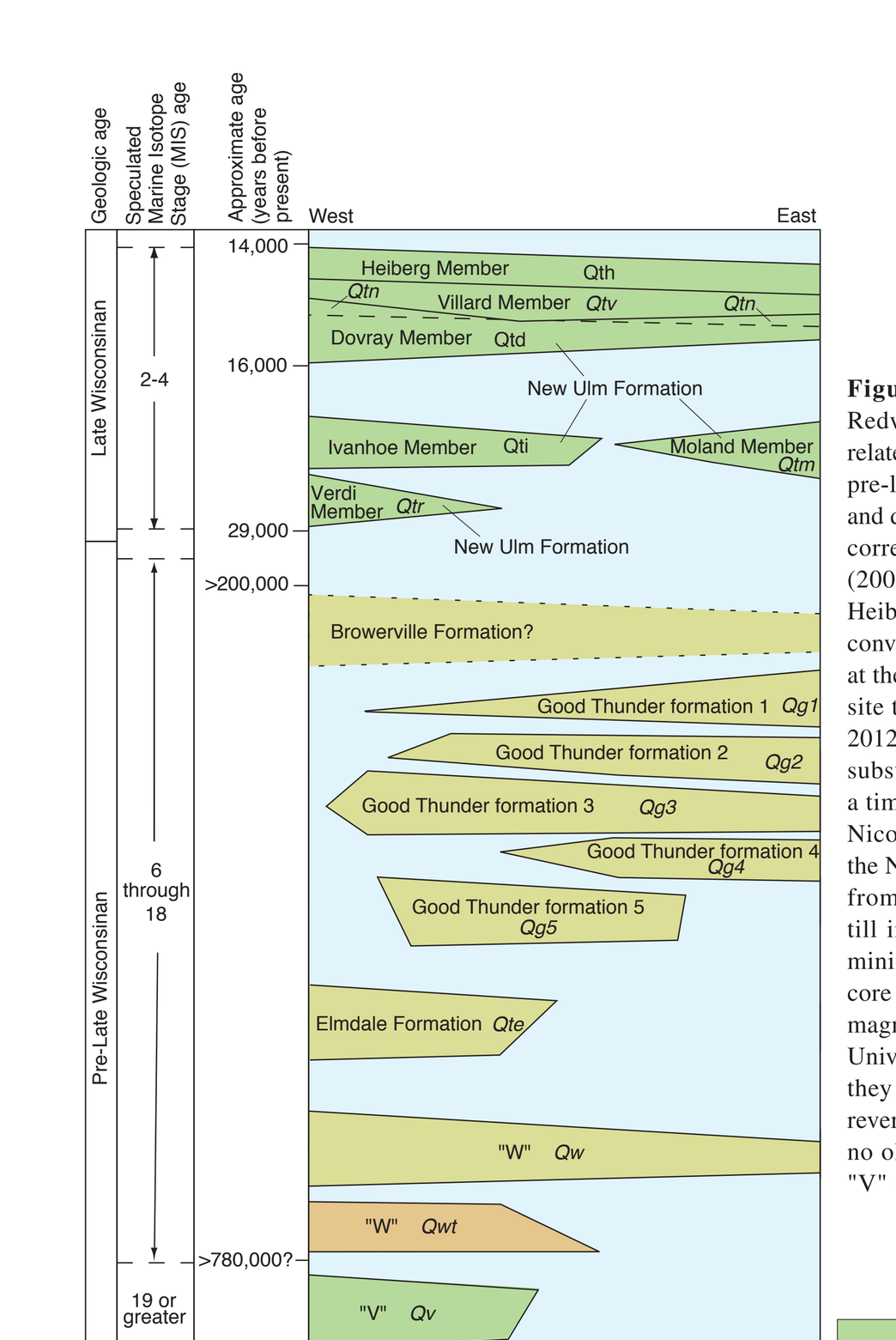

Figure 3. Diagram showing relative age, location (across Redwood County from west to east), provenance (Fig. 2), and related unit labels from the cross sections for late Wisconsinan and pre-late Wisconsinan glacial deposits (Table 1). The age column and deposit drawings are not to scale. Marine Isotope Stage (MIS) correlations were estimated using figures in Jennings and others (2006). The age shown for the end of deposition for till of the Heiberg Member of the New Ulm Formation is the calendar year conversion of a radiocarbon date (12,260 ± 90 yr BP) from wood at the contact between the till and overlying lake sediment from a site to the southeast in Blue Earth County (Jennings and others, 2012). The Browerville Formation has not been recognized in the subsurface in Redwood County and its presence here is used as a time marker. Studies in Sibley (Lusardi and others, 2012) and Nicollet (Meyer and others, 2012b) Counties placed it between the New Ulm and Good Thunder formations. 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). 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 Bruhnes normal-Matuyama reversed polarity boundary, dated at 780,000 yr BP, and therefore no older than MIS 18 (Lisiecki and Raymo, 2005). Position of "V" sequence units as older than 780,000 yr BP is speculative.

CROSS SECTION SYMBOLS

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

Scientific drill hole—Cored rotary-sonic drill holes with their associated unique numbers. Unique numbers in parentheses denote borings on adjacent cross section lines used for reference (FIg. 1).

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.

Bedrock contact—Point representing the contact between bedrock units at the bedrock surface. Unit labels are shown between the contact points and match those on Plate 2, *Bedrock Geology*.

INTRODUCTION

The *Quaternary Stratigraphy* plate shows the unconsolidated materials expected to be encountered between the land and bedrock surfaces in Redwood County. Cross sections A–A' through F–F' are representative of 57 cross sections (Fig. 1) that were constructed to create a three-dimensional model of the Quaternary deposits of Redwood 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): rotary-sonic drill core from ten drill holes completed by the Minnesota Geological Survey; outcrops along the Redwood River (Patterson and others, 1999); outcrops along Ramsey and Highwater Creeks; rotary-sonic drill core in adjacent Renville (Knaeble, 2013) and Brown (Knaeble, in press) Counties; 54 shallow auger borings completed by the Minnesota Geological Survey for Plate 3, *Surficial Geology*; shallow auger borings completed by the Minnesota Geological Survey for Patterson (1997), Patterson and others (1999), and Jennings (2010); drill cutting descriptions from the Minnesota Geological Survey cuttings library; U.S. Geological Survey borings (Broussard and others, 1973); water-well drillers' logs; and Minnesota Department of Transportation bridge boring logs (Minnesota Department of Transportation, 2014). Where there are more data along the cross section lines, 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 thus potentially more eroded and dissected units are examined. Where the above data are scarce along the cross section lines, units composed of till are generally portrayed (modeled) as continuous, with relatively uniform thicknesses and minimal elevation change, and the less common, thinner, lacustrine, sand and gravel units are portrayed as discontinuous. Glacial till is portrayed as more widespread and continuous because the source ice typically carried abundant fine-grained sediment and spread it over broad areas. By contrast, sand and gravel units are depicted as more discontinuous because they formed by streams flowing along isolated depressions on, beneath, and in front of glaciers. These factors should be kept in mind when viewing the cross sections.

Cross section locations are shown on Figure 1 and on Plate 3, *Surficial Geology*. Some cross section 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 (stream cut exposures), and other units are a combination of multiple units from Plate 3. Organic deposits (unit Qo from Plate 3), alluvial fan sediment (unit Qf from Plate 3), modern lake sediment (unit Qhl from Plate 3), and colluvium (unit Qc from Plate 3) are too thin to show on the cross sections, but may appear on the rotary-sonic logs (Figs. 4 through 13). Unit modifications were made in order to produce subsurface models showing the interfaces between sand and till layers that could be processed to create the sand-distribution models on Plate 5. A few key stratigraphic control points (rotary-sonic drill holes) are shown on the cross sections with an associated unique number. Some rotary-sonic drill core from Renville (Knaeble, 2013) and Brown (Knaeble, in press) Counties were used for interpretation because they were near the county border and provided significant detail. These drill sites 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 shown at the base of the Quaternary deposits between associated black dots (unit contact lines).

Figure 2 is a map showing the general up-ice location of major provenances (source regions) for tills in Minnesota and the extent of the material, divided as to depositional ice lobe, currently at the surface. A schematic illustration showing the relationships between age, provenance, stratigraphic position, and location of the sediments deposited in Redwood County by major glacial episodes is shown in Figure 3. Logs of the ten rotary-sonic cores, recovered during drilling for the Minnesota Geological Survey by Traut Companies, are shown in Figures 4 to 13. Analyses of the texture and clast composition of the Quaternary sediments were completed for selected geologic units, and are listed in Table 1.

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—units that appear only on the cross section and have 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 Qa and Qrk are combined into unit Qa). 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. It should also be noted that all of the till units described below may include pods, lenses, and thin layers of outwash sand and gravel, and sand, as well as lacustrine sand, silt, and clay.

HOLOCENE

Qa — **Sand, gravely sand, silt and clay—alluvium** (modified unit)—Map units Qa and Qrk from Plate 3. May be thin (less than 18 inches [48 centimeters]) over bedrock or include bedrock in some areas where associated with unit Qrk.

HOLOCENE AND PLEISTOCENE

Qsw — **Sand and gravelly sand—glacial River Warren fluvial deposits** (*Surficial Geology* unit).

PLEISTOCENE

Late Wisconsinan deposits

New Ulm Formation (Des Moines-lobe deposits)—See Figures 2 and 3; Plate 3, Figures 3 and 4.

Qs — ***Silty sand, sand, sandy silt, gravelly sand, and sandy gravel—glacial-stream sediments***—(*Surficial Geology* unit).

Heiberg Member—The uppermost member of the New Ulm Formation. Found in all rotary-sonic borings except for RWR-1, RWR-3, and RWR-6 (see Figs. 3, 5, 7, 8, 10, 11, 12, 13; Table 1; Plate 3, Fig. 4).

Qsh — **Sand, gravelly sand, and sandy gravel—glacial-stream sediment** (new unit)—Sediment deposited by glacial meltwater chiefly associated with the Heiberg Member of the New Ulm Formation (Johnson and others, 2016).

Qth — **Loam till deposits with patchy areas of thin glacial-lake sediment** (modified unit)—Map units Qmh, Qwh, and Qth from Plate 3. Primarily loamy till that contains abundant clasts of gray, siliceous shale, typically composing 35 to 60 percent of the very coarse-grained sand fraction (Table 1; Plate 3, Fig. 4). May include thin lake sediment (unit Qhl), debris flows, and inclusions of sand and gravel, particularly near the land surface.

Villard Member—Found at the surface in rotary sonic boring RWR-3 and also within RWR-4, RWR-5, RWR-7, and RWR-8. See Figures 3, 6, 7, 8, 10, and 11; Table 1; Plate 3, Figure 4.

Qsv — **Sand, gravelly sand, and sandy gravel—glacial-stream sediment** (new unit)—Sediment deposited by glacial meltwater chiefly associated with the Villard Member of the New Ulm Formation (Johnson and others, 2016), but may include proglacial meltwater deposits of the overlying Heiberg Member.

Qtv — **Loam till deposits with patchy areas of thin glacial-lake sediment** (modified unit)—Map units Qwv and Qtv from Plate 3. Also found in the subsurface beneath Heiberg Member deposits, but in places beneath thin lake sediment, debris flows, and locally sorted and redeposited materials. Till of this unit commonly contains clasts of gray, siliceous shale, typically composing 15 to 25 percent of the very coarse-grained sand fraction (Table 1). May include thin lake sediment (unit Qhl) and debris flows at the surface.

Unnamed member—A thin (4 to 9 feet [1 to 3 meters]) unit found beneath the Villard Member in rotary-sonic borings RWR-3, RWR-5, RWR-7, and RWR-8. May correlate with the "Lower Heiberg Member till" from Blue Earth County (Meyer and others, 2012a). See Figures 6, 8, 10, and 11; Table 1.

Qsn — **Sand, gravelly sand, and sandy gravel—glacial-stream sediment** (new unit)—Sediment deposited by glacial meltwater; associated with the melting of the ice that deposited the underlying till (unit Qtn), but may include proglacial meltwater deposits of the overlying Villard Member.

Qtn — **Loam till deposits** (new unit)—Primarily loamy till, which contains abundant clasts of gray, siliceous shale, composing 28 to 49 percent of the very coarse-grained sand fraction (Table 1).

Dovray Member—Discontinuous deposits attributed to the Altamont phase of the Des Moines lobe (Johnson and others, 2016). Exposed at the surface (boring RWR-6) generally south of the Cottonwood River, otherwise found in the subsurface in most of the county (borings RWR-2, RWR-7, RWR-8, and RWR-10). See Figures 3, 5, 9, 10, 11, and 13; Table 1; Plate 3, Figure 4.

Qsd — **Sand, gravelly sand, and sandy gravel—glacial-stream sediment** (new unit)—Sediment deposited by glacial meltwater. May include proglacial meltwater deposits of the overlying Villard and Heiberg Members (units Qtv and Qth, respectively).

Qtd — **Loam till deposits with patchy areas of thin glacial-lake sediment** (modified unit)—Map units Qtd and Qwd from Plate 3. Till tends to contain less matrix sand and an intermediate amount of gray, siliceous shale clasts than the overlying Villard and Heiberg Member deposits. Typically, shale content ranges from 20 to 35 percent of the very coarse-grained sand fraction (Table 1). May include thin lake sediment (unit Qhl) and debris flows at the surface.

Moland Member—Discontinuous deposits of an earlier phase of the Des Moines lobe (Johnson and others, 2016). Exposed in places along the Cottonwood and Redwood Rivers, but otherwise found only in the subsurface near the Minnesota River (borings RWR-7, RWR-8, RWR-9, and 10). See Figures 3, 10, 11, 12, and 13; Table 1; Plate 3, Figure 4.

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

Qtm — **Loam till deposits** (new unit)—Till tends to be denser and contains more matrix sand than the Ivanhoe Member and fewer clasts of gray, siliceous shale than the Dovray, Villard, and Heiberg Member deposits. Typically, shale content ranges from 5 to 18 percent of the very coarse-grained sand fraction (Table 1).

Ivanhoe Member—Discontinuous deposits attributed to the Bemis phase of the Des Moines lobe (Johnson and others, 2016). Exposed only in the southwest corner of the county and only observed in rotary-sonic boring RWR-1. See Figures 3 and 4; Table 1; Plate 3, Figure 4.

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

Qli — **Silt with some very fine-grained sand** (new unit)—Only encountered in rotary-sonic boring RWR-1. Approximately 9 feet (3 meters) of finely laminated black and light gray lacustrine sediment becomes massive (not laminated) in the lower 3 feet (1 meter).

Qti — **Clay loam till deposits** (modified unit)—Map units Qti and Qwi from Plate 3. Till tends to be denser and contains more matrix clay than other members, along with containing fewer clasts of gray, siliceous shale than all but the Moland Member deposits. Typically, shale content ranges from 10 to 23 percent of the very coarse-grained sand fraction (Table 1).

Verdi Member—Discontinuous deposits attributed to the earliest advance of the Des Moines lobe (Johnson and others, 2016) that extend beyond the Bemis moraine. Not exposed at the surface in Redwood County and only observed in rotary-sonic boring RWR-1. See Figures 3 and 4; Table 1; Plate 3, Figure 4.

Qtr — **Loam till deposits** (new unit)—Till tends to be siltier and contains a higher percentage of carbonate and Cretaceous non-siliceous shale clasts than other members. Shale content ranges from 6 to 14 percent of the very coarse-grained sand fraction (Table 1).

Pre-late Wisconsinan deposits

Good Thunder formation—Light olive-brown to dark gray bedded sediment and dense, loam to clay loam till of Winnipeg provenance (Figs. 2, 3) was originally recognized and informally named the Good Thunder formation by Johnson (unpub. data). Studies in Sibley (Lusardi and others, 2012), Blue Earth (Meyer and others, 2012a), Nicollet (Meyer and others, 2012b), and Renville (Knaeble, 2013) Counties suggested multiple units comprise the formation. The till typically contains abundant clasts of carbonate and may contain some gray shale, depending on the unit (Table 1). The Good Thunder formation has been identified in rotary-sonic drill core samples from five borings (RWR-1, RWR-4, RWR-8, RWR-9, and RWR-10) and outcrop exposures, too small to portray on the surficial map (Plate 3), along the Redwood River and Ramsey Creek. These units vary in thickness and are absent in parts of the county (especially where bedrock is shallow). The upper portion of each Good Thunder formation unit is locally oxidized to yellow-brown or oxidized/reduced to green or green-blue, suggesting that a significant period of exposure and weathering took place between depositional events. Some of these units probably correlate with the Lake Henry and Eagle Bend Formations of central Minnesota (Johnson and others, 2016). Although all five Good Thunder formation till 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 contain pods, lenses, and thin layers of outwash sand and gravel and sand. In other previously mapped counties (Renville and Sibley), thin, red, glacial sediments of Superior provenance (Fig. 2) have been observed between Good Thunder formation units; however, these were not encountered in Redwood County.

Qs1 — ***Sand and gravel*** (new unit)—Chiefly composed of stream sediment derived from unit *Qg1*, but may also include materials from overlying units.

Qg1 — ***Loam till*** (new unit)—Contains slightly more gray shale and other Cretaceous rock fragments than Good Thunder formation units *Qg2*, *Qg4*, and *Qg5* (Table 1).

Qs2 — ***Sand and gravel*** (new unit)—Commonly composed of stream sediment from unit *Qg2*, but may include some materials derived from overlying units *Qg1*, *Qti*, and *Qtm*.

Qg2 — ***Loam till*** (new unit)—Locally oxidized, contains trace amounts of gray shale and other Cretaceous rock fragments, similar to unit *Qg4*, but also contains an average of 3 percent red clasts (Table 1). Locally can include material derived from units *Qg1* and *Qg3*, and fine-grained lake sediment.

Qs3 — ***Sand and gravel*** (new unit)—Commonly composed of stream sediment derived from unit *Qg3*; may include some materials derived from overlying units *Qg1* and *Qg2*.

Qg3 — ***Loam till*** (new unit)—Contains approximately 10 percent gray shale and other Cretaceous rock fragments (Table 1), which makes this unit easy to confuse with Des Moines-lobe till deposits in outcrops along the Minnesota River valley bluffs. Locally can include material from units *Qg2* and *Qg4*, and fine-grained lake sediment.

Qs4 — ***Sand and gravel*** (new unit)—Commonly composed of stream sediment from unit *Qg4*; may include some materials derived from overlying units *Qg2* and *Qg3*.

Qg4 — ***Loam till*** (new unit)—Contains trace amounts of gray shale and other Cretaceous rock fragments, similar to unit *Qg2* (Table 1). Locally can include material from unit *Qg5*, older undifferentiated units, and fine-grained lake sediment. Green to greenish-blue (reduced) sediment is present in places and forms the upper contact of this unit.

Qs5 — ***Sand and gravel*** (new unit)—Commonly composed of stream sediment from unit *Qg5*; may include some materials from overlying units *Qg3* and *Qg4*, and older undifferentiated units.

Qg5 — ***Loam till*** (new unit)—Contains trace amounts of gray shale and other Cretaceous rock fragments (Table 1). Its moderate carbonate content distinguishes it from other Good Thunder formation units. Locally can include material from unit *Qg4*, older undifferentiated units, and fine-grained lake sediment. In places an organic soil horizon has developed, commonly in lake sediment, forming the upper contact of this unit. Some wood fragments are present.

Elmdale Formation—Yellow-brown to dark gray bedded sediment and dense loam to clay loam till of Winnipeg provenance (Figs. 2, 3) associated with the "W" sequence units of central and north-central Minnesota (Meyer, 1997). The till contains small to moderate amounts of carbonate, some gray shale, and 2 percent red clasts (Table 1). Commonly thin and patchy. Locally contains significant amounts of incorporated saprolite (weathered bedrock) and bedrock.

Qte — ***Loam till*** (new unit)—Recognized in rotary-sonic drill hole RWR-1 (Fig. 4). Locally includes materials from the underlying units *Qw*, *Qwt*, *Qv*, and *Qvt*.

Other "W" sequence units—Brown to very dark gray or grayish-brown to black bedded sediment and dense loam and clay loam tills of Winnipeg and Rainy provenance (Figs. 2, 3) associated with the "W" sequence units of central and north-central Minnesota (Meyer, 1997). These tills contain small amounts of carbonate, zero to trace percent of gray shale clasts, and average 2 percent red clasts (Table 1). Commonly thin and patchy, and where present appears to be the basal glacial unit above bedrock. Locally contains significant amounts of incorporated saprolite (weathered bedrock) and bedrock.

Qws — ***Sand and gravel*** (new unit)—Commonly composed of stream sediment from unit *Qw*; locally includes materials from overlying units and reworked bedrock.

Qw — ***Loam till*** (new unit)—Recognized in three rotary-sonic drill holes (RWR-3, RWR-6, and RWR- 7; Figs. 6, 9, and 10, respectively). Locally includes materials from the underlying units *Qwt*, *Qv*, and *Qvt*, older glacial deposits, and bedrock.

Qwt — ***Loam till*** (new unit)—Recognized in two rotary-sonic drill holes (RWR-1 and RWR-3; Figs. 4 and 6, respectively). Locally includes materials from the underlying "V" sequence units, older glacial deposits, and bedrock.

"V" sequence units—Brown to very dark gray or grayish-brown to black bedded sediment and dense loam and clay loam tills of Riding Mountain and Winnipeg provenance (Figs. 2, 3) associated with the "V" sequence units of central and north-central Minnesota (Meyer, 1997). These tills contain moderate amounts of carbonate, an average of 7 to 8 percent gray shale clasts, and an average of 2 percent red clasts (Table 1). Only present in the southwest corner of the county, appears to be the basal glacial units above bedrock. Locally contains significant amounts of incorporated saprolite (weathered bedrock) and bedrock.

Qvs — ***Sand and gravel*** (new unit)—Commonly composed of stream sediment from unit *Qv*; locally includes materials from overlying units and reworked bedrock.

Qv — ***Loam till*** (new unit)—Recognized in rotary-sonic drill hole RWR-1 (Fig. 4). Locally includes materials from older glacial deposits, and bedrock.

Qss — ***Sand and gravel*** (new unit; shown on Fig. 4)—Commonly composed of stream sediment from unit *Qvt*; locally includes materials from overlying units and reworked bedrock.

Qvt — ***Loam till*** (new unit)—Recognized in rotary-sonic drill hole RWR-1 (Fig. 4). Locally includes materials from older glacial deposits, and bedrock.

Undifferentiated deposits

Qsu — **Undifferentiated sand and gravel** (new unit)—Commonly composed of stream sediment from the underlying till unit; may include materials from units *Qtu* and *Qu* and reworked bedrock. May include till in places.

Qtu — **Undifferentiated till** (new unit)—May contain older New Ulm Formation deposits (in the northwest corner of the county, as in Fig. 5) but typically contains one or more pre-late Wisconsinan deposits (Fig. 3): the Good Thunder or Elmdale formation, "W" or "V" sequence, or older deposits. Although some water wells extend below this boundary, the data are too few to make meaningful correlations.

Qsb — **Undifferentiated sand and gravel** (new unit)—Stream sediment that occurs below unit *Qtu*; may include materials from units *Qtu* and *Qu* and reworked bedrock. May include till in places. Not shown on the printed cross sections, but included in the digital files accompanying this atlas.

Qu — **Undifferentiated sediment** (new unit)—Includes till, sand, gravel, and fine-grained lake sediments. Shown in areas where control data are scarce or absent.

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Jon Mitchell, director of the Redwood County Environmental Office, assisted in siting rotary-sonic drilling locations on county properties. William Rabenberg permitted us to drill at the Redwood County Highway Department yards in Wabasso, Milroy, and Lucan. Karl Ramey helped site the Gilfillan Farm boring. Pauline Nickel and Jodi Getting allowed access to the University of Minnesota Southwest Research and Outreach Center. Minnesota Geological Survey staff members Bruce Bloomgren, Alan Knaeble, Alex Gjorvad and Matt Matko provided support during rotary-sonic drilling. Valerie Stanley processed and V.W. Chandler interpreted the paleomagnetic measurements for samples of rotary-sonic core from RWR-8. Vania Stefanova analyzed and interpreted pollen samples in rotary-sonic core from RWR-6 and RWR-8. 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.

REFERENCES

Broussard, W.L., Anderson, H.W., and Farrell, D.F., 1973, Water resources of the Cottonwood River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Atlas 466, 3 pls.

Hobbs, H.C., 1998, Use of 1-2 millimeter sand-grain composition in Minnesota Quaternary studies, *in* Patterson, C.J., and Wright, H.E., Jr., eds., Contributions to Quaternary studies in Minnesota: Minnesota Geological Survey Report of Investigations 49, p. 193-208.

Jennings, C.E., 2010, Sediment source apportionment to the Lake Pepin TMDL—Source characterization middle Minnesota watershed: Minnesota Geological Survey Open-File Report 10-1, scale 1:100,000.

Jennings, C.E., Aber, J.S., Balco, G., Barendregt, R., Bierman, P.R., Rovey, C.W., II, Roy, M., Thorleifson, L.H., and Mason, J.A., 2006, Mid-Quaternary in North America, *in* Elias, S.A., ed., Encyclopedia of Quaternary science: Oxford, England, Elsevier, p. 1044-1050.

Jennings, C.E., Lusardi, B.A., and Gowan, A.S., 2012, Surficial geology, pl. 3 *of* Lusardi, B.A., project manager, Geologic atlas of Blue Earth County, Minnesota: Minnesota Geological Survey County Atlas C-26, 6 pls., scale 1:100,000.

Johnson, M.D., Adams, R.S., Gowan, A.S., Harris, K.L., Hobbs, H.C., Jennings, C.E., Knaeble, A.R., Lusardi, B.A., and Meyer, G.N., 2016, Quaternary lithostratigraphic units of Minnesota: Minnesota Geological Survey Report of Investigations RI-68.

Knaeble, A.R., 2013, Quaternary stratigraphy, pl. 4 *of* Setterholm, D.R., project manager, Geologic atlas of Renville County, Minnesota: Minnesota Geological Survey County Atlas C-28, 5 pls., scale 1:100,000.

———in press, Quaternary stratigraphy, pl. 4 *of* Boerboom, T.J., project manager, Geologic atlas of Brown County, Minnesota: Minnesota Geological Survey County Atlas C-37, 5 pls., scale 1:100,000.

Knaeble, A.R., and Meyer, G.N., 2007, Quaternary stratigraphy, pl. 4 *of* Setterholm, D.R., project manager, Geologic atlas of Todd County, Minnesota: Minnesota Geological Survey County Atlas C-18, 6 pls, scale 1:100,000.

Lisiecki, L.E., and Raymo, M.E., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records: Paleoceanography, v. 20, 17 p.

Lusardi, B.A., Meyer, G.N., Knaeble, A.R., Gowan, A.S., and Jennings, C.E., 2012, Quatenary stratigraphy, pl. 4, *of* Meyer, G.N., project manager, Geologic atlas of Sibley County, Minnesota: Minnesota Geological Survey County Atlas C-24, 6 pls., scale 1:100,000.

Meyer, G.N., 1997, Pre-late Wisconsinan till stratigraphy of north-central Minnesota: Minnesota Geological Survey Report of Investigations 48, 67 p.

Meyer, G.N., Knaeble, A.R., Lusardi, B.A., Jennings, C.E., and Gowan, A.S., 2012a, Quaternary stratigraphy, pl. 4, *of* Meyer, G.N., project manager, Geologic atlas of Blue Earth County, Minnesota: Minnesota Geological Survey County Atlas C-26, 6 pls., scale 1:100,000.

Meyer, G.N., Lusardi, B.A., Knaeble, A.R., Jennings, C.E., and Gowan, A.S., 2012b, Quaternary stratigraphy, pl. 4, *of* Meyer, G.N., project manager, Geologic atlas of Nicollet County, Minnesota: Minnesota Geological Survey County Atlas C-25, 6 pls., scale 1:100,000.

Minnesota Department of Transportation, 2014, Office of materials and road research web site: St. Paul, Minn., <http://www.mrrapps.dot.state.mn.us/gisweb/viewer.htm>.

Patterson, C.J., 1997, Surficial geology of southwestern Minnesota, *in* Patterson, C.J., ed., Contributions to the Quaternary geology of southwestern Minnesota: Minnesota Geological Survey Report of Investigations 47, p. 1-45.

Patterson, C.J., Knaeble, A.R., Setterholm, D.R., and Berg, J.A., 1999, Quaternary stratigraphy, pl. 2, *of* Patterson, C.J., ed., Regional hydrogeologic assessment, Quaternary geology of the upper Minnesota River basin, Minnesota: Minnesota Geological Survey Regional Hydrogeologic Assessment RHA-4, pt. A., 2 pls., scale 1:200,000.

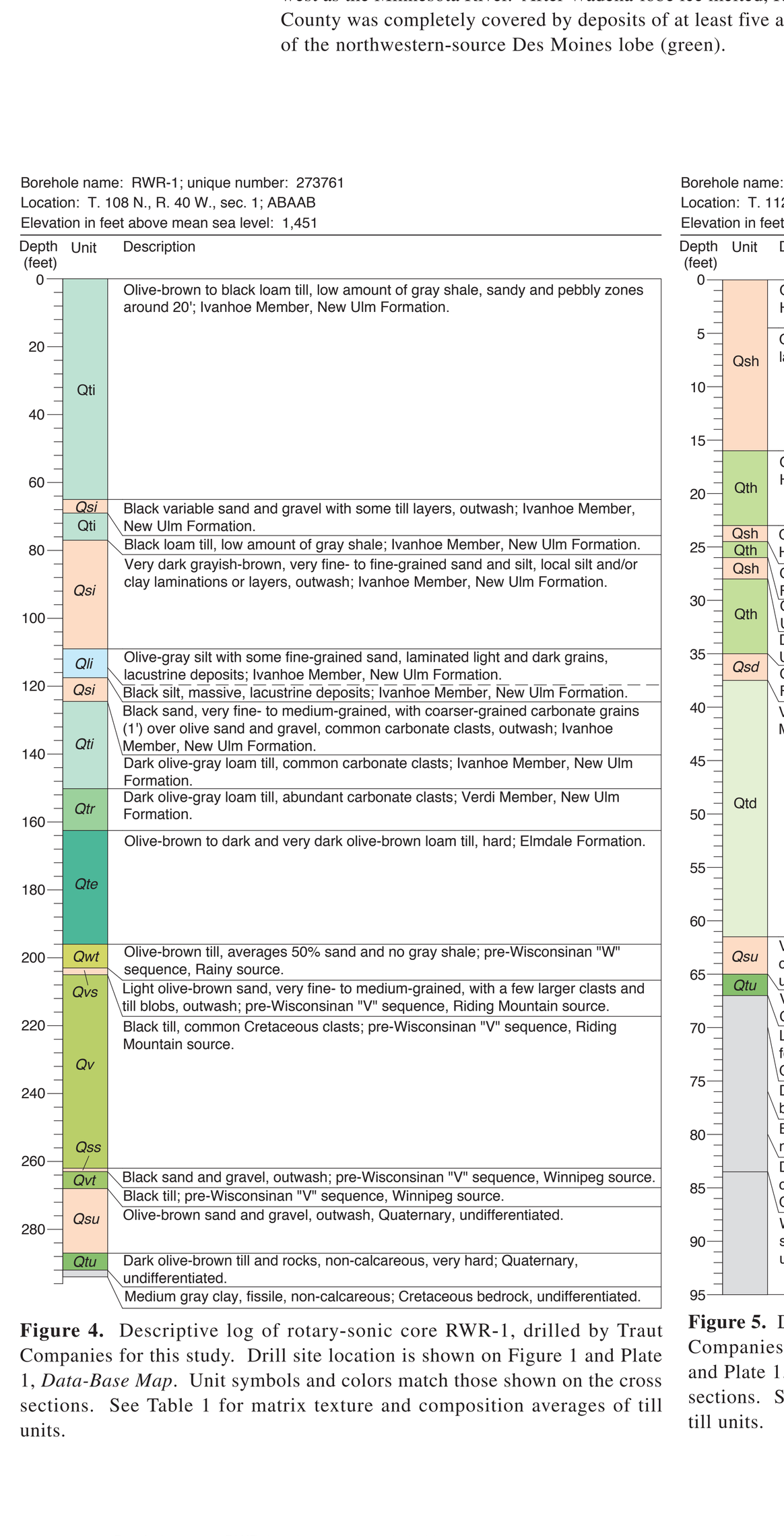

Figure 4. Descriptive log of rotary-sonic core RWR-1, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1, *Data-Base Map*. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

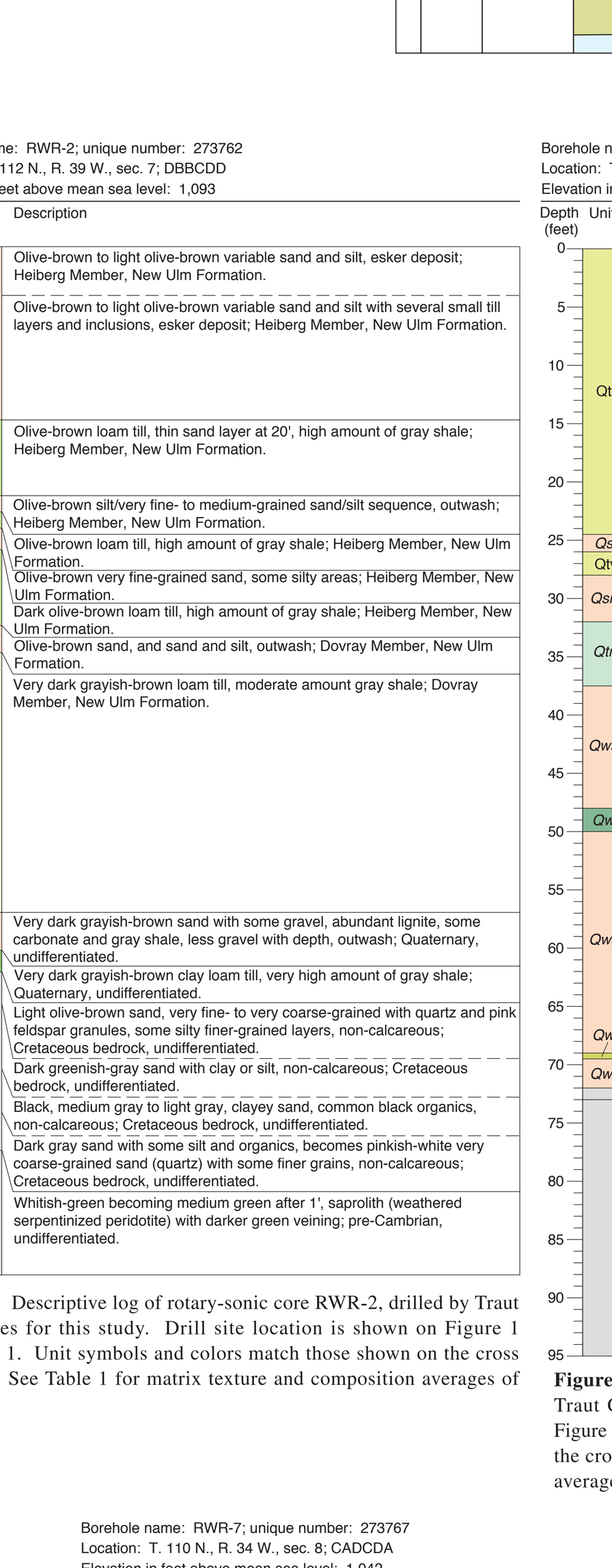

Figure 5. Descriptive log of rotary-sonic core RWR-2, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

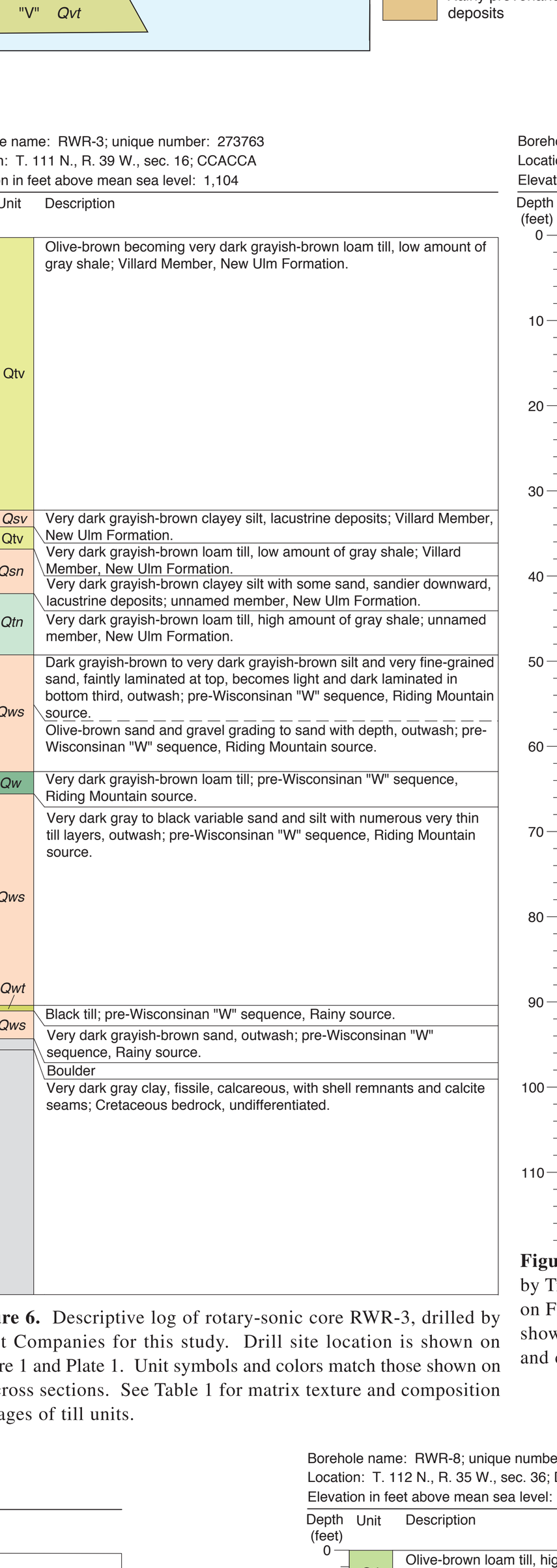

Figure 6. Descriptive log of rotary-sonic core RWR-3, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

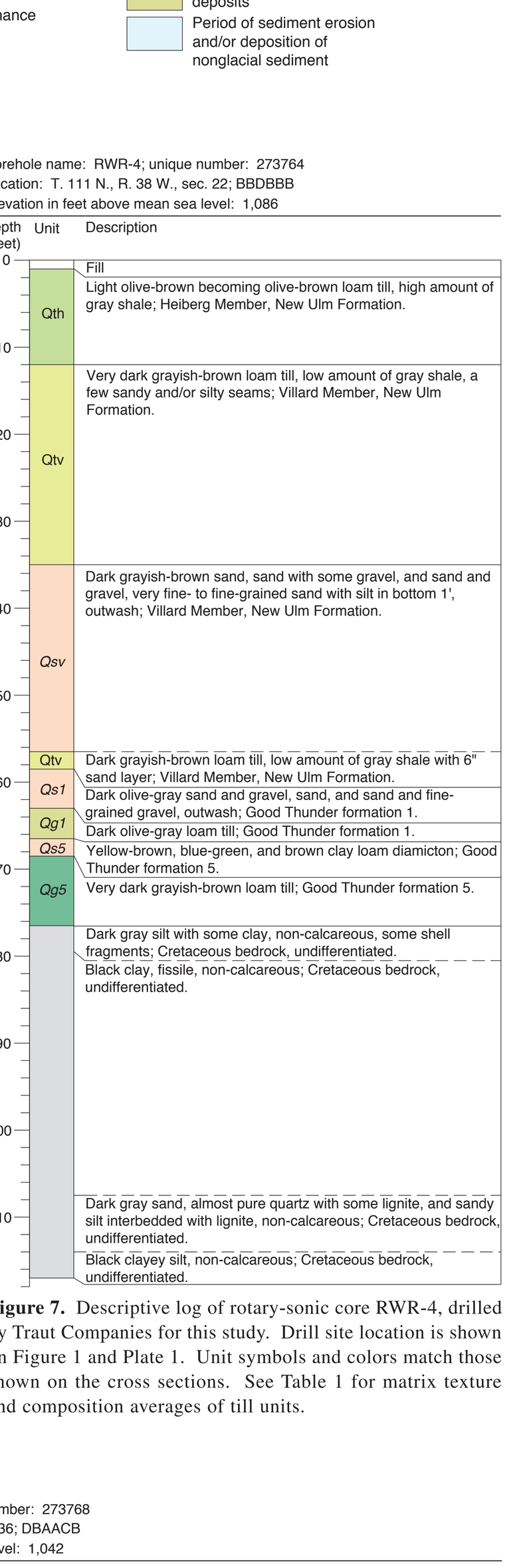

Figure 7. Descriptive log of rotary-sonic core RWR-4, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

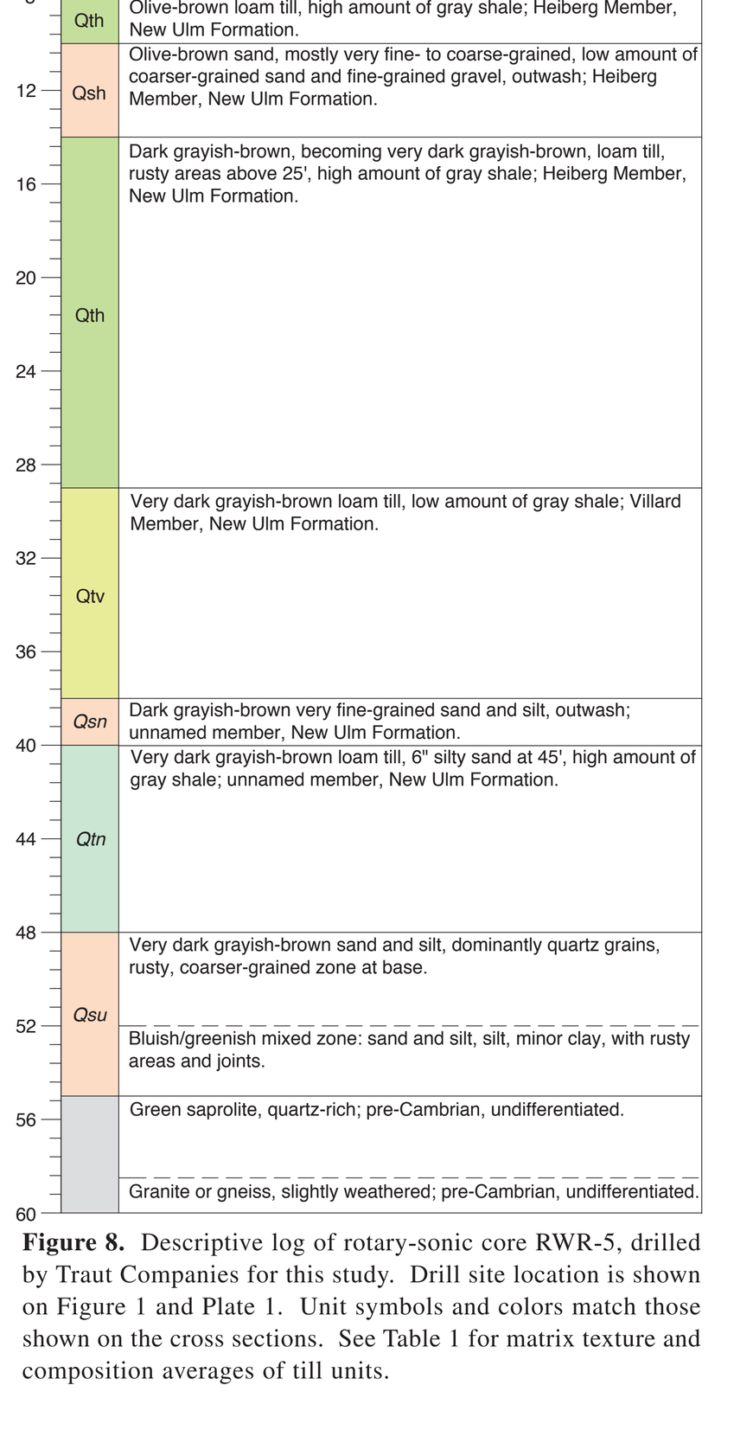

Figure 8. Descriptive log of rotary-sonic core RWR-5, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

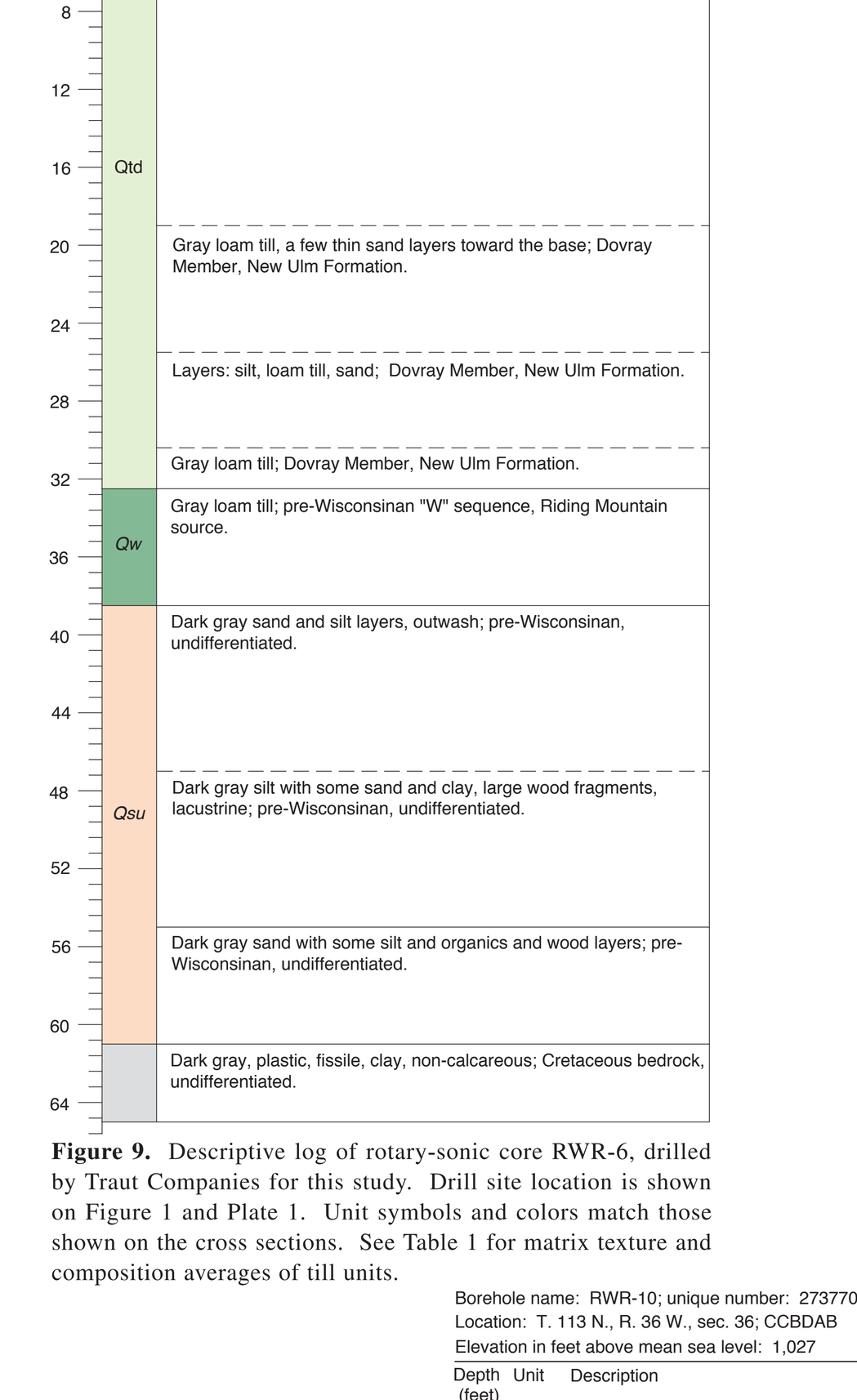

Figure 9. Descriptive log of rotary-sonic core RWR-6, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

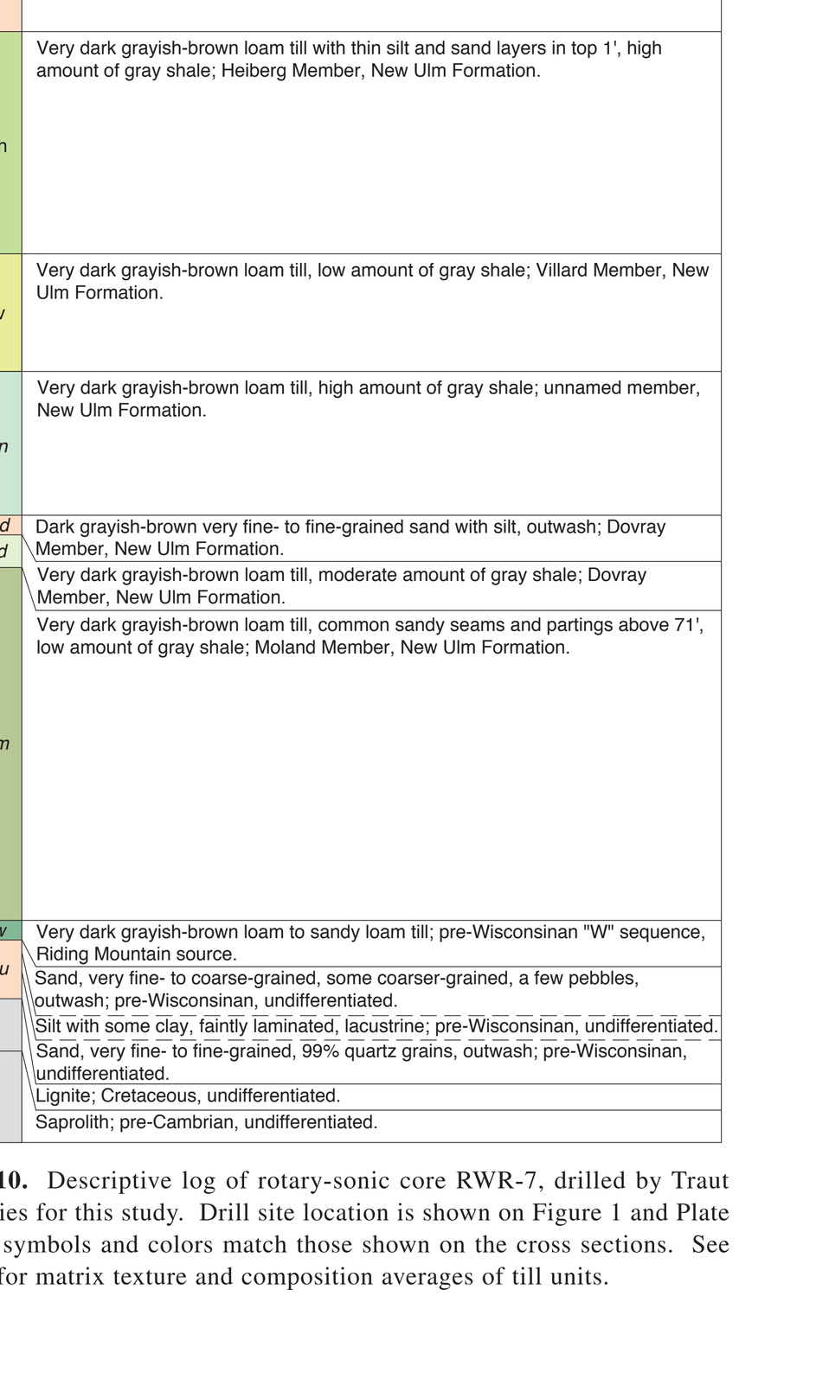

Figure 10. Descriptive log of rotary-sonic core RWR-7, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

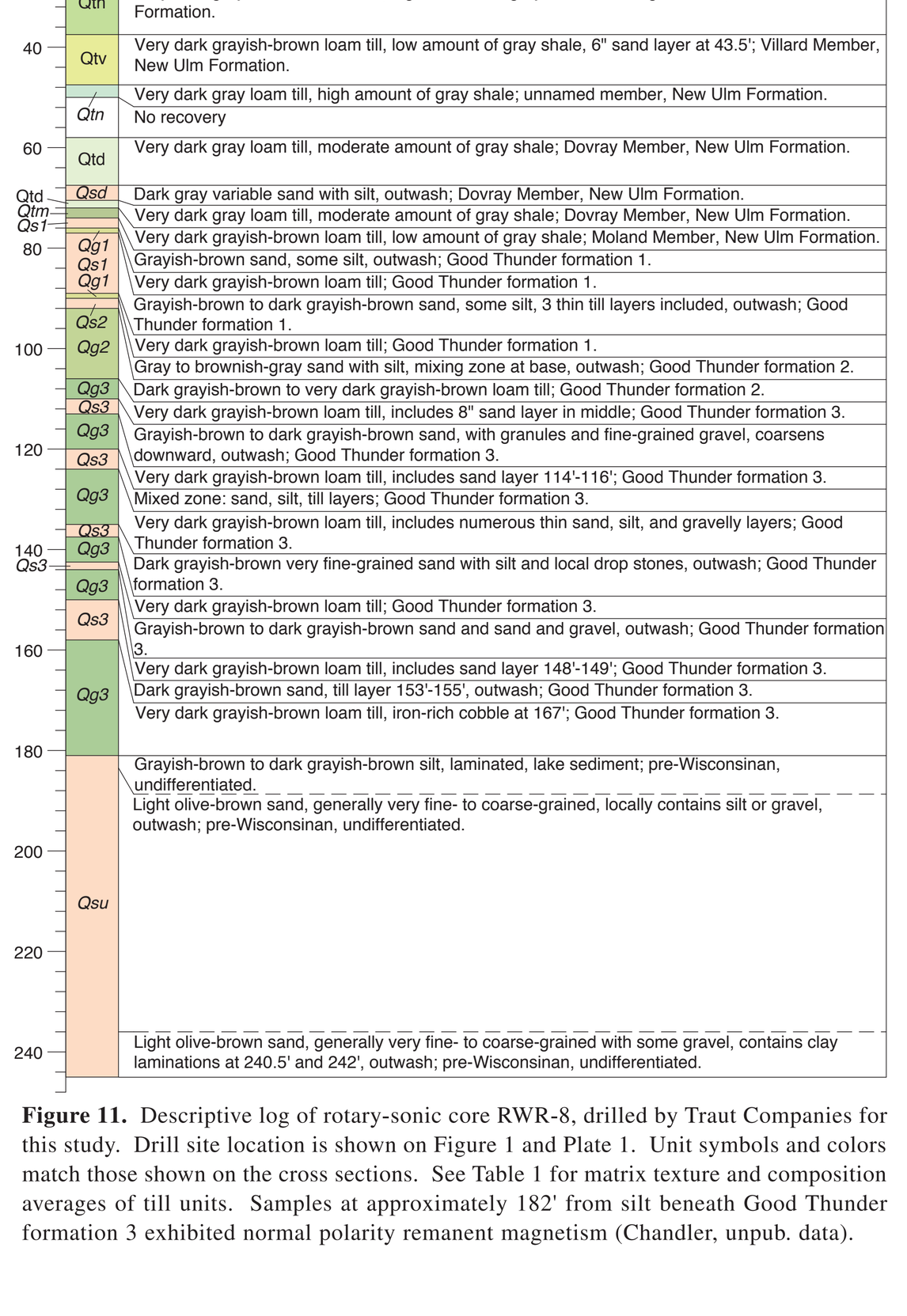

Figure 11. Descriptive log of rotary-sonic core RWR-8, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. Samples at approximately 182' from silt beneath Good Thunder formation 3 exhibited normal polarity remanent magnetism (Chandler, unpub. data).

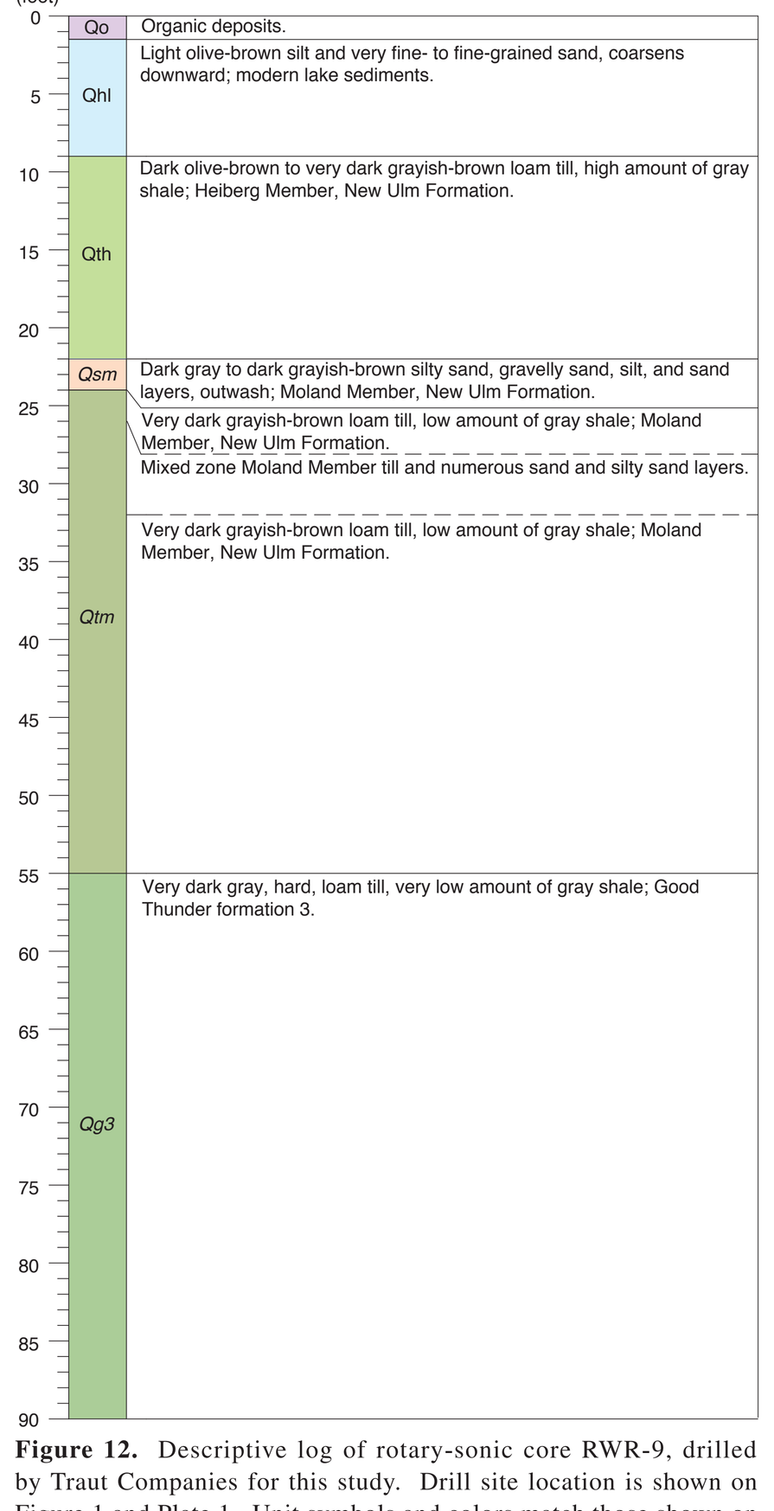

Figure 12. Descriptive log of rotary-sonic core RWR-9, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

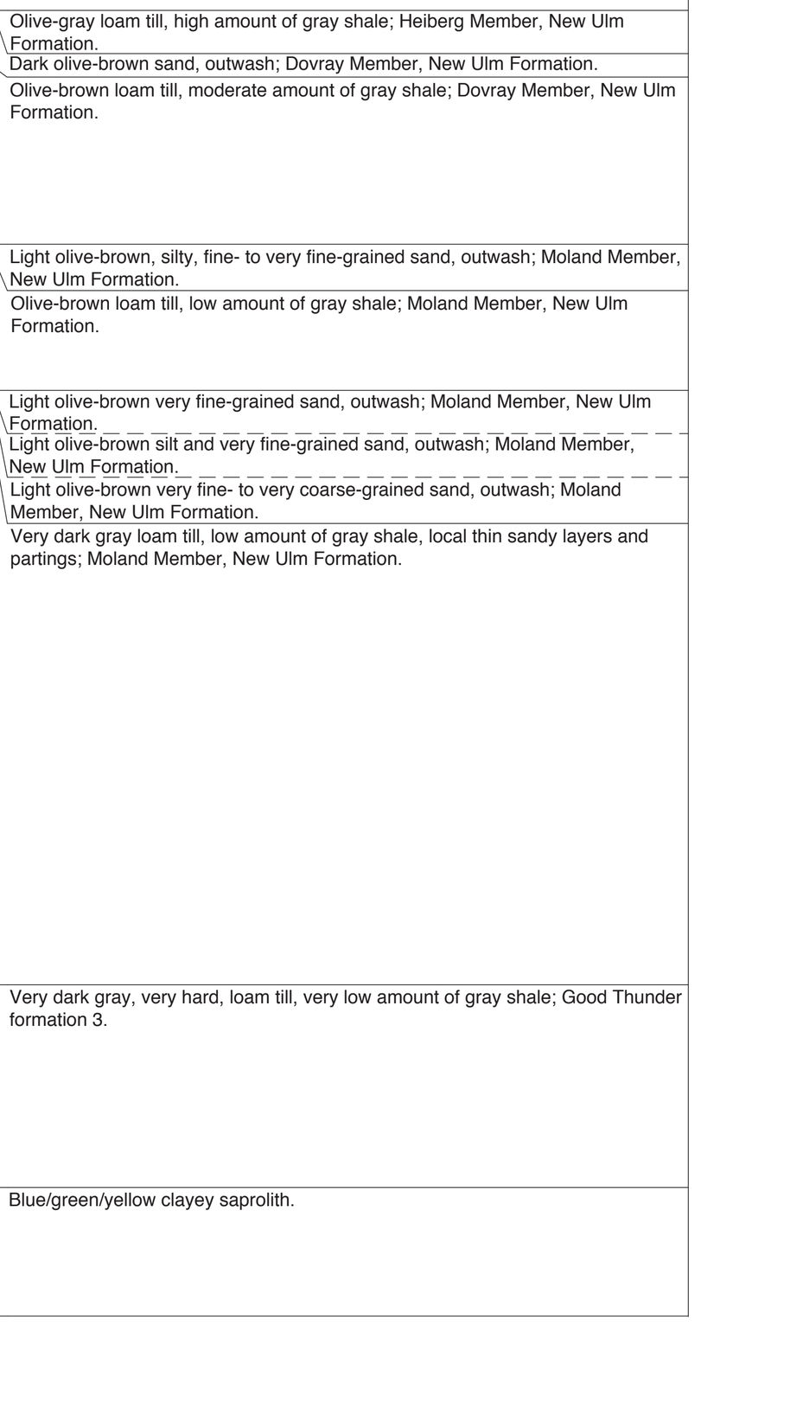

Figure 13. Descriptive log of rotary-sonic core RWR-10, drilled by Traut Companies for this study. Drill site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

Table 1. Average values for the matrix texture and sand composition of tills recognized in Redwood 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 crystalline rocks, carbonate rocks, and gray shale modified from the classification system of Hobbs (1998). Also shown is the percentage of Cretaceous grains, which helps to classify samples. The Precambrian crystalline 1-2 millimeter fraction is further differentiated by crystalline rock type into light grains (granite and gneiss), dark grains (mafic-igneous and other metamorphic rocks), and red grains (iron-formation, rhyolite, agate, and sandstone). Clear quartz is a further differentiation of the Precambrian crystalline light 1-2 millimeter grain-size 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			
	Total number of samples	Gravel (percentage of total sample weight)	Sand	Silt	Clay	Total number of samples	Crystalline	Carbonate	Shale	Cretaceous	Light	Dark	Red	Clear quartz
Late Wisconsinan														
Deposits of the Des Moines lobe														
New Ulm Formation														
Heiberg Member till (units Qth, Qmh, Qwh on Plate 3, unit Qth on cross sections)	171	5	39	42	19	170	35	23	42	43	87	12	1	16
Villard Member till (units Qtv, Qwv on Plate 3, unit Qtv on cross sections)	63	5	44	40	16	63	49	32	19	21	88	12	0	16
Unnamed till with high shale content (unit *Qtn* on cross sections)	8	8	39	39	22	8	34	26	40	42	88	12	0	16
Dovray Member till (units Qtd, Qwd on Plate 3, unit Qtd on cross sections)	64	6	40	41	19	64	43	29	28	30	87	12	1	16
Moland Member till (unit *Qtm* on cross sections)	83	7	48	36	15	83	54	34	11	14	87	13	0	15
Ivanhoe Member till (units Qti, Qwi on Plate 3, unit Qti on cross sections)	47	6	35	39	26	47	55	31	14	16	86	13	1	16
Verdi Member till (unit *Qtr* on cross sections)	5	7	34	48	17	5	42	50	9	17	81	19	0	15
Pre-late Wisconsinan deposits														
Good Thunder formation														
Till 1 (unit *Qg1* on cross sections)	7	5	40	40	20	7	64	33	3	6	85	14	1	13
Till 2 (unit *Qg2* on cross sections)	6	7	48	37	15	6	68	32	0	1	81	16	3	16
Till 3 (unit *Qg3* on cross sections)	70	6	36	42	22	68	57	37	6	9	86	14	0	17
Till 4 (unit *Qg4* on cross sections)	2	11	44	39	17	2	60	39	1	3	88	11	1	17
Till 5 (unit *Qg5* on cross sections)	8	4	36	39	25	8	71	27	2	5	86	13	1	22
Elmdale Formation till (unit *Qte* on cross sections)	12	2	43	31	26	12	76	23	1	4	83	15	2	23
Unnamed pre-Wisconsinan Riding Mountain/Winnipeg till (unit *Qw* on cross sections)	18	3	31	47	22	13	81	18	1	6	83	15	2	23
Unnamed pre-Wisconsinan Rainy till (unit *Qwt* on cross sections)	5	3	49	29	22	5	86	14	0	1	83	15	2	25
Unnamed pre-Wisconsinan Riding Mountain till (unit *Qv* on cross sections)	49	6	31	42	27	49	51	41	8	19	78	20	2	25
Unnamed pre-Wisconsinan Winnipeg till (unit *Qvt* on cross sections)	2	7	36	40	24	2	53	40	7	15	83	15	2	23