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Anthony C. Runkel, Interim Director

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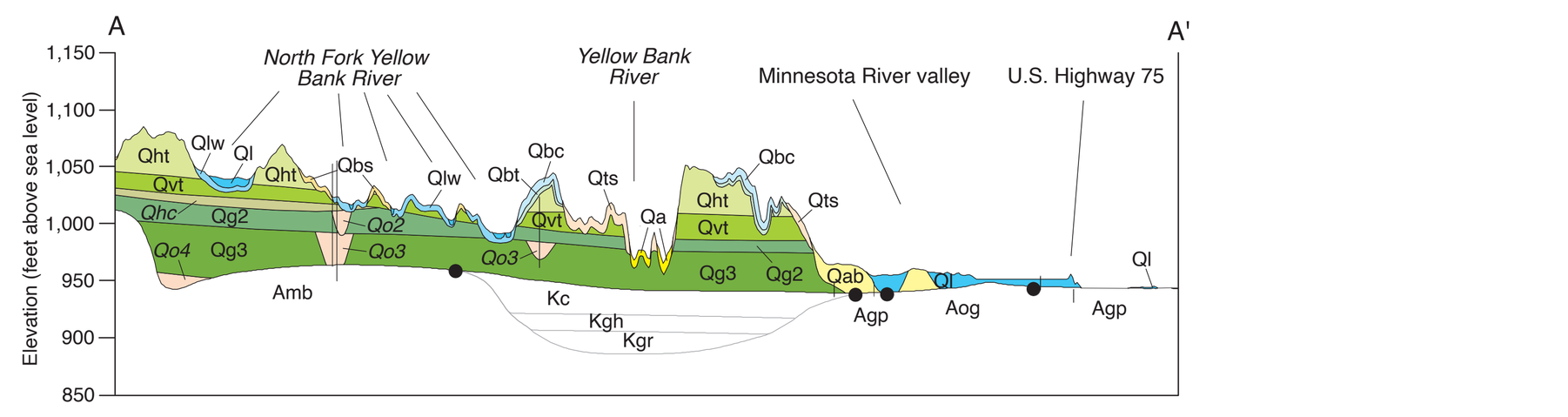
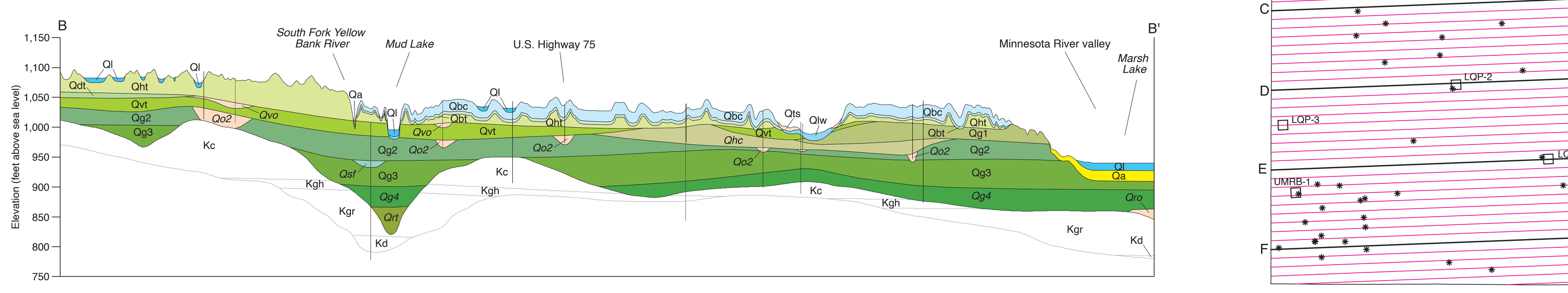
QUATERNARY STRATIGRAPHY

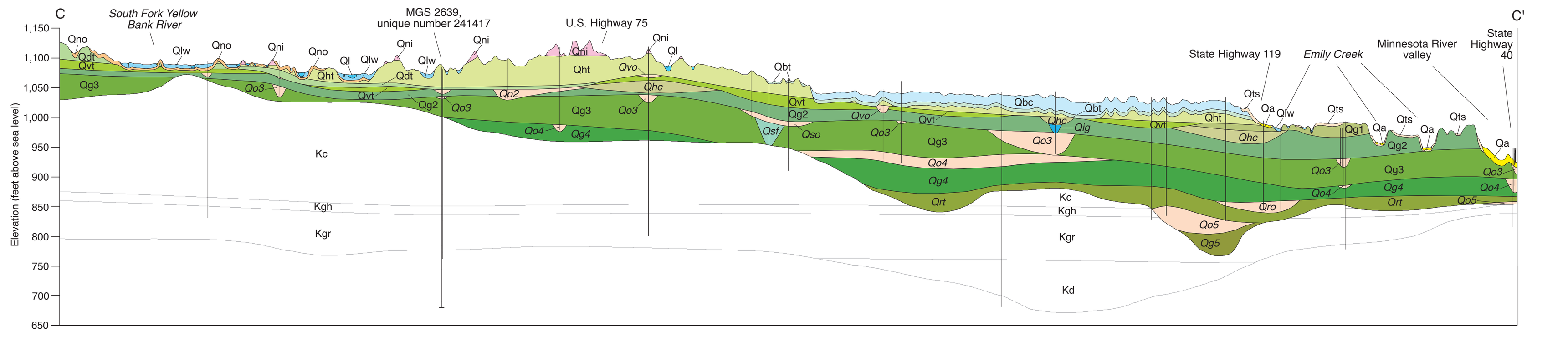
By

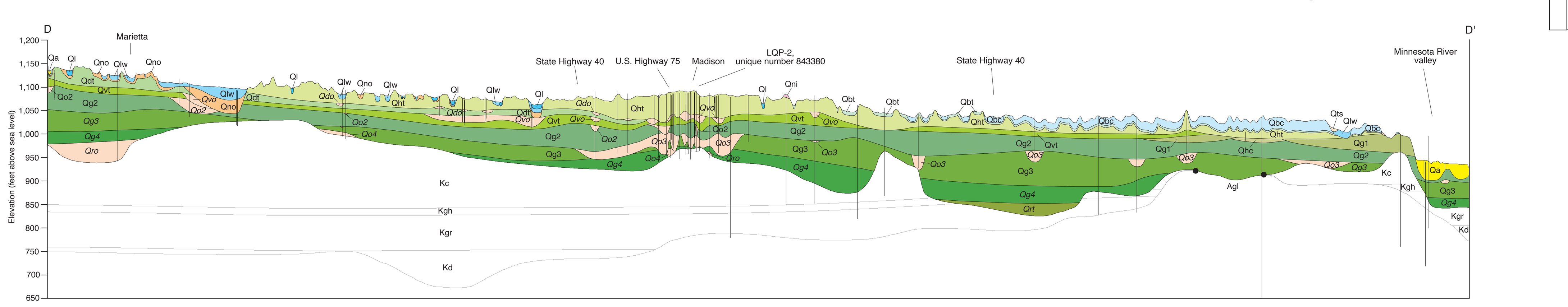
Angela J. Radke

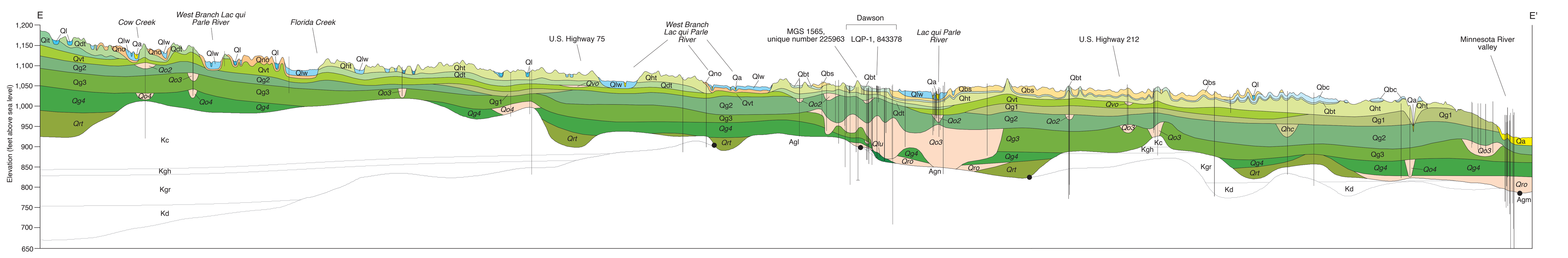
2023

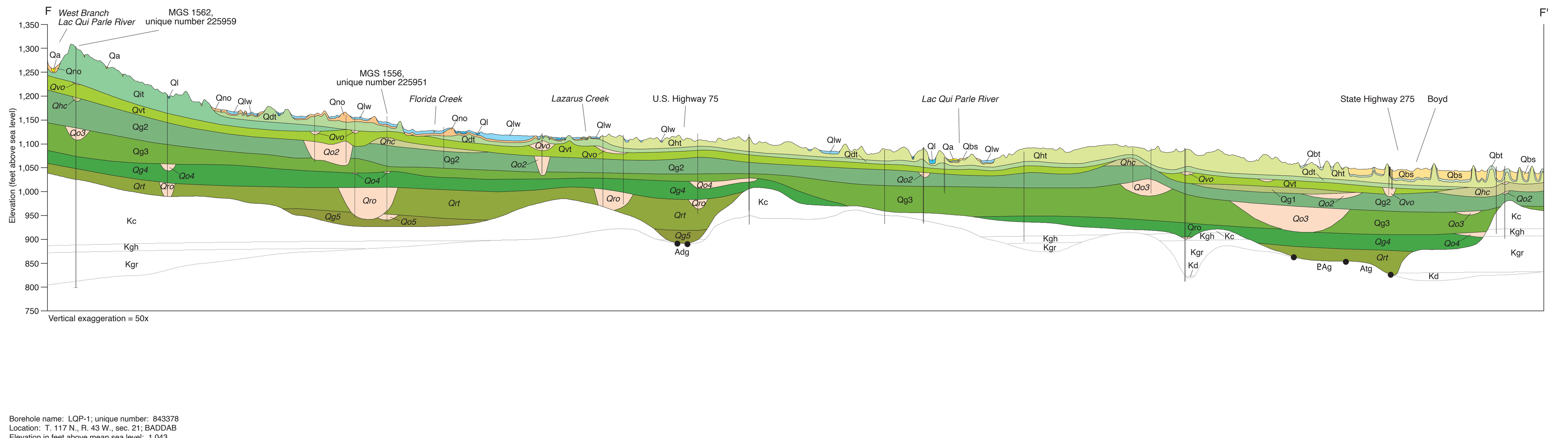












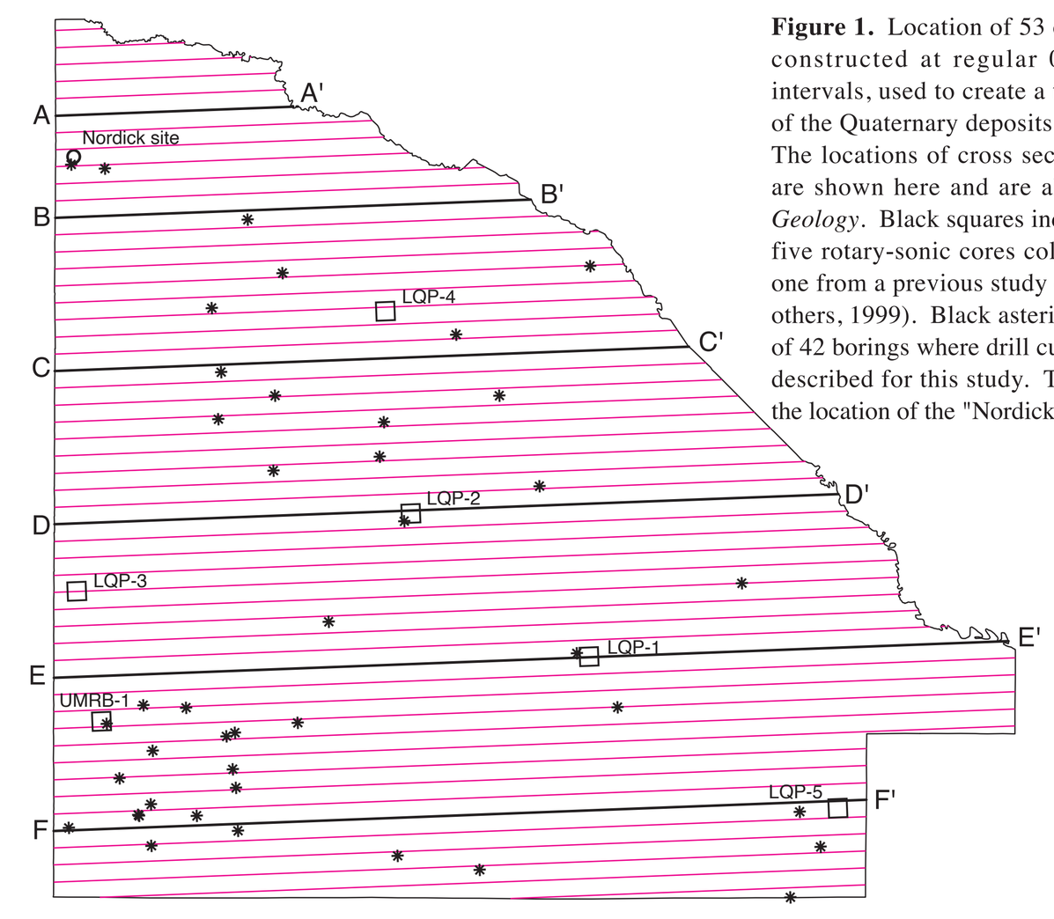


Figure 1. Location of 53 east–west cross sections, constructed at regular 0.6-mile (1-kilometer) intervals, used to create a three-dimensional model of the Quaternary deposits of Lac qui Parle County. The locations of cross sections A–A' through F–F' are shown here and are also on Plate 3, *Surficial Geology*. Black squares indicate the locations of the five rotary-sonic cores collected for this study and one from a previous study (UMRB-1; Patterson and others, 1999). Black asterisks indicate the locations of 42 borings where drill cuttings were collected and described for this study. The black circle indicates the location of the "Nordick Site" outcrop in Figure 8.

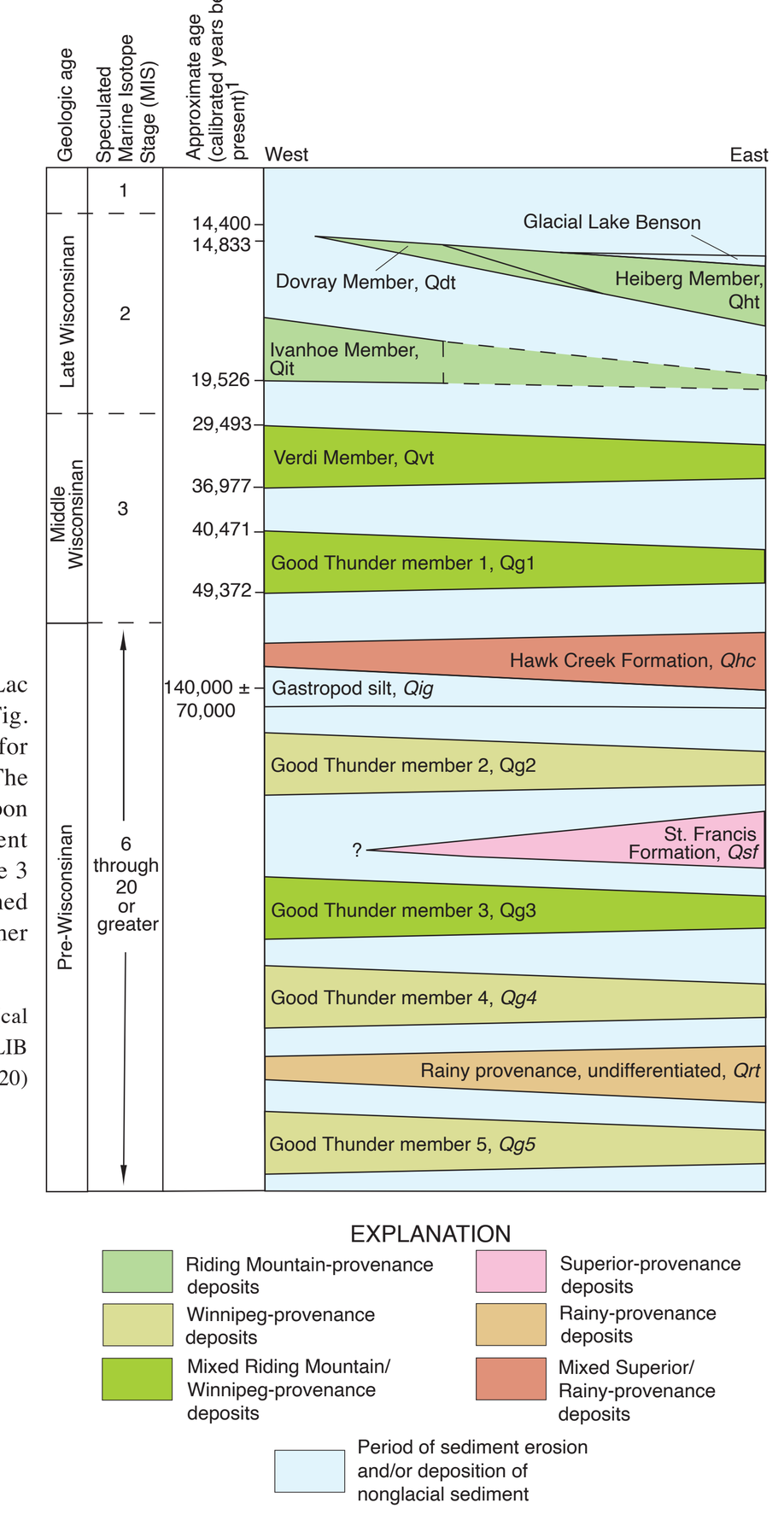


Figure 2. Diagram showing relative age, location (across Lac qui Parle County from west to east), provenance, (Plate 3, Fig. 2, Table 1), and related unit labels from the cross sections for late, middle, and pre-Wisconsinan glacial tills (Table 1). The age column and unit drawings are not to scale. All radiocarbon ages shown are calibrated to calendar years before present (cal YBP; Stuiver and others, 2020). See the text on Plate 3 for a discussion of the glacial geologic history. The dashed line for the Ivanhoe member represents its interpreted former extent prior to being eroded.

[1]Ages are in calibrated/calendar years before present (cal YBP) and recalibrated from published radiocarbon dates using CALIB radiocarbon calibration program, Calib 8.2 (Stuiver and others, 2020) with 2 sigma error.

MAP SYMBOLS

Geologic contact—Approximate.

Sampled drill hole—Includes cored rotary-sonic drill holes, archived split-spoon core holes, and cutting sets from drill holes. Well cuttings may not have been collected from throughout the entire thickness of the material drilled. The rotary-sonic hole is labeled with its assigned name and unique number.

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 (within 0.3 mile [0.5 kilometer]) the cross-section line and therefore may have a slightly different surface elevation.

Bedrock contact—Cretaceous bedrock contact below the Quaternary stratigraphy. See Plate 2, *Bedrock Geology*.

Bedrock contact point—Shown at the base of Quaternary deposits with the associated bedrock unit label where Precambrian rock is the uppermost bedrock; see Plate 2.

INTRODUCTION

The Quaternary Stratigraphy plate shows the unconsolidated materials expected to be encountered between the land surface and bedrock surface in Lac qui Parle County. Cross sections A–A' through F–F' are representative of 53 cross sections (Fig. 1) spaced 0.6 mile (1 kilometer) apart that were constructed to create a three-dimensional model of the Quaternary deposits in the county. These deposits are assigned to the lithostratigraphic units defined in Johnson and others (2016) unless otherwise indicated. 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 supplementary digital files that accompany this plate. The Quaternary geologic units shown on the cross sections were defined from interpretation of new data collected for this study and from existing data and samples from previous investigations (see Plate 3, *Surficial Geology*, Index to Previous Mapping). These data sources include: two rotary-sonic drill cores contracted by the Minnesota Department of Natural Resources and collected by the Minnesota Geological Survey (LQP-1, LQP-2; Figs. 1, 3, 4), three rotary-sonic drill cores contracted and collected by the Minnesota Geological Survey (LQP-3, LQP-4, LQP-5; Figs. 1, 5, 6), one archived rotary-sonic core drilled for a previous study (UMRB-1; Fig. 1; Patterson and others, 1999), 42 well cutting sets archived in the Minnesota Geological Survey cuttings library, outcrops, soil auger samples, and water-well and soil-boring drillers' logs (Plate 1, *Database Map*).

On each of the cross sections shown, rotary-sonic holes, well cutting sets, and water wells are displayed as black vertical lines; rotary-sonic holes are labeled with their assigned names and wells with cuttings are labeled with a unique line symbol and their assigned names. The elevation where wells are shown to begin may not match the surface elevation on the cross-section line. This is because data for each line are gathered from up to 0.3 mile (0.5 kilometer) from both the north and south sides of the line where the surface elevation may be higher or lower. Bedrock units described on Plate 2, *Bedrock Geology*, are labeled and shown at the base of the Quaternary deposits. Vertical exaggeration is 50x for all cross sections to show the commonly thin, complex units of the Quaternary section. Figure 2 is a time-distance illustration showing the inferred relationships between age, provenance, stratigraphic position, and general geographic location of the sediments deposited by major glacial episodes. Descriptions from the five rotary-sonic cores drilled for this study are in Figures 3 through 7, and the texture and composition of selected geologic units are summarized in Table 1.

The complexity of subsurface units shown on the cross sections is partly a function of the amount of data available. Where data are sparse, units are portrayed as continuous with relatively uniform thicknesses and minimal changes in elevation. In areas of higher data density, units are portrayed with more complexity. Glacial till and fine-grained lacustrine sediments are generally considered more continuous than sand and gravel units because of the way glaciers deposit these sediment types. Till was typically laid down as laterally extensive sheets deposited directly by ice. Sand and gravel were deposited by streams and therefore tends to be more discrete and discontinuous. By convention, subsurface sand and gravel units are associated with the underlying till unit. However, these sand and gravel units likely represent deposition by meltwater from ice that deposited both the underlying and overlying till units. All the units described on Plate 3 match the units mapped on this plate. Additional Pleistocene units are present only in the subsurface and are thus mapped and described on this plate and Plate 5. Typically, areas below the depth of available water-well records and above the bedrock surface are mapped as "undifferentiated sediment." In this instance, effort was made to differentiate the entirety of the Quaternary sediment package from the surface to bedrock. The degree of uncertainty increases with depth as data available for interpretation decreases; therefore, units differentiated in closer proximity to bedrock are an approximation.

The Good Thunder formation member tills, which compose a significant thickness of Quaternary sediment in Lac qui Parle County, have not yet been formalized because additional work in southern Minnesota is needed to correlate them to existing stratigraphic framework to the north (Johnson and others, 2016). One interpretation is that the upper two members (1 and 2) of the Good Thunder formation are correlative to the Sauk Centre and Meyer Lake Members of the Lake Henry Formation, two carbonate-rich tills defined in central Minnesota (Knaeble and Meyer, 2007; Knaeble, 2013; Johnson and others, 2016; Staley, 2019). In Lac qui Parle County, however, this correlation was not made after examination of age constraints on these units. The timing of deposition of the Lake Henry Formation is constrained by a U-Th series minimum age of greater than 200,000 years from interglacial marl found atop the Browerville Formation, a till stratigraphically above the Lake Henry Formation members (Knaeble and Meyer, 2007; Johnson and others, 2016). If the Good Thunder formation tills are correlative, this age implies that all Good Thunder formation tills are greater than 200,000 years old. However, an age date from adjacent Grant County in northeastern South Dakota conflicts with this correlation, where an organic lacustrine sequence known as the "Gastropod silt" occurs beneath a red, Superior-provenance till known as the Hawk Creek Formation (Gilbertson, 1990; Pirkl and others, 1998; Johnson and others, 2016). This same sequence of red till above organic lacustrine sediment is present in core LQP-4 (Fig. 6) and has been found in outcrop in northwestern Lac qui Parle County (Fig. 8) and central Chippewa County (Pirkl and others, 1998). An amino-acid age of 140,000 ± 70,000 years before present (YBP) was determined from gastropods within the lacustrine sequence (Gilbertson, 1990). The results of this study placed the Hawk Creek Formation ice advance between Good Thunder formation members 1 and 2 (Fig. 2), meaning the Hawk Creek Formation and Good Thunder formation member 1 were deposited sometime after 140,000 years ago. These conflicting age constraints complicate the correlation of the Good Thunder formation tills to the Lake Henry Formation. In addition, the uppermost member of the Good Thunder formation (unit Qg1) likely correlates to the Sheldon Creek Formation in Iowa, deposited during the earliest advance of the Des Moines lobe during the middle Wisconsinan glaciation (see Plate 3). Additional age constraint is difficult to attain considering these units approach or are older than the limit for radiocarbon dating (about 50,000 years). Other dating methods with a greater age limit such as optically-stimulated luminescence (OSL) may show a clearer correlation in future projects.

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 all five rotary-sonic cores collected in 2019 and 2020 as part of a broader program of analyses (Thorleifson and others, 2019). 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 in Lac qui Parle County indicated that several elements appear to correlate with provenances that are characterized by shale, carbonate, Lake Superior-derived, and crystalline sediments (Table 2). Elements appearing to correlate with shale (such as Riding Mountain-provenance units Qht and Qdt) include barium, manganese, rhenium, vanadium, thallium, antimony, and zinc. Calcium appears to correlate with carbonate-rich tills, such as Winnipeg-provenance units Qg2 and *Qg4*. Elements appearing to correlate with both Riding Mountain- and Winnipeg-provenance tills such as units Qvt and Qg3 include arsenic, bismuth, cadmium, cesium, lithium, magnesium, and molybdenum. Elements appearing to correlate with Lake Superior-derived sediment, such as the Superior-provenance red-colored, upper portion of the Hawk Creek Formation (unit *Qhc*), include cobalt, copper, iron, titanium, and yttrium. Elements appearing to correlate with both Lake Superior-derived and crystalline-derived debris, such as the Rainy-provenance-appearing lower portion of the Hawk Creek Formation (unit *Qhc*), include hafnium, potassium, sodium, and zirconium. Other elements may correlate with provenance, oxidation, or hydrologic controls. Future analysis on these units, and units elsewhere in Minnesota, will allow for comparisons over larger spatial distances. Staley (2019) and Gowan (2020) provided geochemical results for some of the same units in other southwest Minnesota counties, for comparison.

ACKNOWLEDGEMENTS

Rotary-sonic drilling was conducted by Traut Drilling Company. Minnesota Geological Survey staff members Kevin Murphy and Emily Bauer provided essential support during rotary-sonic drilling. Thanks are extended to all landowners who allowed drilling on their property. Special thanks to David Craigmile for last-minute coordination of a drilling location.

DESCRIPTION OF CROSS-SECTION UNITS

Each unit on the cross sections is placed in one of two categories, as indicated in parentheses after the description: 1. *Surficial Geology* unit—a unit having an identical description, label, and color as on Plate 3, *Surficial Geology* (see Plate 3 for detailed descriptions); 2. Subsurface unit—a unit that is depicted only in the subsurface that has a unique label and color (the subsurface sand and gravel units have the same color to emphasize their status as potential aquifers).

HOLOCENE

Ql — **Organic clayey silt to sand** (*Surficial Geology* unit)—*Lacustrine sediment*.

Qa — **Silty clay loam to loamy fine- to medium-grained sand** (*Surficial Geology* unit)—*Alluvium*.

Qab — **Loamy fine-grained sand, sandy gravel, to gravelly sand** (*Surficial Geology* unit)—*Alluvium overtop bedrock*.

Qts — **Silty clay loam to loamy fine- to medium-grained sand and gravel** (*Surficial Geology* unit)—*Terrace sediment*.

PLEISTOCENE

Late Wisconsinan

Qlw — **Silty clay loam to silt loam** (*Surficial Geology* unit)—*Fine-grained lacustrine sediment*.

Glacial Lake Benson sediments

Qbs — **Sand and gravel, sand, loamy sand, to sandy loam** (*Surficial Geology* unit)—*Sandy lacustrine sediment*.

Qbc — **Silt loam, silty clay loam, silty clay, to clay** (*Surficial Geology* unit)—*Fine-grained lacustrine sediment*.

Qbt — **Silty clay loam, silt loam, to loam** (*Surficial Geology* unit)—*Till/lacustrine sediment mix*.

New Ulm Formation—Sediment deposited by ice of the Riding Mountain provenance Des Moines lobe during the late Wisconsinan glaciation (Fig. 2; Plate 3, Fig. 2). Units Qni and Qno are not attributed to specific members and are therefore undifferentiated.

Qni — **Silt loam, loam, sandy loam, loamy sand, gravelly sand, and sandy gravel** (*Surficial Geology* unit)—*Ice-contact sediment*.

Qno — **Fine-grained sand to sandy gravel** (*Surficial Geology* unit)—*Outwash*.

Heiberg Member

Qht — **Loam to clay loam diamicton** (*Surficial Geology* unit)—*Till*.

Dovray Member

Qdo — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with the Dovray Member. *Outwash*.

Qdt — **Clay loam to loam** (*Surficial Geology* unit)—*Till*.

Ivanhoe Member

Qio — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with the Ivanhoe Member. *Outwash*.

Qit — **Clay loam to loam** (*Surficial Geology* unit)—*Till*.

Middle Wisconsinan

New Ulm Formation—Sediment of mixed Winnipeg and Riding Mountain provenance deposited during the middle Wisconsinan glaciation by an ice advance along a similar trajectory as the late Wisconsinan Des Moines lobe (Fig. 2; Plate 3, Fig. 2).

Verdi Member

Qvo — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with the Verdi Member. *Outwash*.

Qvt — **Loam to clay loam** (*Surficial Geology* unit)—*Till*.

Good Thunder formation (Knaeble, 2013)—Sediment deposited by ice of mixed Winnipeg and Riding Mountain provenance. The uppermost member is interpreted to have been deposited during the middle Wisconsinan glaciation by an ice advance along a similar trajectory as the late Wisconsinan Des Moines lobe (Fig. 2; Plate 3, Fig. 2).

Good Thunder formation member 1

Qo1 — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with Good Thunder formation member 1. *Outwash*.

Qg1 — **Loam to clay loam** (*Surficial Geology* unit)—*Till*.

Pre-Wisconsinan

Hawk Creek Formation—Sediment of Superior provenance (Plate 3, Fig. 2). Formally defined by Match (1972), the Hawk Creek Formation consists of red to gray till and outwash containing abundant clasts of basalt, red sandstone, and rhyolite indicative of Superior provenance. The upper portion of the Hawk Creek Formation till is commonly a red sandy loam and the lower portion is a gray loam with streaks of red (Fig. 8). The 1-2 millimeter very coarse-grained sand fraction of the till indicates that this color change corresponds to a change in its lithologic composition whereby it decreases in red, Superior-provenance grains and increases in carbonate, resembling Rainy-provenance deposits (Table 1; LQP-4, Fig. 6). This change in composition and color is interpreted to be the result of erosion and incorporation of underlying carbonate-rich tills as ice that deposited the Hawk Creek Formation till advanced across central Minnesota. Included in this formation is the underlying organic-rich lacustrine sediment known as the "Gastropod silt" that yielded an amino acid age date of 140,000 ± 70,000 YBP (Fig. 8; Pirkl and others, 1998).

Qho — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with the Hawk Creek Formation. *Outwash*.

Qhc — **Sandy loam to loam** (subsurface unit)—Massive and unsorted, calcareous, yellowish-red (5YR 4/6) where oxidized, very dark gray where unoxidized (7.5YR 3/1 to 2.5Y 3/1), sandy loam to loam diamicton interpreted to be glacial till. Contains scattered pebbles and cobbles and may be overlain by a boulder lag. Average lithologic compositions of the very coarse-grained sand fraction for both the upper red and lower gray portions of the unit are shown in Table 1. Encountered in outcrop in northwestern Lac qui Parle County (Fig. 8), in rotary-sonic core LQP-4 (Fig. 6), and various cutting sets throughout the county. *Till*.

Qig — **Silt loam to sandy loam** (subsurface unit)—Massive to thinly bedded, calcareous, dark gray (5Y 4/1) to black (5Y 2.5/1) where unoxidized, fining-upward sequence of silt loam to sandy loam interpreted to be lacustrine sediment. Contains abundant organic material including gastropod shells, beetles, wood, and other plant debris. Pollen and beetle assemblages indicate the climate was subarctic and wet, and the sediment was deposited adjacent to a wooded area, possibly in a proglacial lake (Pirkl and others, 1998). Encountered in outcrop in northwestern Lac qui Parle County (Fig. 8), and in rotary-sonic core LQP-4 (Fig. 6). *Lacustrine sediment*.

Good Thunder formation (Knaeble, 2013)—Sediment deposited by ice of mixed Winnipeg and Riding Mountain provenance. An informal formation first defined in Renville County (Knaeble, 2013), it consists of five total members, all of which occur in Lac qui Parle County.

Good Thunder formation member 2

Qo2 — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with Good Thunder formation member 2. *Outwash*.

Qg2 — **Loam** (*Surficial Geology* unit).

St. Francis Formation—Sediment of Superior provenance (Plate 3, Fig. 2). Prevalent in central Minnesota, the St. Francis Formation was identified in few locations in Lac qui Parle County from well logs indicating sandy, brown/red deposits beneath Good Thunder formation member 2 sediment.

Qso — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with the St. Francis Formation. *Outwash*.

Qsf — **Sandy loam to loam** (subsurface unit)—Massive and unsorted, red to brown sandy loam to loam diamicton interpreted to be glacial till. Likely contains scattered pebbles and cobbles. Not encountered physically but described in well logs and interpreted to be Superior provenance. *Till*.

Good Thunder formation member 3

Qo3 — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with Good Thunder formation member 3. *Outwash*.

Qg3 — **Loam to silt loam** (*Surficial Geology* unit).

Good Thunder formation member 4

Qo4 — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with Good Thunder formation member 4. *Outwash*.

Qg4 — **Loam to silt loam** (subsurface unit)—Massive and unsorted, calcareous, olive-brown (2.5Y 4/4) where oxidized, very dark gray (2.5Y 3/1) where unoxidized, loam to silt loam diamicton interpreted to be glacial till. Contains scattered pebbles and cobbles. Average lithologic composition of the very coarse-grained sand fraction is shown in Table 1. The lithologic composition of this member is similar to unit Qg3, but contains little to no Cretaceous shale and slightly less carbonate. Encountered overtop bedrock in four of the five new rotary-sonic cores (LQP-1, 2, 3, and 4). *Till*.

Unnamed formation of Rainy provenance—Undifferentiated sediment of Rainy provenance. May correlate to a W-sequence unit of central, north-central, and east-central Minnesota (Meyer, 1997). Encountered in archived rotary-sonic core UMRB-1 (Patterson and others, 1999).

Qro — **Fine-grained sand to sandy gravel** (subsurface unit)—Fine-grained sand to sandy gravel deposited by meltwater associated with unnamed Rainy-provenance sediment. Discontinuous, and likely contains meltwater deposits associated with the overlying Good Thunder formation member 4. *Outwash*.

Qrt — **Loam to sandy loam diamicton** (subsurface unit)—Unsorted, brown to gray, loam to sandy loam diamicton of Rainy provenance interpreted to be glacial till. Encountered in cutting sets in southwestern Lac qui Parle County. *Till*.

Good Thunder formation member 5

Qo5 — **Fine-grained sand to sandy gravel** (subsurface unit)—Discontinuous, fine-grained sand to sandy gravel deposited by meltwater associated with Good Thunder formation member 5. *Outwash*.

Qg5 — **Loam to silt loam** (subsurface unit)—Massive and unsorted, loam to silt loam diamicton interpreted to be glacial till. Encountered in cutting sets in southwestern Lac qui Parle County. *Till*.

Undifferentiated deposits

Qlu — **Silt loam to silty clay loam** (subsurface unit)—Massive to thinly bedded, calcareous, dark gray where unoxidized, fining-upward sequence of silt loam to silty clay loam interpreted to be lacustrine sediment. Encountered in rotary-sonic core LQP-1 (Fig. 3).

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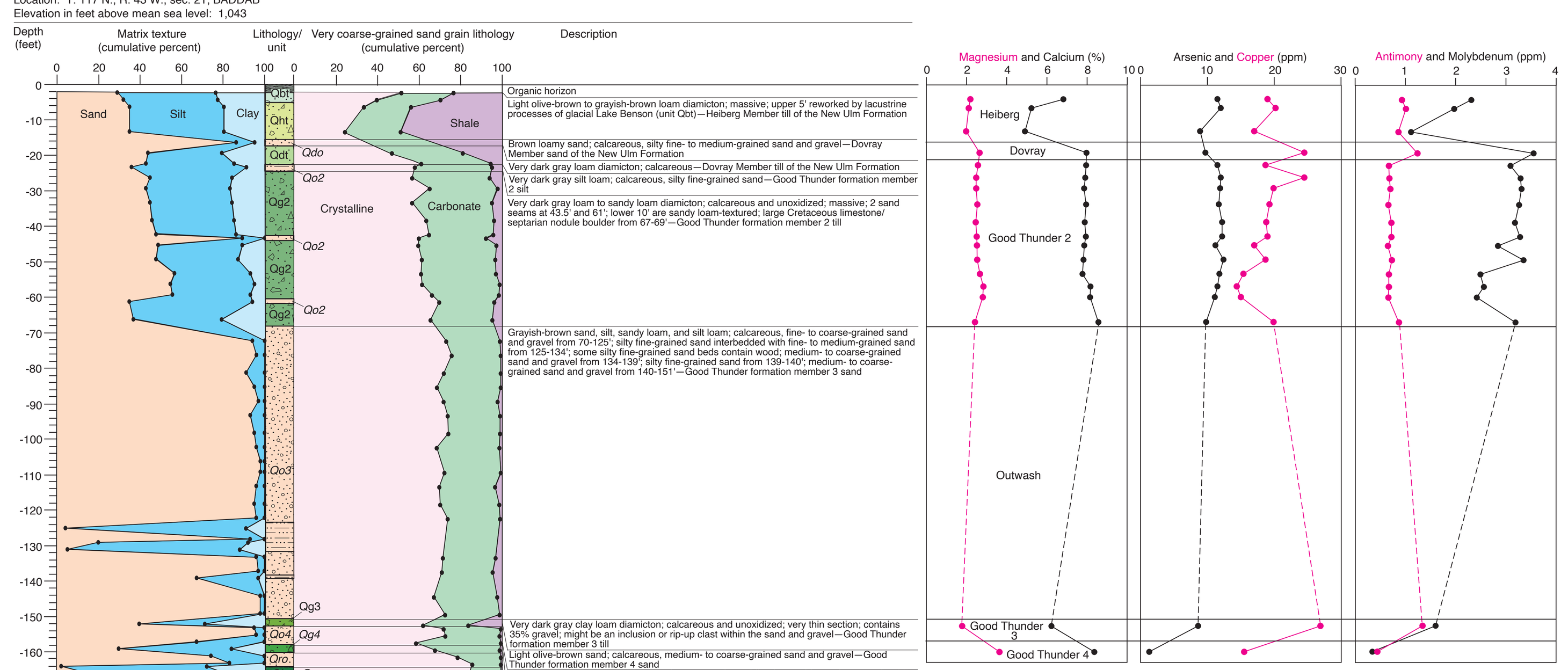

Figure 3. Descriptive log of rotary-sonic core LQP-1 drilled by Traut Companies for the Minnesota Department of Natural Resources and collected by the Minnesota Geological Survey for this study. Drill-site location is shown on Figure 1 and Plate 1, *Database Map*. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. Downhole concentrations of selected elements of the less than 63-micron fraction of till samples are depicted in percent (%) of the total sample, or in parts per million (ppm).

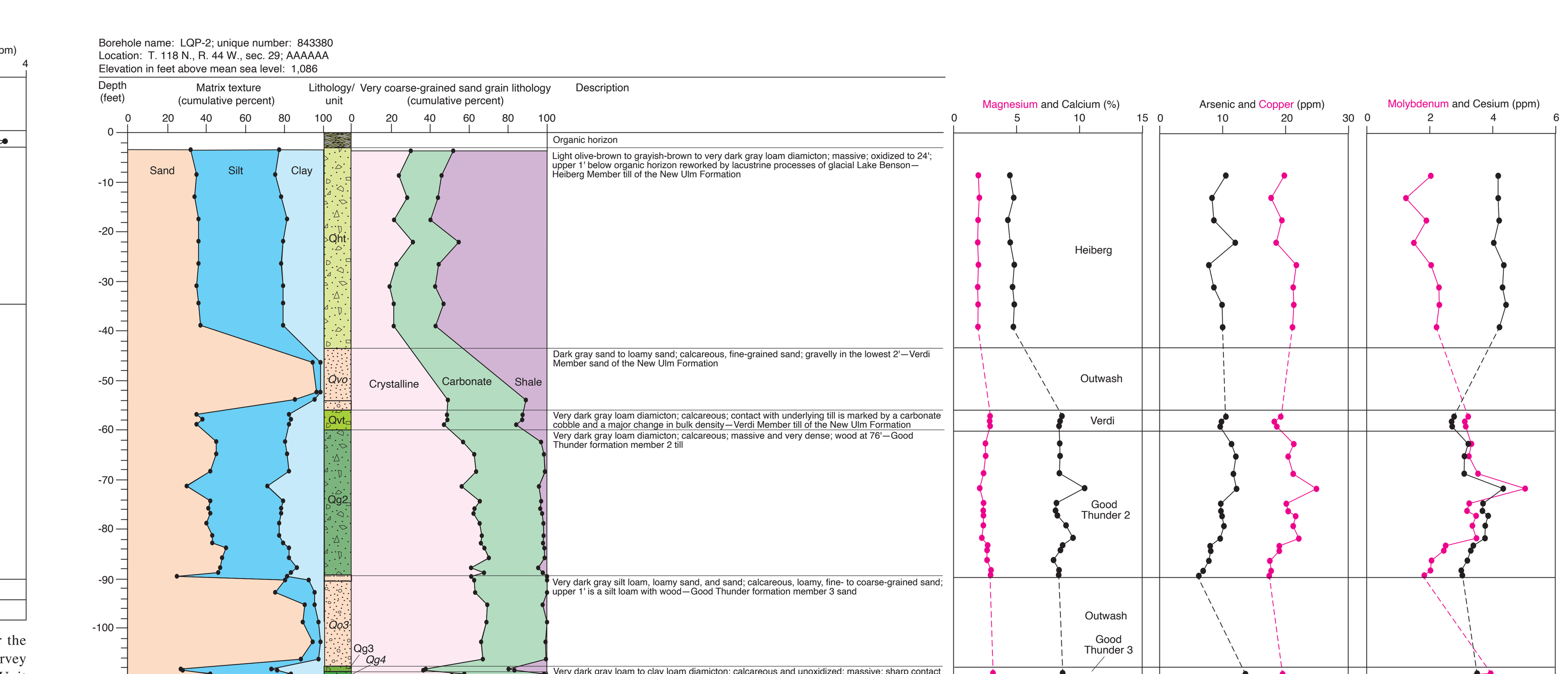

Figure 4. Descriptive log of rotary-sonic core LQP-2 drilled by Traut Companies for the Minnesota Department of Natural Resources and collected by the Minnesota Geological Survey for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. Downhole concentrations of selected elements of the less than 63-micron fraction of till samples are depicted in percent (%) of the total sample, or in parts per million (ppm).

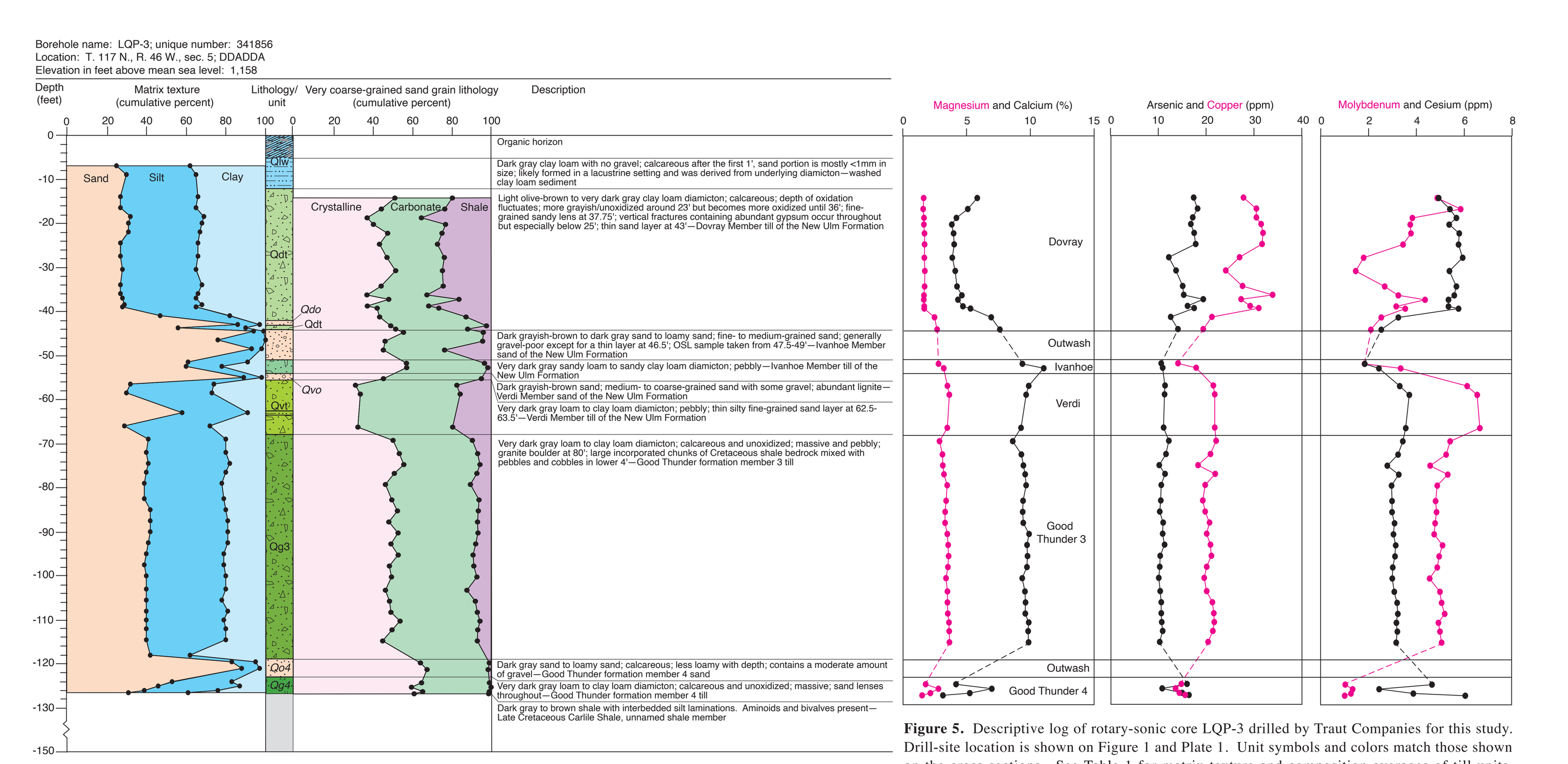

Figure 5. Descriptive log of rotary-sonic core LQP-3 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. Downhole concentrations of selected elements of the less than 63-micron fraction of till samples are depicted in percent (%) of the total sample, or in parts per million (ppm).

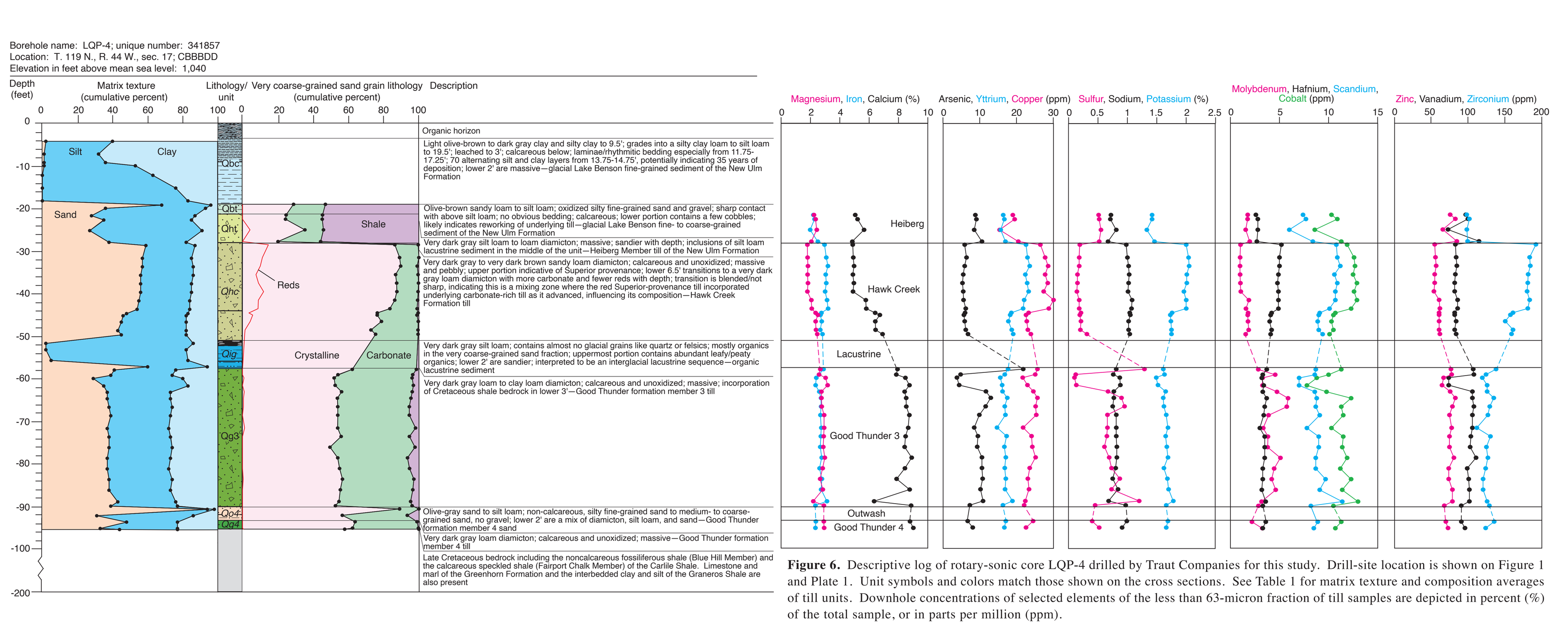

Figure 6. Descriptive log of rotary-sonic core LQP-4 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units. Downhole concentrations of selected elements of the less than 63-micron fraction of till samples are depicted in percent (%) of the total sample, or in parts per million (ppm).

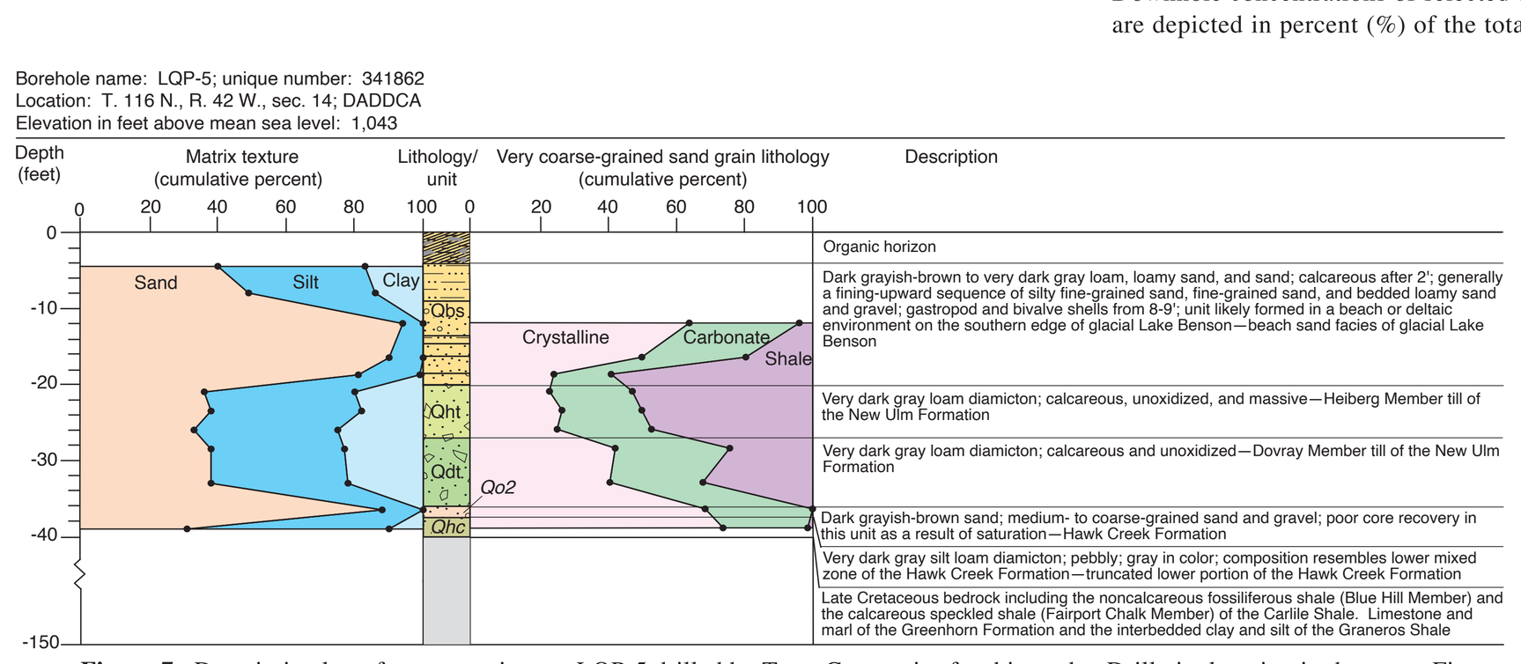

Figure 7. Descriptive log of rotary-sonic core LQP-5 drilled by Traut Companies for this study. Drill-site location is shown on Figure 1 and Plate 1. Unit symbols and colors match those shown on the cross sections. See Table 1 for matrix texture and composition averages of till units.

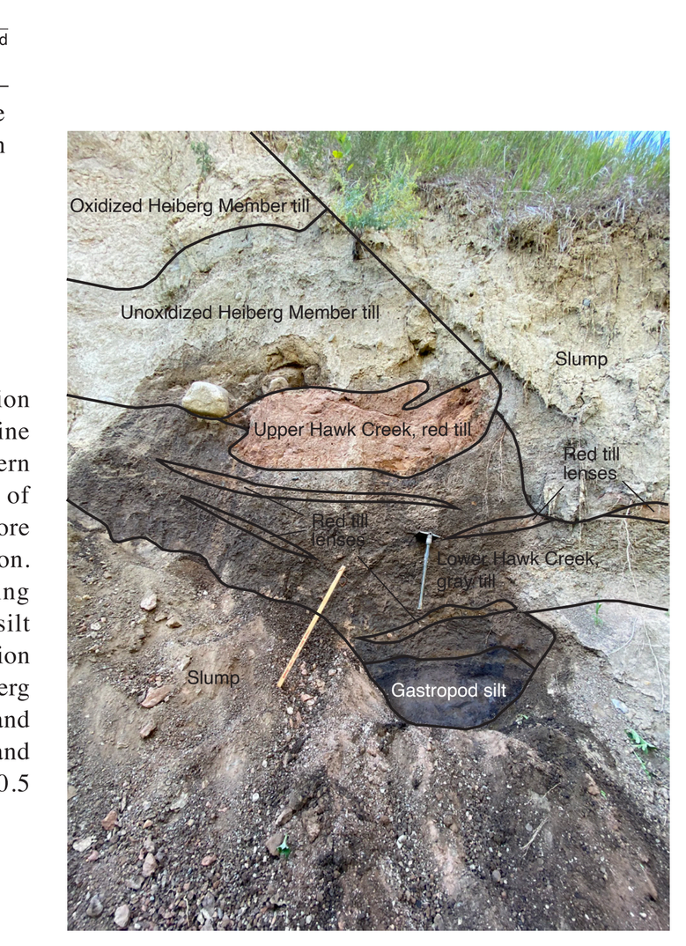

Figure 8. An exposure of the Hawk Creek Formation till (unit Qhc) and underlying Gastropod silt lacustrine sediment (unit Qig) at the "Nordick site" in northwestern Lac qui Parle County (Fig. 1). The upper portion of the Hawk Creek Formation till is red and contains more Superior-provenance clasts than the lower, gray portion. Note the red streaks in the lower, gray till indicating this is a mixed zone. The organic-rich Gastropod silt lacustrine sediment underlies the Hawk Creek Formation till in this location. The oxidized and unoxidized Heiberg Member till overlies the Hawk Creek Formation till, and the contact is marked by a concentration of boulders and cobbles. Entrenchment tool is 21.5 inches (about 0.5 meter) long for scale.

Table 1. Average values for the matrix texture and composition of select tills recognized in Lac qui Parle 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 using the classification system of Hobbs (1998). The Precambrian crystalline 1-2 millimeter fraction is further differentiated by crystalline rock type: light (felsic rock types including granite, gneiss, and other light-colored metamorphic rock types), dark (mafic rock types including basalt, gabbro, diabase, and also dark-colored metamorphic rock types), and red (iron formation, rhyolite, agate, and sandstone).

	MATRIX TEXTURE						CLAST TYPE									
			Percentage of the less than 2-millimeter fraction				Percentage of total grains counted of the 1-2 millimeter fraction						Percentage of total crystalline grains counted			
Geologic unit	Total number of samples	Gravel (percentage of total sample weight)	Sand	Silt	Clay	Average USDA texture	Crystalline	Carbonate	Shale	Precambrian	Paleozoic	Cretaceous	Light	Dark	Red	Clear quartz
Late Wisconsinan tills																
Heiberg Member (unit Qht)	211	4	34	45	21	Loam	29	22	49	29	20	51	85	14	1	18
Dovray Member (unit Qdt)	60	4	33	41	26	Loam	43	31	26	43	27	30	85	15	T	17
Ivanhoe Member (unit Qit)	13	5	32	39	29	Clay loam	59	31	10	58	27	15	84	15	1	20
Middle Wisconsinan tills																
Verdi Member (unit Qvt)	26	5	37	43	20	Loam	44	41	15	44	37	19	86	14	T	14
Good Thunder formation 1 (unit Qg1)	18	5	34	44	22	Loam	42	50	8	42	46	12	89	11	T	16
Pre-Wisconsinan tills																
Hawk Creek Formation, upper (unit *Qhc*)	12	4	58	29	13	Sandy loam	88	12	0	88	11	1	63	26	11	25
Hawk Creek Formation, lower (unit *Qhc*)	14	8	44	40	16	Loam	76	23	1	76	20	4	82	16	2	20
Good Thunder formation 2 (unit Qg2)	35	7	43	39	18	Loam	63	34	3	63	30	7	85	14	1	14
Good Thunder formation 3 (unit Qg3)	42	5	37	40	23	Loam	51	42	7	51	37	12	85	15	T	14
Good Thunder formation 4 (unit *Qg4*)	9	4	42	39	19	Loam	61	38	1	61	34	5	85	15	T	13

T = trace amount

Table 2. Average concentrations of elements from till samples. Provenance sources for the till and elements that are diagnostic for the provenance are highlighted. Bold text and italic text show highest and lowest average values for each element, respectively. If there is no apparent difference in the concentrations, no distinctions are made. Samples were processed by ALS Geochemistry in Nevada.

Till unit	Ag ppm	Al %	As ppm	Ba ppm	Be ppm	Bi ppm	Ca %	Cd ppm	Ce ppm	Co ppm	Cr ppm	Cs ppm	Cu ppm	Fe %	Ga ppm	Ge ppm	Hf ppm	In ppm	K %	La ppm	Li ppm	Mg %	Mn ppm	Mo ppm
Heiberg (unit Qht) n=18	0.13	5.07	9.67	**625**	1.29	0.21	5.06	0.35	56.6	9.76	54	3.78	20.0	2.45	12.62	**0.17**	*2.9*	0.043	1.47	28.6	30.3	2.10	637	1.99
Dovray (unit Qdt) n=18	**0.16**	**6.08**	**14.96**	559	**1.55**	**0.27**	*5.04*	**1.10**	67.1	9.70	**67**	**4.97**	27.6	**3.13**	**14.42**	0.15	3.2	**0.053**	1.69	33.2	**42.6**	1.90	**691**	3.23
Verdi (unit Qvt) n=7	0.11	*4.57*	10.38	449	*1.16*	0.21	8.39	0.46	*56.4*	9.0	*50*	3.23	20.0	*2.26*	*11.56*	0.14	3.1	0.039	1.43	*28.3*	34.8	3.02	605	4.25
Upper Hawk Creek (unit *Qhc*) n=8	0.08	5.74	*5.79*	498	1.44	*0.16*	5.14	*0.20*	71.4	**12.6**	54	2.68	**28.2**	3.09	14.08	0.16	**5.0**	0.042	**2.01**	33.6	29.6	*1.87*	560	*1.19*
Lower Hawk Creek (unit *Qhc*) n=6	0.09	5.29	6.27	488	1.22	0.17	6.79	0.30	63.2	9.8	52	*2.56*	21.5	2.61	12.06	0.14	4.0	*0.034*	1.68	30.9	*26.2*	2.54	572	1.76
Good Thunder 2 (unit Qg2) n=26	0.11	4.62	10.49	426	1.21	0.20	8.31	0.47	65.3	*8.25*	52	3.17	19.4	2.32	11.94	0.14	3.5	0.040	1.43	32.5	32.2	2.54	*502*	3.04
Good Thunder 3 (unit Qg3) n=38	0.11	5.00	10.40	*424*	1.27	0.22	**8.91**	0.52	60.8	10.36	52	3.34	22.2	2.47	12.23	*0.13*	3.2	0.040	1.51	30.0	36.4	**3.09**	641	**4.46**
Good Thunder 4 (unit *Qg4*) n=8	0.08	5.60	9.70	440	1.46	0.20	6.92	0.27	**73.8**	9.4	54	3.57	*17.4*	2.76	14.04	0.15	4.0	0.049	1.58	**36.2**	39.3	2.65	562	1.47

Till unit	Na %	Nb ppm	Ni ppm	P ppm	Pb ppm	Rb ppm	Re ppm	S %	Sb ppm	Sc ppm	Se ppm	Sn ppm	Sr ppm	Ta ppm	Te ppm	Th ppm	Ti %	Tl ppm	U ppm	V ppm	W ppm	Y ppm	Zn ppm	Zr ppm
Heiberg (unit Qht) n=18	0.66	*10.4*	27.4	616	14.1	67.0	0.009	0.32	0.95	8.6	2	1.3	*184.5*	0.67	0.06	7.89	0.283	0.52	2.9	117	1.0	17.4	83	*108.1*
Dovray (unit Qdt) n=18	0.93	13.3	**34.5**	**931**	**17.5**	**81.8**	0.012	0.52	**1.87**	9.7	**3**	1.6	229.1	0.83	**0.08**	8.94	0.330	0.68	3.8	**152**	**1.1**	21.1	**96**	116.4
Verdi (unit Qvt) n=7	*0.6*	10.6	28.0	*584*	*13.2*	63.2	0.013	0.74	0.84	*7.5*	2	1.24	188.9	*0.66*	0.06	*7.81*	*0.267*	0.65	3.6	88	0.9	*16.0*	67.4	114.6
Upper Hawk Creek (unit *Qhc*) n=8	1.0	11.5	30.3	664	14.1	74.0	*0.003*	*0.17*	0.63	**10.7**	1	1.40	194.9	0.75	0.05	9.07	**0.401**	*0.47*	*2.6*	84	0.8	**22.7**	*56.9*	**183.4**
Lower Hawk Creek (unit *Qhc*) n=6	1.0	10.6	26.7	695	14.1	63.2	0.004	0.26	0.69	8.6	2	*1.22*	222.7	0.68	0.05	8.71	0.319	0.51	2.7	*79*	0.8	18.2	58.8	153.4
Good Thunder 2 (unit Qg2) n=26	0.75	12.1	26.0	700	13.5	64.5	0.013	0.62	0.82	7.7	2	1.3	**229.5**	0.75	0.06	8.70	0.274	0.63	3.4	92	0.9	18.5	59	132.6
Good Thunder 3 (unit Qg3) n=38	0.67	11.1	31.6	618	14.9	67.0	**0.014**	**0.75**	0.92	8.2	2	1.3	213.4	0.69	0.06	8.66	0.278	0.68	**3.9**	94	0.9	16.8	70	119.8
Good Thunder 4 (unit *Qg4*) n=8	0.8	**16.6**	*24.1*	626	15.4	73.7	0.005	0.50	*0.62*	9.3	1	**1.54**	212.4	**1.03**	0.06	**9.75**	0.319	0.50	2.7	92	0.9	18.3	60.5	150.9

PROVENANCE: Riding Mountain, Rainy, Winnipeg, Superior

GIS compilation by R.S. Lively
Edited by Lori Robinson