UNIVERSITY OF MINNESOTA

Minnesota Geological Survey

Harvey Thorleifson, Director

CORE DESCRIPTIONS, BOREHOLE GEOPHYSICS, AND UNIT INTERPRETATIONS IN SUPPORT OF PHASE I AND II USGS HYDROLOGIC PROPERTIES OF TILL INVESTIGATION

Amie E. Staley, Kaleb Wagner, Maurice Nguyen, and Robert Tipping

Minnesota Geological Survey, 2609 Territorial Road, St. Paul MN, 55114, USA.

Minnesota Geological Survey Open File Report 18-03 **July 2018**

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

Funded through the Environment and Natural Resources Trust Fund as recommended by the Legislative and Citizens Commission on Minnesota Resources (LCCMR).

Contents

Executive Summary

This report summarizes the contributions of the Minnesota Geological Survey to a three-year study conducted in two phases – Environment and Natural Resources Trust Fund (ENRTF), M.L. 2014, Chp. 226, Sec. 2, Subd. 03h, and ENTRF, M.L. 2016, Chp. 186, Sec. 2, Subd. 04h, led by the United States Geological Survey (USGS) Minnesota Water Science Center, which seeks to further knowledge on the sources and rates of recharge to confined aquifers. Such knowledge enables policy makers and planners to support water resource management by further clarifying the hydrologic properties of tills that govern both recharge to and protection of the underlying confined glacial aquifers that provide drinking water for many Minnesotans. Geologic cores from sites in Litchfield (LF01, LF02), Cromwell (CW02), and Olivia (MN OB-7), Minnesota, and the University of Minnesota Hydrogeology field site (HB1-15, HT-200) (UM field site) near Akeley, Minnesota, were described both in the field and in the laboratory, and characterized using conventional sediment processing and analysis techniques. All cores are archived at the Minnesota Department of Natural Resources core repository in Hibbing, Minnesota, with the exception of core HT-200, which was described and disposed of in the field. Borehole geophysical logs were collected for all drill holes of adequate diameter, including gamma, electromagnetic induction, and spontaneous potential and resistivity logs.

Manual logging and analysis of core materials from all sites revealed readily interpretable successions of unconsolidated Quaternary deposits. Core CW02 is capped by a thin veneer of fine-grained loam to silt loam textured diamicton interpreted as the Alborn Member till of the Aitkin Formation. This overlies Cromwell Formation sand and gravel and a thicker subjacent package of sandy loam textured diamicton interpreted as till of the Cromwell Formation. These deposits are attributed to the Superior lobe of the Laurentide Ice Sheet during the Late Wisconsinan glacial episode. Thin glaciolacustrine and deltaic deposits overlie alternating sandy loam to loam textured diamicton interpreted as the Villard Member till of the New Ulm Formation in core LF01. A similar till sequence is apparent in LF02, though here diamict facies are intercalated with thin beds of sorted sediment. Both LF01 and LF02 finish in the coarser-grained, low-shale Moland Member of the New Ulm Formation. Sediments in the Litchfield cores were emplaced by the Des Moines lobe of the Laurentide Ice Sheet during the Late Wisconsinan glacial episode.

Examination of core MN OB-7 acquired near Olivia revealed a thick sequence of pre-Illinoian aged diamicton interpreted as till, confining a sand and gravel aquifer interpreted as glacial outwash, capped by a thin cover of Holocene alluvial sand and gravel. Textural and lithological properties of the thick till sequence, consisting largely of loam to clay loam textured diamicton enriched in Paleozoic carbonate, are indicative of a Winnipeg-source area, and warrant assignment to the informal Good Thunder formation. At the UM field site, core materials recovered from HB1-15 and HT-200 include thick (> 200 ft / 61 m) deposits of Hewitt Formation till and outwash. The Hewitt Formation largely represents the advance of the Wadena lobe from the north-northeast (Rainy provenance) around the onset of the Late Wisconsinan glacial episode, and its eventual demise. The aquifer of interest at the site, represented by a 23 ft (7 m) package of fine-grained sand and gravel, lies beneath the Hewitt Formation and is perched atop a thick sequence of pre-Wisconsinan age deposits of various provenances.

List of Figures

(mafic-rich igneous and metamorphic), and red (reddish basalt, rhyolite, arkose, iron formation, and agate) grain types.

Figure 7. Qualitative identification of depth intervals where conductivity and gamma trends deviate from each other, Cromwell observation well cluster 1. Rock-water conductivity measurements typically track gamma logs, with increasing conductivity associated with increased clay or silt content. Deviations from these trends may indicate changes in fluid conductivity due to changes in water chemistry. Both logs from EM-Induction sonde.

Figure 8. Qualitative identification of depth intervals where conductivity and gamma trends deviate from each other, Litchfield observation wells LF01-F and LF02-F. Rock-water conductivity measurements typically track gamma logs, with increasing conductivity associated with increased clay or silt content. Deviations from these trends may indicate changes in fluid conductivity due to changes in water chemistry. Both logs from EM-Induction sonde.

List of Tables

List of Appendices

Introduction

Confined aquifers set within glacigenic valley-fill sequences are an important source of drinking water for residents in many areas of Minnesota. Generally, these sequences are comprised of packages of low-permeability tills and fine-grained glaciolacustrine sediments (i.e., aquitards) which overlie and/or encompass high permeability glaciofluvial sands and gravels (i.e., aquifers). Aquitards in these systems act as crucial elements by protecting underlying confined aquifers from land-surface contamination, but rates and sources of recharge to these aquifers remain poorly understood. Estimations of aquifer connectivity within buried-valley sequences in Minnesota are confounded by significant variability in the hydraulic properties of glacial sediments across the state, much of which is attributable to the differing substrates and dynamics of the various ice lobes that deposited them. The ability to accurately characterize these properties has considerable implications for groundwater modeling, which is commonly used to inform policy and planning decisions.

This report summarizes the contributions of the Minnesota Geological Survey (MGS) to a three-year study conducted in two phases – Environmental and Natural Resources Trust Fund (ENRTF), M.L. 2014, Chp. 226, Sec. 2, Subd. 03h, and ENTRF, M.L. 2016, Chp. 186, Sec. 2, Subd. 04h, led by the United States Geological Survey (USGS) Minnesota Water Science Center, which seeks to further knowledge on the sources and rates of recharge to confined aquifers set within buried-valley sequences in Minnesota. Six cores (including one collected for a previous study) of unconsolidated Quaternary deposits were extracted from known confined glacial aquifer settings, in four regions across Minnesota, in order to target variability in the material properties of the aquitards that confine them.

Methods

Core retrieval and handling

Unlithified Quaternary sediments were collected on-site in June, 2015 at Litchfield (cores LF01, LF02) and Cromwell, MN (core CW02) (Figure 1) by hollow-stem coring methods, and at the UM field site (core HT-200) and Olivia, MN (core MN OB-7) (Figure 1) in May and August, 2017 by rotary-sonic coring methods. An additional rotary-sonic core collected by the MGS in

December 2014 (core HB1-15) was also reviewed as part of this investigation (Figure 1). Because HB1-15 had been collected, examined and archived previously by MGS, adjacent HT-200 was described in the field only. LF01, LF02, and CW02 were obtained by workers within the USGS drilling contract group, whereas cores MN OB-7 and HT-200 were obtained by Traut Drilling Company under contract by the USGS. HB1-15 was obtained by Traut Drilling Company under contract by the MGS. Core samples from HT-200 were turned over to the UM Hydrogeology field camp for student exercises.

Continuous 2 inch (5 cm) diameter core was retrieved at the Litchfield and Cromwell sites by hollow-stem auger using a cutter head and split core barrel assembly with acetate liner. Filled liners were transported to MGS facilities for description and sampling. Each 5 ft (1.5 m) interval was scored along the outer edge of the casing with a circular saw, and the core materials split using a standard mason’s chisel and rubber mallet. Unsampled splits (halves) were shipped to the DNR Drill Core Library at Hibbing, MN for archiving. Continuous 4 inch (10.2 cm) diameter core retrieved at the Olivia and UM field sites (HB1-15 only) was extruded into plastic sleeves, boxed on-site, and transported to MGS facilities. Core materials were similarly split using a mason’s chisel and mallet, and repackaged after sampling and description for archiving at DNR Hibbing facilities. All core sediments were described systematically in terms of texture and sorting, structure, Munsell color, level of consolidation, carbonate content of matrix, and clast lithological assemblage. UM field site core HT-200 was described in the field on the basis of grain size, sorting, color, consolidation, and the presence of carbonate.

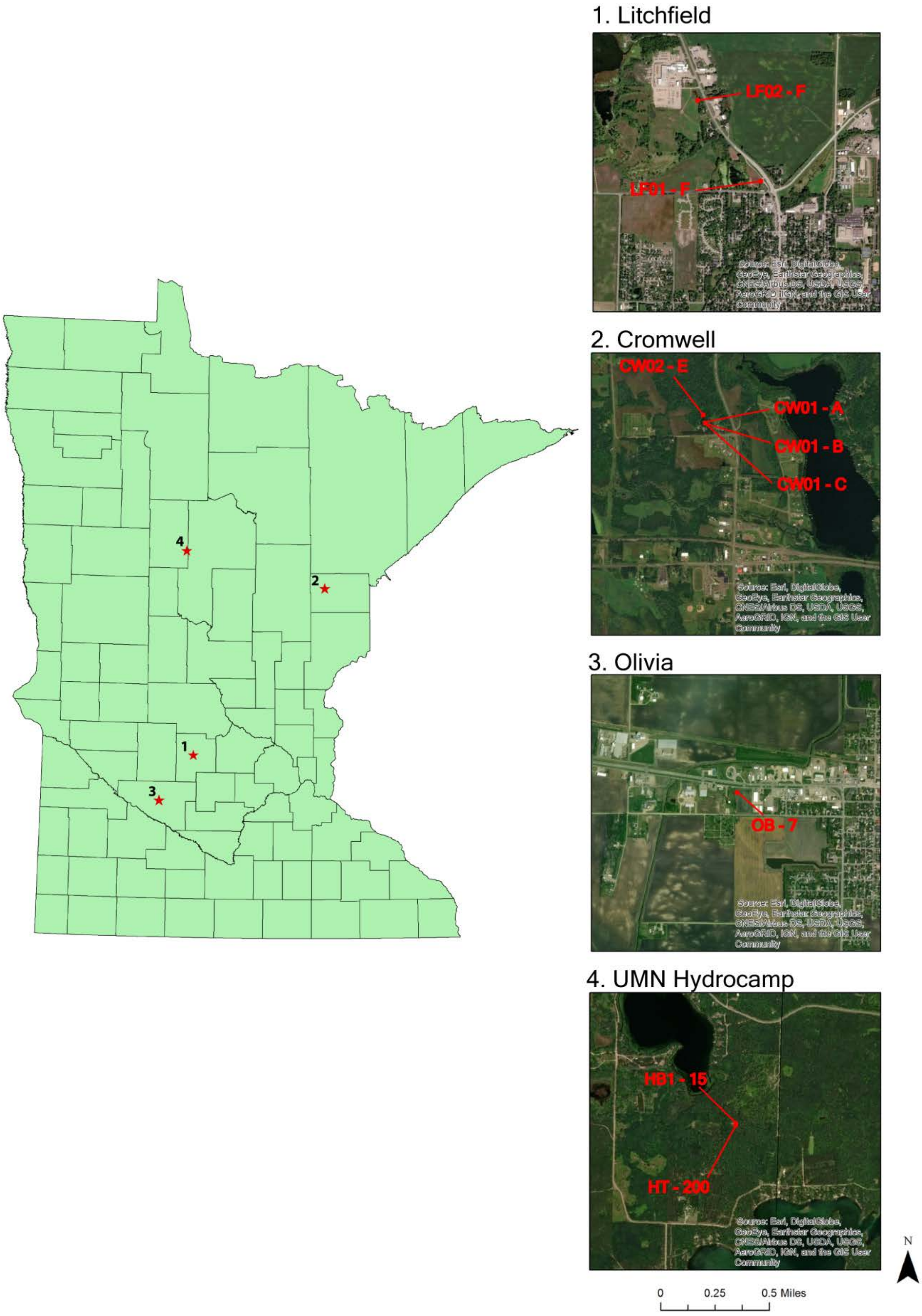


Figure 1. Locations of borehole sites drilled in support of this investigation.

Sample textural and lithological analyses

In total, 273 bulk sediment samples were collected for particle-size (texture) and lithological analysis from the five cores at approximate 3-4 ft (0.9-1.2 m) intervals, with higher sampling density near lithostratigraphic contacts. Particle-size analysis was carried out by laboratory staff at MGS facilities and was conducted in two stages, broadly following ASTM D 422 (Standard Test Method for Particle-Size Analysis of Soils) procedural standards, involving dry sieving of the $< 4.0\ \varphi$ (> 0.63 mm) fraction, and hydrometer analysis of the $> 4.0\ \varphi$ (< 0.63 mm) fraction.

The lithological composition of each sample was determined following the methods of Hobbs (1998). The 1-2 mm very coarse-grained sand fraction of each sample was split into approximately 1 gram (roughly 200 grain) sub-samples, then separated and counted by lithology using a binocular microscope. Textural and lithological variation of the samples was used to determine stratigraphic units encountered within each core. Formal and informal stratigraphic units were assigned based on textural and lithologic properties as defined in Johnson et al. (2016) and inferred from local MGS County Geologic Atlases (Knaeble and Hobbs, 2009b; Knaeble, 2013; Meyer, 2015b; Knaeble, 2018; Lusardi et al., 2018).

Borehole geophysics

Litchfield observation wells LF01-F and LF02-F were logged using EM-Induction and Gamma sondes on June 24, 2015. Litchfield LF02-F was re-logged using the EM-Induction sonde, with an adjustment to narrow the tool diameter, on August 19, 2015, in an attempt to reach the bottom of the hole. Cromwell observation wells CW01-A, CW01-B, and CW01-C were logged using EM-Induction and Gamma sondes on August 13, 2015. Logging was conducted in holes having 2 inch (5 cm) diameter plastic casing inserted into 6 inch (15 cm) diameter holes. Fluid in the holes was aquifer water.

Olivia observation well MN OB-7 and UM field site well HT-200 were logged by the MGS using a gamma sonde on August 1, 2017 and May 24, 2017, respectively. HB1-15 was logged by the MGS on December 16, 2014. For all boreholes, logging was conducted inside the drill rod to the depth drilled at the time of logging. As a result, gamma logs show regularly spaced reductions in gamma signal every 10 ft (3 m). These reductions are caused by a thickening of steel at each drill rod coupling. Logging sondes and software used are manufactured by Century Geophysical Corporation, Tulsa Oklahoma. The EM-Induction sonde, tool type code 9512A, serial number 2704, is owned by the USGS; the Gamma sonde, tool type code 9060A, serial number 202 is owned by the MGS. Logging rates are shown in Table 1.

Table 1. Logging rates for borehole geophysical logs.

Hole name	EM-Induction rate (ft/min)	Gamma rate (ft/min)
Litchfield LF01-F	5	10
Litchfield LF02-F	5	15
Cromwell CW01-A	16	22
Cromwell CW01-B	16	16
Cromwell CW01-C	15	15
Olivia MN OB-7	n/a	5
UM Field Site HT-200	n/a	5
UM Field Site HB1-15	n/a	20

Results

Core descriptions and sample analyses

Manual logging and analysis of core materials from all sites revealed readily interpretable successions of unconsolidated Quaternary deposits that were subsequently related to the Quaternary stratigraphic framework of Minnesota (Johnson et al., 2016) (Figure 2). A total of 7.5 ft (2.3 m) of sand and gravelly sand overlies 8.5 ft (2.6 m) of finer-grained sand and silt at surface in core LF01 (Figure 3A), all of which overlies 70 ft (21.3 m) of alternating sandy loam, to loam textured diamicton interpreted as till of the Villard Member of the New Ulm Formation (QNUL). Similarly, core LF02 (Figure 3B) is comprised of a thick (113.5 ft / 34.6 m) diamicton package interpreted as Villard Member till with variable textures, intercalated with thin (≤ 7.5 ft / 2.3 m) glaciofluvial sequences and occasional sand stringers, flow noses and lenses. Both LF01 and LF02 finish in < 10 ft (3 m) of the coarser-grained, low-shale Moland Member of the New Ulm Formation (QNUM). Core CW02 (Figure 3C) is capped by a thin (5.5 ft /1.7 m) veneer of fine-grained silt loam textured diamicton interpreted as till belonging to the Alborn Member of the Aitkin Formation (QAIA), overlying 20 ft (6 m) of sand and gravel consistent with Cromwell Formation outwash, and a subjacent 76.5 ft (23.3 m) package of sandy loam textured diamicton interpreted as Cromwell Formation till (QCMU).

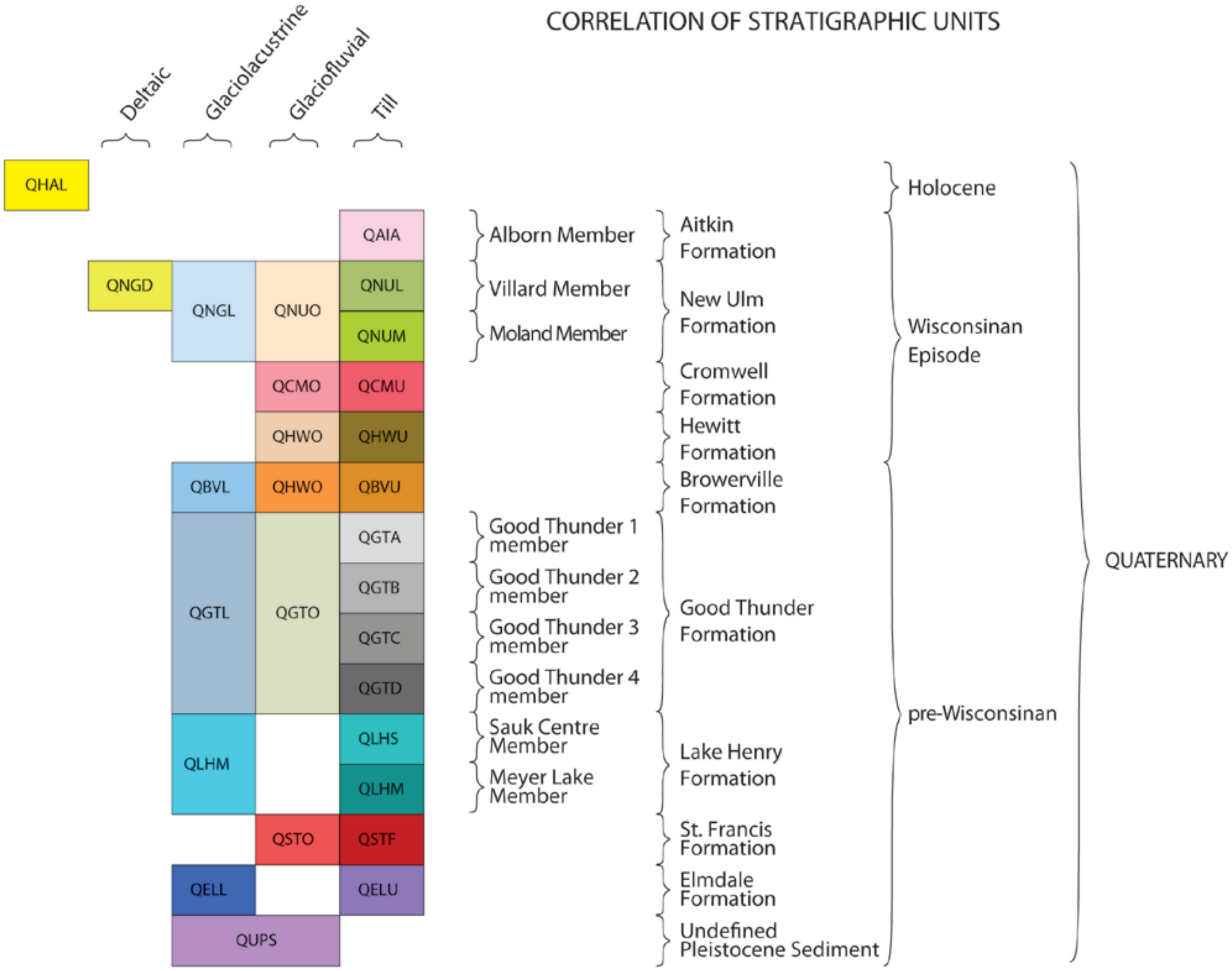


Figure 2. Correlation of stratigraphic units referred to in the text.

Approximately 0.5 ft (0.2 m) of black topsoil caps 4 ft (1.2 m) of fill materials, which overlies 3.5 ft (1.2 m) of organic-rich soil and 6.5 ft (2.2 m) of Holocene stream deposits in core MN OB-7 (Figure 3D). The lower soil is interpreted to represent either an older soil horizon developed during the Holocene prior to being covered by fill, or is part of the modern soil that was stuck in the core barrel during core extraction of the first 5 ft (1.5 m) of core. Below the Holocene section is an approximately 167 ft (60 m) thick, pre-Wisconsinan assemblage consisting largely of loam to silt- and clay-loam textured diamicton, all of which is interpreted as till of the informal Good Thunder formation (QGTA-D). This assemblage contains sparsely distributed inclusions (< 3 ft / 1 m thick) of sand and gravel, thin (<0.5 ft / 0.2 m) silt and clay stringers, and intervallic changes in density/consolidation that constitute unconformities between members. Below the till assemblage is a 49 ft (15 m) thick sand body interpreted as glacial outwash with an average USDA texture of sand (Figure 3D and Appendix A). This unit is utilized as an aquifer by the city of Olivia for part of their municipal water supply. Cretaceous shale bedrock underlies the aquifer at a depth of 229.5 ft (70 m).

Cores HB1-15 (Figure 3E) and HT-200 (Figure 3F) feature 105 ft (32m) of interbedded sand and gravel over 102 ft (31.1 m) of brown, sandy-loam textured diamicton, interpreted, respectively, as glacial outwash and till of the Hewitt Formation (QHWU). In the deeper HB1-15, a coupled paleosol and 9 ft (0.3 m) of fine-grained glaciolacustrine sand and gravel separate these overlying Late Wisconsinan materials from a 268 ft (82 m) sequence of pre-Wisconsinan deposits attributed (in order from top-bottom, youngest-oldest) to the Browerville, Lake Henry, St. Francis, and Elmdale Formations. This hole finishes in 15 ft (4.6 m) of Cretaceous bedrock and Precambrian saprolite.

Grain size distribution of the < 2 mm fraction, and the results of lithologic analyses of the 1-2 mm very coarse-grained sand fraction of all till aquitards in the five analyzed cores are presented in Figures 4 and 5. These results are compared graphically along three axes in Figure 6, illustrating USDA textural classifications, crystalline/carbonate/shale proportions, Precambrian/Cretaceous/Paleozoic ratios, and relative proportions of light, dark, and red grains within the crystalline fraction of the 1-2 mm very coarse-grained sand percentage. The Villard Member of the New Ulm Formation notably contains moderate amounts of shale and other Cretaceous grains (averages of 16% and 18%), with a loam texture. The Moland Member of the

New Ulm Formation trends towards lower shale and Cretaceous percentages (averages of 3 and 4%), with a sandier loam texture. In comparison, the Hewitt Formation contains about 10% more sand than the New Ulm Formation and is lacking, or has very low, carbonate and shale fractions (averages of 3% and 0%). Diamict facies within the Cromwell Formation are also typically characterized by a sandy loam texture, but are enriched in dark and red grain-types (averages of 28% and 32%) and exhibit a redder matrix hue (5YR 3/2 to 7.5YR 3/2) relative to the other units assessed in this study.

Pre-Wisconsinan tills in cores MN OB-7 and HB1-15 generally have finer-grained textures, and contain greater amounts of shale and carbonate than the Wisconsinan-age deposits. The Browerville Formation appears lithologically similar to the Villard Member of the New Ulm Formation, in that it contains roughly 19% Cretaceous grains; however the Cretaceous fraction consists of less gray shale and more of the other Cretaceous identifiers (such as speckled shale, inoceramus fossils, lignite, and pyrite). The informal Good Thunder formation and Lake Henry Formation are lithologically and texturally similar to each other, but are separated mainly based on the Cretaceous fraction, with the former being proportionally enriched in Cretaceous grain-types (< 13%, average 4%) compared to the latter (average 1%).

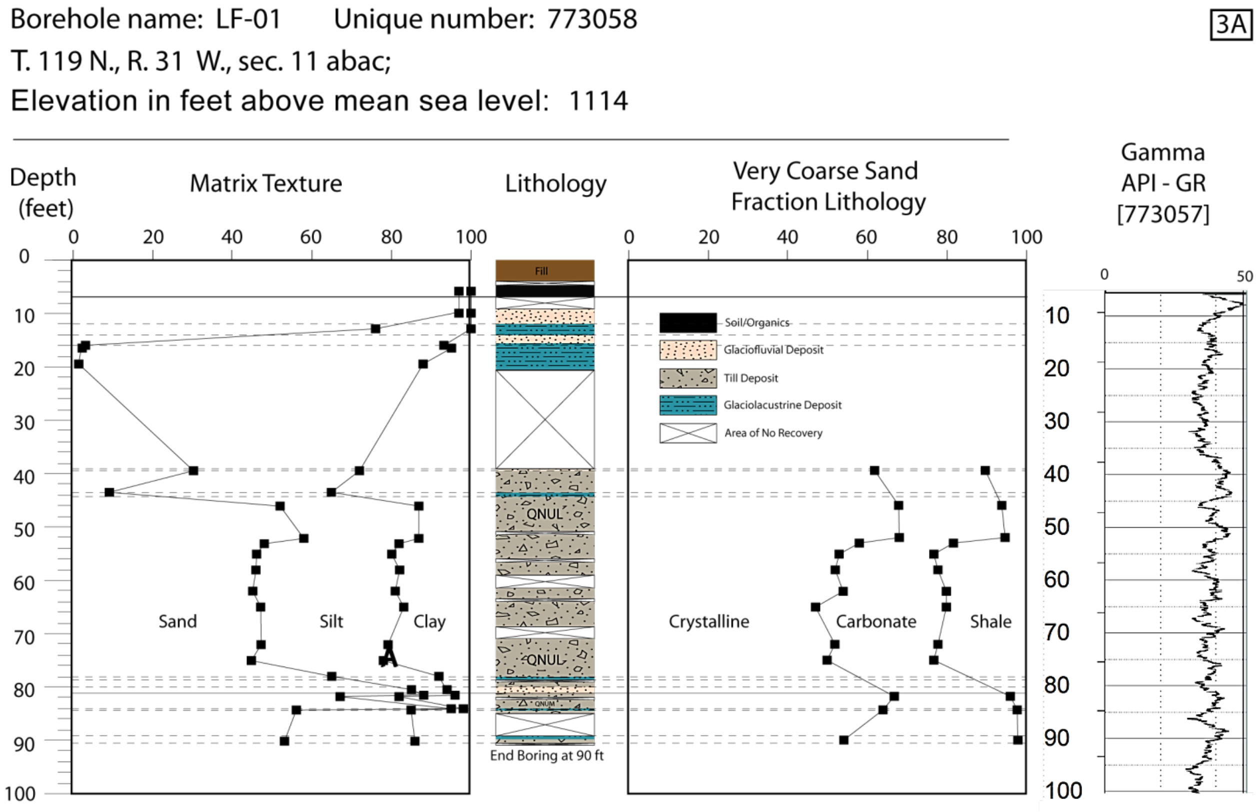


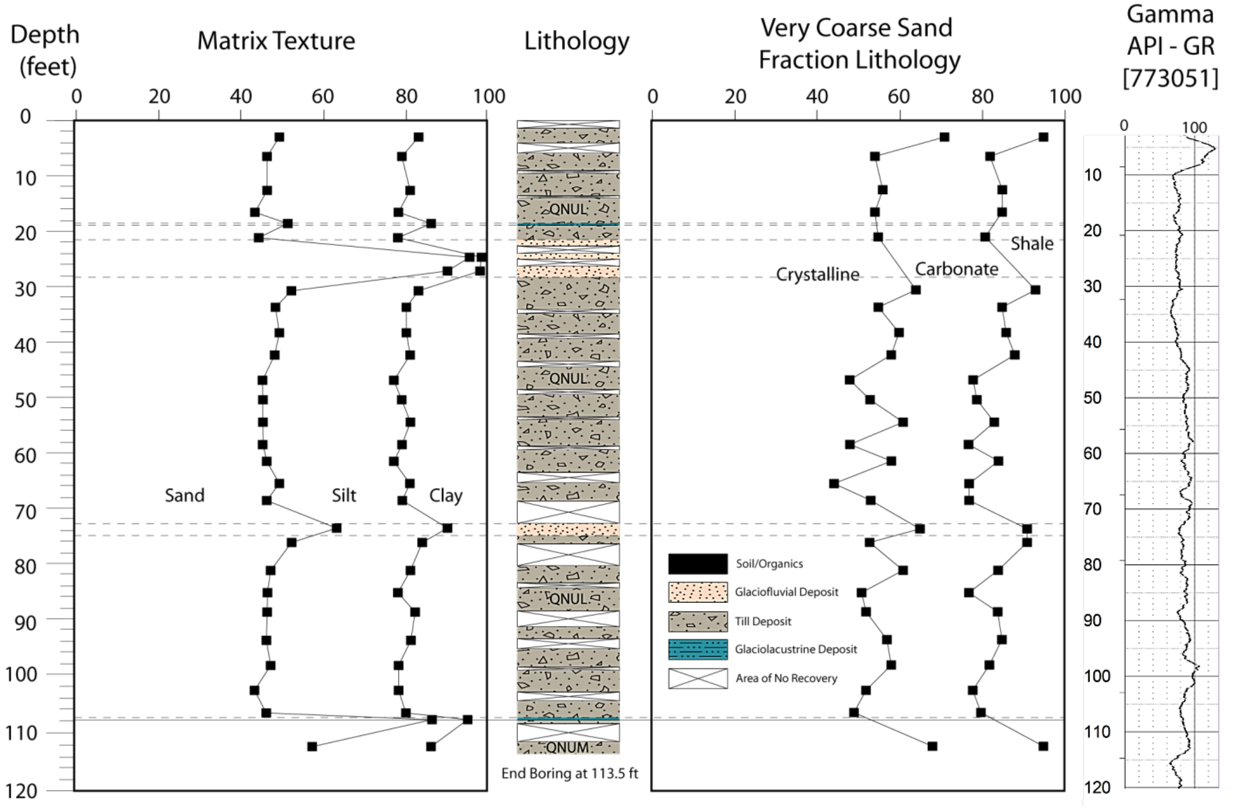
Figure 3. Graphic logs of scientific drill core with sample matrix texture, very coarse-sand fraction (1-2 mm) lithology (relative crystalline, carbonate, and shale), and corresponding gamma logs with depth. Regularly-spaced 10 ft (3 m) reductions in gamma signal due to effects of logging within drilling rod. Unit abbreviations are as follows: QAIA, Alborn Member of the Aitkin Formation; QBVU, Browerville Formation; QCMU, Cromwell Formation; QGTA, Good Thunder 1 member; QGTB, Good Thunder 2 member; QGTC, Good Thunder 3 member; QGTD, Good Thunder 4 member; QHWU, Hewitt Formation; QLHS, Sauk Centre Member of the Lake Henry Formation; QNUL, Villard Member of the New Ulm Formation; QNUM, Moland Member of the New Ulm Formation; QUPS, undefined Pleistocene sediment. A) LF01 – Down-hole gamma shown from adjacent USGS observation well (Unique no: 773057). B) LF02 – Down-hole gamma shown from adjacent USGS observation well (unique no: 773051). C) CW02 – Red line indicates number of red grains (reddish basalt, rhyolite, arkose, iron formation, and agate) counted as a proportion of the crystalline category with depth. D) MN OB-7 – Density contacts marked on log change from relatively low density to moderately high density at 22 ft (7 m) and from moderately high density to high density at 42 ft (13 m) depth. E) HB1-15 – Graphic log ends at confined aquifer of interest; additional core extends to a depth of 490 ft. F) HT-200 – Textural and lithological analyses were not performed on samples collected from this core.

Borehole name: LF-02 Unique number: 773052

T. 119 N., R. 31 W., sec. 02 cacd;

Elevation in feet above mean sea level: 1139

3B

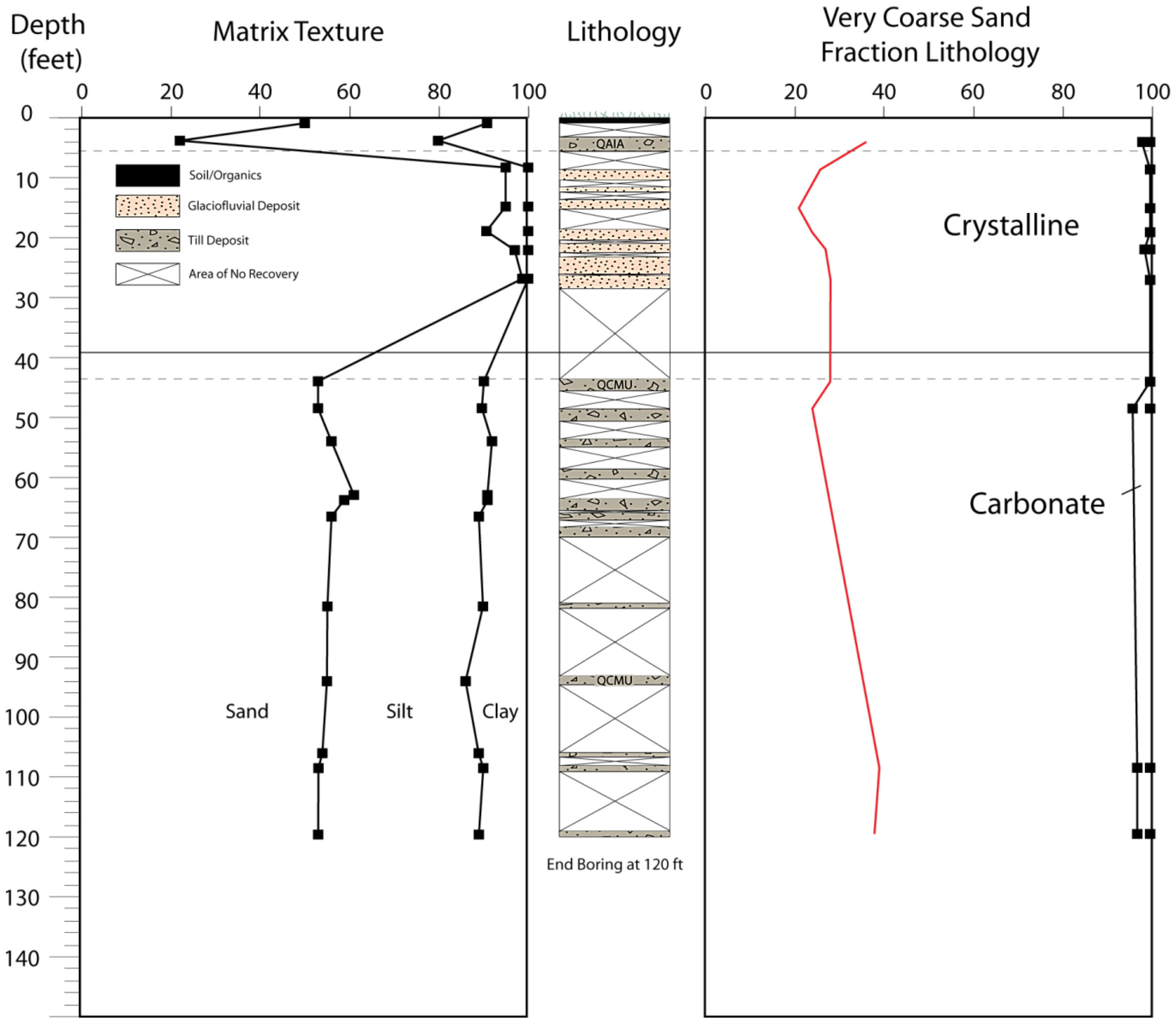


Borehole name: CW-02 Unique number: 773064

3C

T. 49 N., R. 20 W., sec. 33 caba;

Elevation in feet above mean sea level: 1332

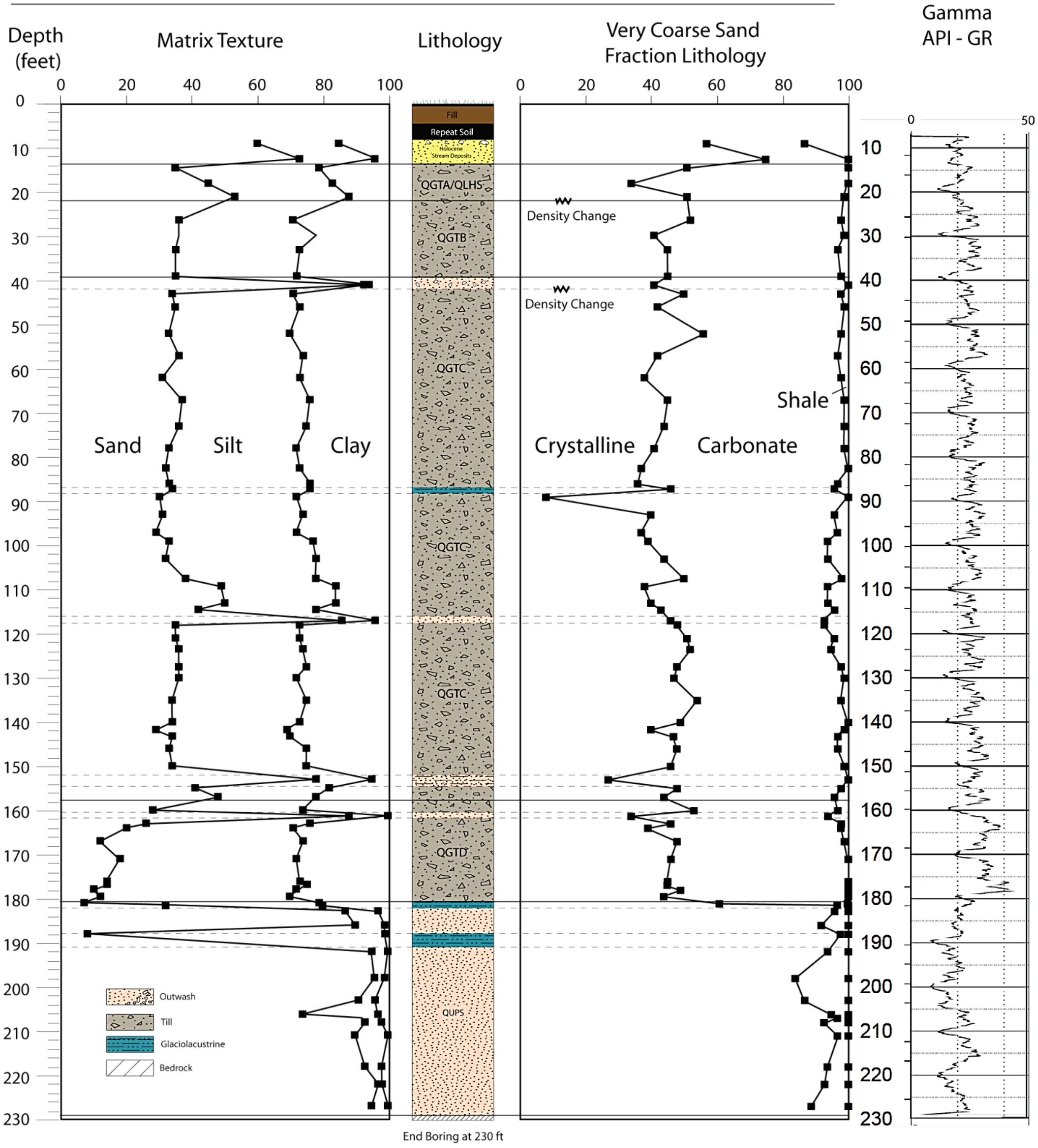


Borehole name: OB-7 Unique number: 773079

T. 115 N., R. 35 W., sec. 12 cddd;

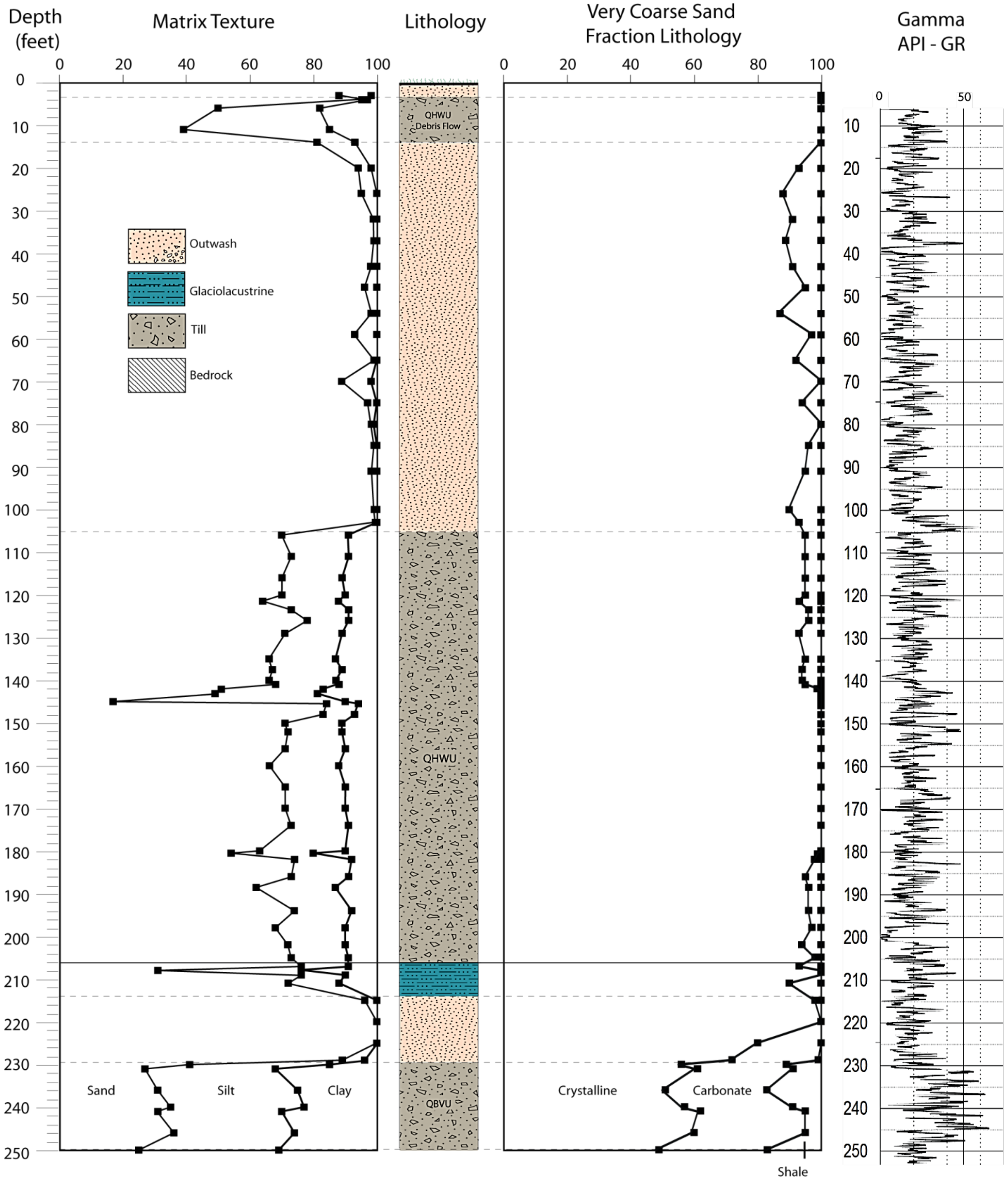
Elevation in feet above mean sea level: 1071

3D



Borehole name: HB1-15 Unique number: 809697 **3E**

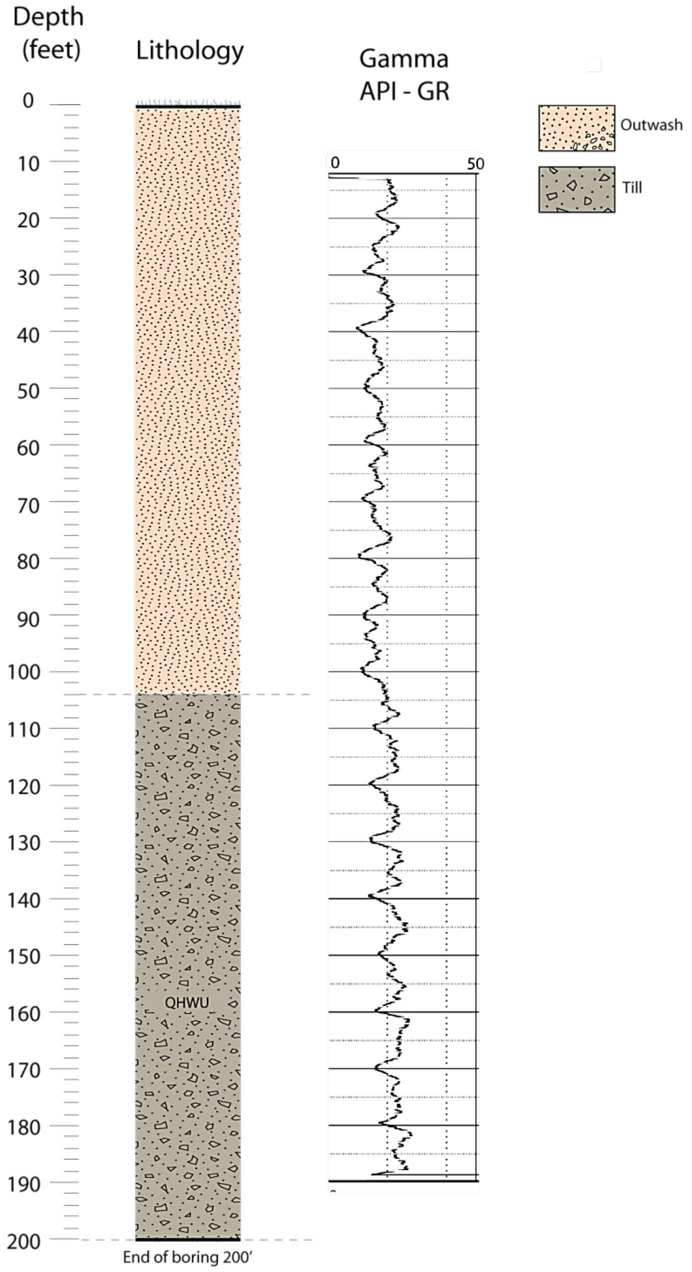
Elevation in feet above mean sea level: 1452

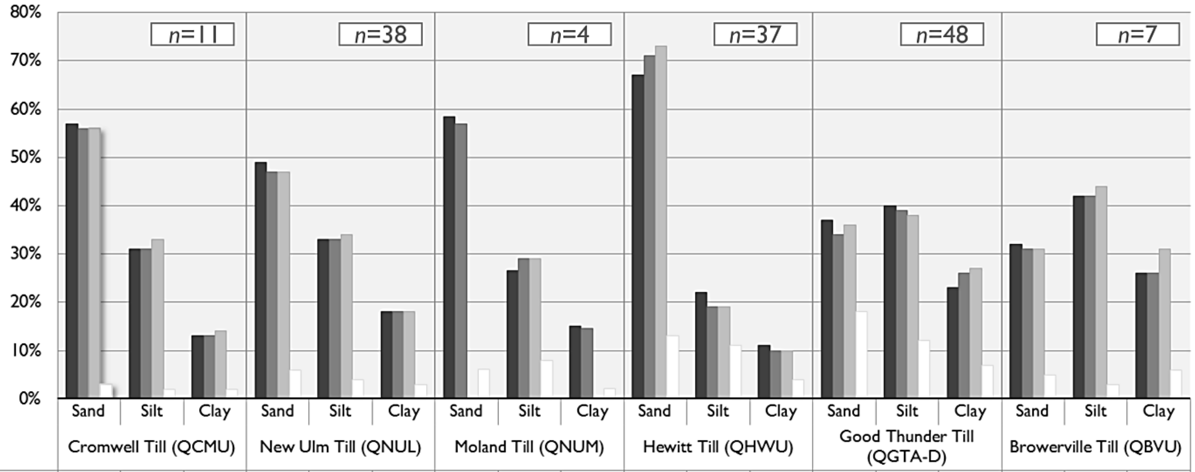


Borehole name: HT200 Unique number: 773078

3F

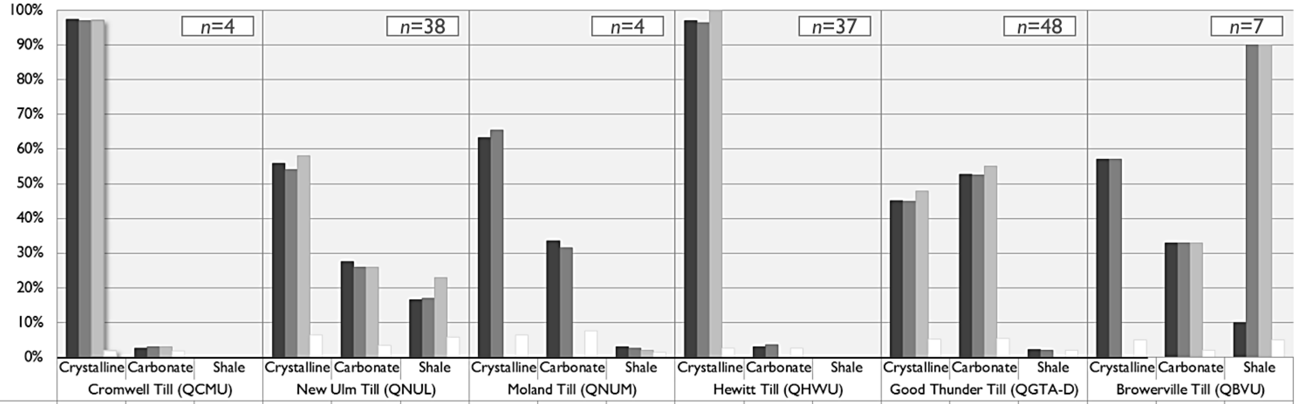
Elevation in feet above mean sea level: 1452





	Cromwell Till (QCMU)			New Ulm Till (QNUL)			Moland Till (QNUM)			Hewitt Till (QHWU)			Good Thunder Till (QGTA-D)			Browerville Till (QBVU)		
	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
■ Mean	0.57	0.31	0.13	0.49	0.33	0.18	0.59	0.27	0.15	0.67	0.22	0.11	0.37	0.4	0.23	0.32	0.42	0.26
■ Median	0.56	0.31	0.13	0.47	0.33	0.18	0.57	0.29	0.15	0.71	0.19	0.1	0.34	0.39	0.26	0.31	0.42	0.26
■ Mode	0.56	0.33	0.14	0.47	0.34	0.18	—	0.29	—	0.73	0.19	0.1	0.36	0.38	0.27	0.31	0.44	0.31
□ St. Dev	0.03	0.02	0.02	0.06	0.04	0.03	0.06	0.08	0.02	0.13	0.11	0.04	0.18	0.12	0.07	0.05	0.03	0.06

Figure 4. Central tendencies of the < 2 mm grain size distributions for till aquitards encountered in this study.



	Cromwell Till (QCMU)			New Ulm Till (QNUL)			Moland Till (QNUM)			Hewitt Till (QHWU)			Good Thunder Till (QGTA-D)			Browerville Till (QBVU)		
	Crystalline	Carbonate	Shale	Crystalline	Carbonate	Shale	Crystalline	Carbonate	Shale	Crystalline	Carbonate	Shale	Crystalline	Carbonate	Shale	Crystalline	Carbonate	Shale
■ Mean	0.98	0.03	0.00	0.56	0.28	0.16	0.63	0.34	0.03	0.97	0.03	0.00	0.45	0.53	0.02	0.57	0.33	0.10
■ Median	0.97	0.03	0.00	0.54	0.26	0.17	0.66	0.32	0.03	0.97	0.04	0.00	0.45	0.53	0.02	0.57	0.33	0.90
■ Mode	0.97	0.03	0.00	0.58	0.26	0.23	—	—	0.02	1.00	0.00	0.00	0.48	0.55	0.00	—	0.33	0.90
□ St. Dev	0.02	0.02	0.00	0.06	0.03	0.06	0.06	0.08	0.01	0.03	0.03	0.00	0.05	0.05	0.02	0.05	0.02	0.05

Figure 5. Central tendencies of the lithologic composition of the 1-2 mm fraction of till aquitards expressed in percent as relative proportions of crystalline (mostly Precambrian), carbonate (mostly Paleozoic), and shale (mostly Cretaceous) grain-types.

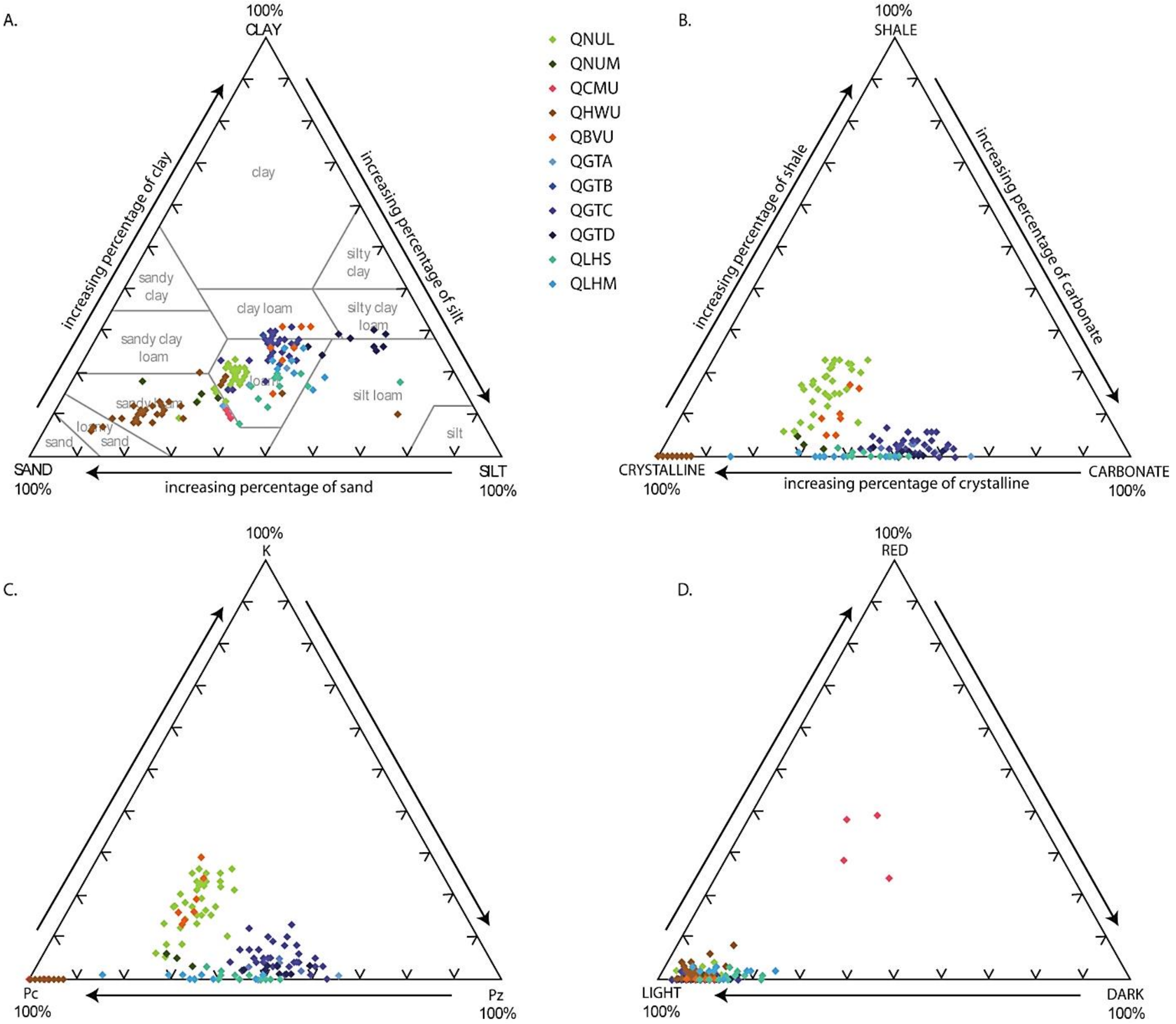


Figure 6. Ternary diagrams of samples collected from till aquitards of interest in cores LF01, LF02, CW02, MN OB-7 and HB1-15. Unit abbreviations are as follows: QNUL, Villard Member of the New Ulm Formation; QNUM, Moland Member of the New Ulm Formation; QCMU, Cromwell Formation; QHWU, Hewitt Formation; QBVU, Browerville Formation; QGTA, Good Thunder 1 member; QGTB, Good Thunder 2 member; QGTC, Good Thunder 3 member; QGTD, Good Thunder 4 member; QLHS, Sauk Centre Member of the Lake Henry Formation.

E) Matrix texture of the < 2 mm grain size fraction based on USDA Textural Classification System.
F) Composition of the very coarse-grained (1-2 mm) sand fraction showing relative crystalline, carbonate, and shale fractions.
G) Composition of the very coarse-grained (1-2 mm) sand fraction showing relative Precambrian (Pc), Paleozoic (Pz), and Cretaceous (K) fractions.
H) Composition of the crystalline portion of the very coarse-grained (1-2 mm) sand fraction displayed as relative proportions of light (granite, gneiss, monomineralic quartz), dark (mafic-rich igneous and metamorphic), and red (reddish basalt, rhyolite, arkose, iron formation, and agate) grain types.

Borehole geophysics

Major hydrogeologic factors that can affect EM response are dissolved solids concentrations in the groundwater and silt and clay content (Williams et al., 1993). In general, boreholes at the Litchfield and Cromwell sites logged using the EM-Induction sonde as part of this investigation have similar log patterns in down-hole conductivity and gamma; increases in conductivity correspond to increasing gamma, likely due to increasing silt and clay content. Deviations from this pattern may correspond to changes in groundwater chemistry. Deviation depth intervals from Cromwell observation well cluster 1 (Figure 7) and Litchfield observation wells LF01-F and LF02-F (Figure 8) identify zones where dissolved solids concentrations change. Wells in Cromwell observation cluster 1 are closely spaced and deviation depth intervals roughly correspond in the upper 100 ft (30.5 m), particularly at depths 18 to 26 ft bgs and 60 to 70 ft bgs (Figure 7). Deviation depth intervals in Litchfield LF01-F and LF02-F correspond to thick sand and gravel intervals in the bottom of the holes (Figures 3A and 3B) and likely represent water chemistry differences in the confined aquifer from water in overlying fine-grained sediment.

During the June 24, 2015 logging of LF02-F, the EM-Induction sonde stopped at 153 ft (46.7 m) below the ground surface prior to logging, approximately 10 ft (3 m) above the completed hole depth. The EM-Induction sonde has a larger diameter than the Gamma sonde and may have become stuck in a section of the casing that was not plumb. LF02-F was re-logged using the EM-Induction sonde on August 19, 2015, this time with several wraps of electrical tape removed from the lower portion of the sonde to reduce tool diameter. The sonde again stopped at 153 ft (46.7 m) below the ground surface, resulting in no EM-induction record for the lower 10 ft (3 m) of LF02-F. EM-Induction and Gamma logs are included in Appendix B.

Prior to this investigation, borehole geophysical work by MGS has not included the EM-Induction sonde. The interpretation presented here is considered qualitative. Boreholes MN OB-7, HT-200, and HB1-15 were not logged using the EM-Induction sonde.

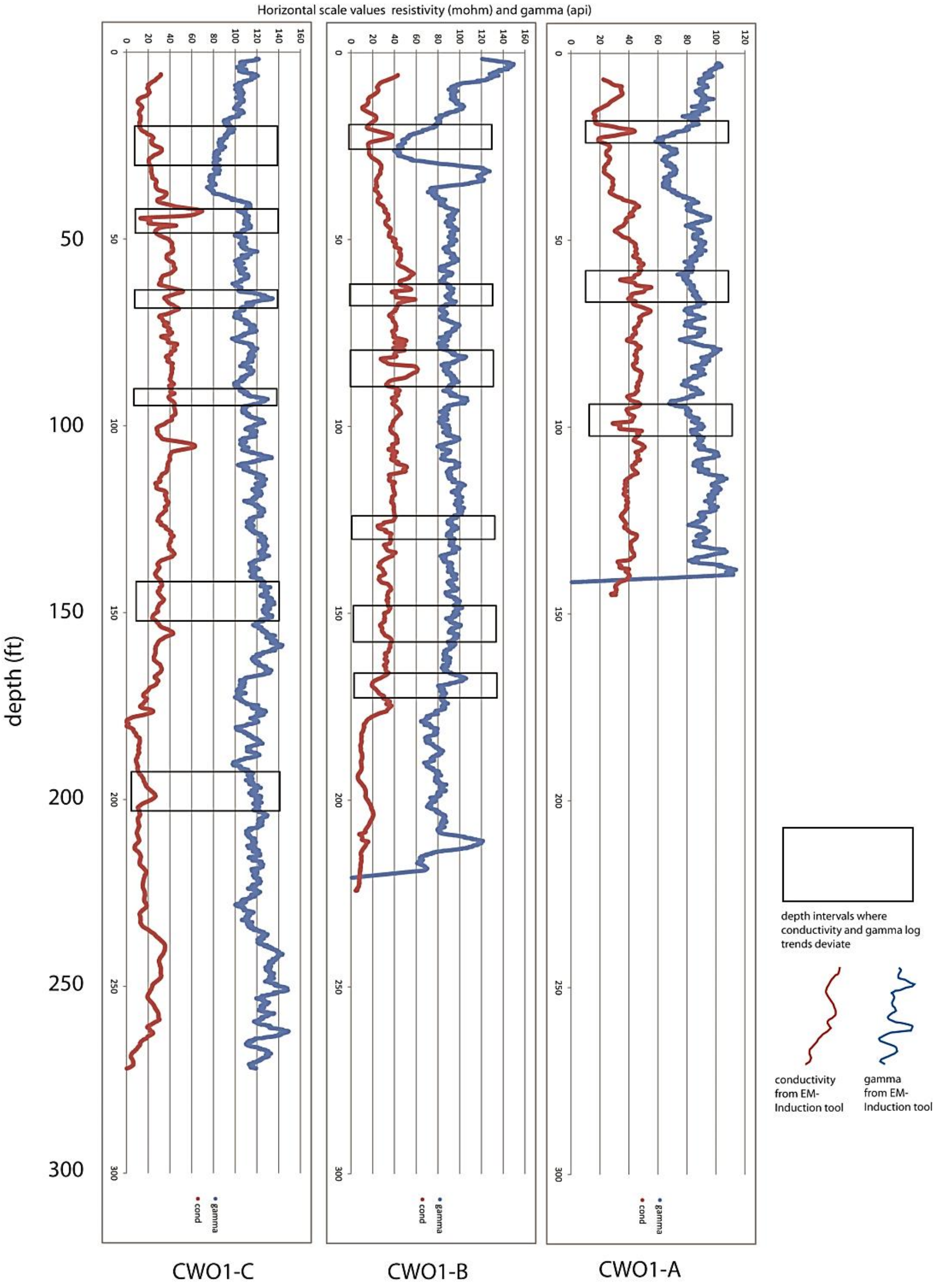


Figure 7. Qualitative identification of depth intervals where conductivity and gamma trends deviate from each other, Cromwell observation well cluster 1. Rock-water conductivity measurements typically track gamma logs, with increasing conductivity associated with increased clay or silt content. Deviations from these trends may indicate changes in fluid conductivity due to changes in water chemistry. Both logs from EM-Induction sonde.

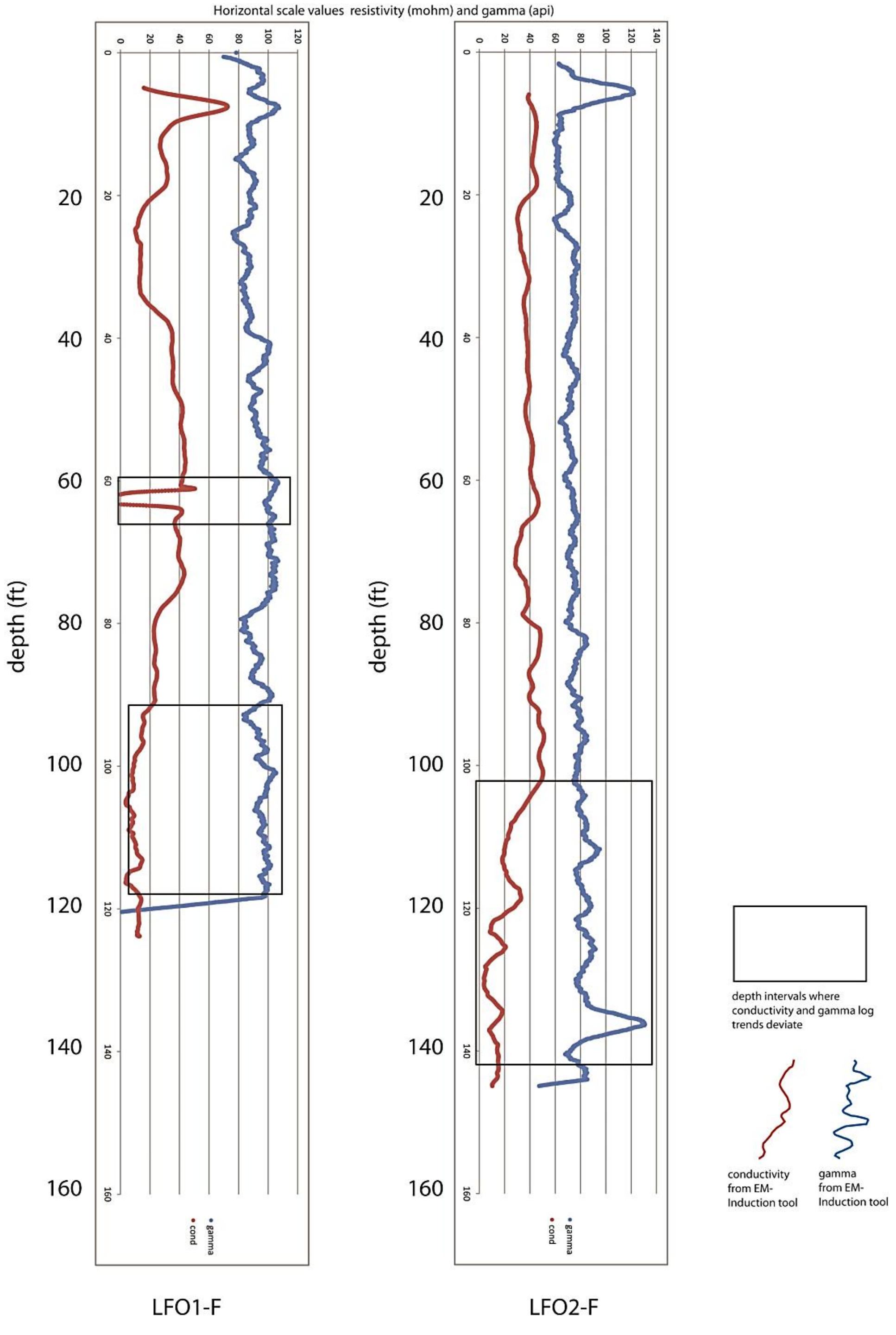


Figure 8. Qualitative identification of depth intervals where conductivity and gamma trends deviate from each other, Litchfield observation wells LF01-F and LF02-F. Rock-water conductivity measurements typically track gamma logs, with increasing conductivity associated with increased clay or silt content. Deviations from these trends may indicate changes in fluid conductivity due to changes in water chemistry. Both logs from EM-Induction sonde.

Discussion

Litchfield

Sediments encountered in the two cores (LF01, LF02) acquired from Litchfield, MN chronicle the incursion of the Des Moines lobe of the Laurentide Ice Sheet (LIS) into south-central Minnesota, and its subsequent demise during the Late Wisconsinan glacial episode. During this stage, ice advanced out of Manitoba and Saskatchewan from the northwest, occupying the present-day Red River Valley, moving through Meeker County, and reaching as far south as Des Moine, Iowa by 14 ka BP (Clayton and Moran, 1982). The Des Moines lobe represented the outlet of several dynamically-coupled ice streams (Patterson, 1997; Jennings, 2006) that eroded, incorporated, and transported materials from two broad source areas up-ice, conventionally referred to as “Riding Mountain” (northwest) and “Winnipeg” (north) provenances, the former of which is enriched proportionally with up to 50% higher gray Cretaceous Pierre shale content in the very-coarse sand (1-2 mm) fraction (Lusardi et al., 2011).

The Villard Member of the New Ulm formation (QNUL) predominantly reflects a mixed Winnipeg provenance. Within the geographic boundaries of its extent, it has an average crystalline/carbonate/shale composition of .52/.31/.17 (Johnson et al., 2016). The reduced shale content, and the sandier texture compared to the Heiberg Member – the coeval and laterally stratigraphic equivalent member of the New Ulm Formation – suggests that multiple ice sheds contributed distinctive lithological signatures to tills of the Des Moines lobe. This greatly impacted its dynamics, with the ice stream depositing the Villard Member having emerged from the north, and overridden and incorporated sandy materials of the Alexandria moraine complex in west-central Minnesota (Hobbs and Goebel, 1982). As this ice stream outlet thinned, it was partially captured by a second and buttressing outlet to the southwest that deposited the Heiberg Member till (the surface unit as little as 5 miles south and west of Litchfield (Meyer, 2015a)), shifting ice flow towards the northeast across most of Meeker County, and enabling ice to overtop the St. Croix moraine, thereby spawning the Grantsburg sublobe (Lusardi et al., 2011). The Villard Member in south-central Minnesota has not been directly dated, however, it is assumed correlative with the Bemis phase that formed the Pine City moraine in east-central Minnesota between approximately 12 ka ^{14}C yr BP (14 ka cal yr BP; Wright and Rubin, 1956; Clayton and Moran, 1982) and 13 ka ^{14}C yr BP (16 ka cal yr BP; Jennings et al., 2013).

Recent work documents large-scale reorganizations of ice flow during the late last glacial within catchment areas of the Des Moines lobe in southern Saskatchewan and Manitoba (Ross et al., 2009; O'Cofaigh et al., 2010), and these shifts are likely linked, in combination with local factors, to subtle variations in till texture, color and visible clast lithologies documented here down-core in LF01 and LF02. The coarser texture, faint proportional increase in felsic igneous lithologies, the introduction of sparse Late Precambrian North Shore Volcanic Group (NSVG) red volcanics, and the associated proportional reduction of Cretaceous shale grains in the 1-2 mm fraction near the base of both cores (Figures 3A and 3B), indicate local incorporation of older northeast-sourced (Rainy provenance materials), most likely till and/or outwash of the underlying Hewitt Formation (including that of the Alexandria moraine complex) deposited by the Wadena lobe early in the Late Wisconsinan. The presence of Cretaceous shale corroborates that this is likely a northwest-sourced till, as the pure Hewitt Formation is devoid of this lithology. Textural and lithologic statistics for the four samples collected from this unit (Figure 6 and Appendix A) are consistent with those of the Moland Member (QNUM), the lowest member in the New Ulm Formation (Johnson et al., 2016). The Moland Member is speculated to have been deposited in an earlier advance than the Bemis phase of the Des Moines lobe, by ice which assumed a generally similar trajectory, though was less laterally confined and did not reach as far south. The Moland Member of the New Ulm Formation is inferred as correlative to the Sheldon Creek Formation of Iowa, which has been attributed to two separate advances at approximately 26,000 to 40,000 ^{14}C yr BP (31,000 to 43,700 cal yr BP) (Kilgore et al., 2007).

With the exception of the thin Moland package at the base of these cores, at both sites, it is inferred that all changes in the nature of the tills reflect variability within a single member of the New Ulm formation. This may be driven by fluctuating ice stream dynamics and interactions at the ice-bed interface, rather than oscillations between members (i.e., Villard vs. Heiberg), as mean sand, silt, and clay proportions of all tills designated here as Villard are within 1 standard deviation of values reported by workers in surrounding counties for the Villard Member of the New Ulm Formation (e.g., Lusardi, 2009; Lusardi et al., 2012, Meyer, 2015b). Moreover, discrete members of the New Ulm Formation retain well-understood and distinctive lithologic assemblages (Johnson et al., 2016), and exhibit unique areal distributions on bivariate plots comparing sand and shale percentages (Harris, 1998). The results of systematic counts of the very coarse sand (1-2 mm) fraction completed for this study are consistent with the established lithologic characteristics of the Villard Member as defined in Johnson et al. (2016). Down-hole 1-2 mm grain counts were completed by the MGS on samples from a rotary-sonic core (MS-3) drilled 0.17 miles west of LF02 in support of the Meeker County Geological Atlas (Meyer, 2015b), and all tills described there from the surface to a depth of 134 ft (40.1 m) were interpreted as Villard Member of the New Ulm Formation.

The uppermost sands and gravelly sands encountered at surface in LF01 are interpreted as deltaic sediments deposited as interflow and underflow plumes into glacial Lake Litchfield II (represented in the sediment archive in LF01 from 12-20.5 ft / 3.7-6.2 m), which formed following recession from a late-stage re-advance of the Des Moines lobe, when drainage was blocked to the north by stagnant ice, and to the east, by the western margin of the Grantsburg sublobe in Wright County (Meyer, 2015a). The thin outwash sequence bounded by till, present from 21.75-28 ft (6.6-8.5 m) in core LF02, possibly marks the position of this re-advance in the local stratigraphy. Though the difference in surface elevation between LF01 and LF02 is minor (< 25 ft / 7.6 m), the latter boring is sited on a till knob which evidently escaped inundation by the lake, suggesting glacial Lake Litchfield II was relatively shallow and possibly short-lived.

Cromwell

Core materials recovered from CW02 primarily record activity of the Superior lobe of the LIS in northeastern Minnesota during the Late Wisconsinan glacial episode. During the St. Croix phase, the first of multiple, successively less-expansive configurations of the Superior lobe recognized within the Late Wisconsinan, ice (sourced from the Labrador-Québec divide centered south of Ungava Bay) occupied the Lake Superior lowland and advanced – confluently with the Rainy lobe – south into west-central and south-central Minnesota, culminating in the deposition of the St. Croix moraine between 15 and 20 ka cal yr BP (Wright, 1972; Clayton and Moran, 1982; Johnson and Mooers, 1988). Subsequently, the Superior lobe contracted back into the Lake Superior basin, fronted by networks of small proglacial lakes depositing fine sands, silts and clays which were later incorporated into the basal deposits of a second Superior lobe advance (the Automba phase) roughly13.5-14 ka cal yr BP, which generated the Mille Lacs Moraine along its westernmost extent (Wright, 1972).

Tills and associated meltwater deposits of the St. Croix and Automba phases of the Superior lobe are lithostratigraphically assigned to the Cromwell Formation (Wright et al., 1970; Johnson et al., 2016). Materials of this formation are present in core CW02 from 8.5 ft (2.6 m) through to the base (120 ft / 36.6 m), and consist of 76.5 ft (23.3 m) of subglacial till overlain by a 20 ft (6 m) sequence of variously graded and stratified proglacial outwash. Large (≤ 17 ft / 5.2 m) and frequent intervals of core loss and/or zero recovery in CW02 preclude detailed consideration of the glacial stratigraphy at this location; in particular, because differentiation of Automba and St. Croix phase deposits based on texture or lithology is problematic and generally relies on stratigraphic sense. Though no formal assignment is offered here, the entire package of sediments below 8.5 ft (2.6 m) is assumed to be Automba Phase in origin, in keeping with more regional subsurface mapping completed by the MGS for the Carlton County Geologic Atlas (Knaeble and Hobbs, 2009a; Knaeble and Hobbs, 2009b), including description of a rotary-sonic core (Unique #: 257600) drilled to 162 ft (49.4 m) depth 2.5 miles (4 km) north of CW02. This package is hence interpreted as a continuous record marking sedimentation during a single phase of advance (subglacial till) and retreat (proglacial outwash over subglacial till) of the Superior lobe. Mean sand proportions of Cromwell Formation tills derived here are within 2 standard deviations, silt proportions within 3 standard deviations, and clay values equivalent to those reported by Knaeble and Hobbs (2009b). Counts of the 1-2 mm very coarse-grained sand fraction conducted on till samples from CW02 (Figure 6) also fall well within an accepted range for the Cromwell Formation (Johnson et al., 2016).

The Cromwell Formation in CW02 is capped by 5.5 ft (1.7 m) of distinctive reddish-brown (5YR 4/4-7.5YR 4/4) silty diamicton interpreted as the Alborn Member of the Aitkin Formation (QAIA). The Aitkin Formation includes all deposits associated with the St. Louis sublobe of the Koochiching Lobe, which advanced from the northwest as a piedmont glacier into glacial lakes Aitkin I and Upham I that formed following retreat of the Superior Lobe from its maximum Automba Phase configuration 12.5 ka 14C yr BP (15 ka cal yr BP) (Jennings et al., 2013). The prominent red color and silt loam to clay loam texture of the Alborn Member derives from incorporation of fine-grained glacial Lake Upham I sediments and underlying Automba Phase deposits. It exists at the surface as only a narrow (1-8 miles / 1.6-12.9 km wide) rim which demarcates the boundary of the St. Louis sublobe beyond the former extent of Glacial Lake Upham II, which formed following the sublobe’s collapse (Johnson et al., 2016). Two samples of

Alborn Member till retrieved at surface from core CW02 diverge widely in terms of texture. Clear indications of pedogenesis, including leaching, oxidation, root infiltration, fines translocation and ped development through the 0-1.5 ft (0-0.5 m) interval, and the presence of a platy, illuviated, argillic horizon from 3.5-5.5 ft (1-1.7 m) suggest extensive modification by soil-forming processes, and hence, that a representative sample of Alborn Member till was not obtained. Consequently, these samples have not been isolated for statistical comparison in any of the plots presented above. It is important to note that the assignment of this uppermost diamicton in CW02 to the Alborn Member is somewhat tenuous, given local similarities in clast lithologies, and the tendency for soil-forming processes to sufficiently alter Cromwell Formation tills such that they may be texturally indistinguishable from those of the Alborn Member (Alan Knaeble, pers comm.). Knaeble and Hobbs (2009a) depict the surface unit at site CW02 as Cromwell Formation till, however this assessment was based locally on a hand sample obtained from a surface exposure, and thus did not account for the underlying 20 ft (6 m) of sorted outwash deposits, which are considered here as a significant bounding unit between formations. The Alborn Member is construed as relatively patchy in the mapping of Knaeble and Hobbs (2009a) and exists at surface as close as 3 miles (4.8 km) east of CW02.

Olivia

Detailed characterization paired with textural and lithologic analysis of samples collected from MN OB-7 core indicate a thick package of pre-Wisconsinan deposits, capped by thin Holocene materials (Figure 3D and Appendix A). The texture and lithology of tills in MN OB-7 were compared to those encountered previously in the regional stratigraphy. While the New Ulm Formation till has been mapped greater than 50 ft (15.2 m) thick in Renville County (Knaeble, 2013), there were no samples indicating that the New Ulm Formation till was preserved at this location. The till in MN OB-7 contains a high carbonate percentage (>50%) with a presence of Cretaceous grains (1-10%) and low gray shale percentage (<10%), typical of glacial sediments of Winnipeg provenance (Johnson et al., 2016). This unit is therefore interpreted to be the informally named Good Thunder formation (Meyer, 2015b; Knaeble, 2013). Members within the formation are incompletely defined, and therefore the member separation in core MN OB-7 is tentative until a more formal definition is established. On average, MN OB-7 till samples vary only slightly in texture and lithology from one another. Member breaks are primarily based on density changes of material with depth, but also on subtle differences in Cretaceous percentages (Figure 3D). While most of the surrounding area is mapped as having New Ulm Formation till 50-100 ft thick at the surface, this core does not contain any New Ulm Formation Till.

Based on low Cretaceous content and a density change from low to moderately high at 22 ft (6.7 m), an 8.5 ft (2.8 m) thick till underlying the Holocene stream deposits is informally interpreted as Good Thunder 1 member (QGTA). Good Thunder 1 member may correlate to the Sauk Centre Member (QLHS) of the Lake Henry Formation because of similarities in texture and lithology. Therefore this unit could be interpreted as either QGTA or QLHS. A small spike in Cretaceous grains (2-5%) extending 17 ft (6 m) below the QLHS/QGTA interval is indicative of a second member, the Good Thunder 2 member (QGTB). A second density change in the till below a thin (3 ft / 1 m) sand layer separates a third member, Good Thunder 3 member (QGTC), which is 119 ft (40 m) thick. Sand bodies are commonly present between individual till units, and are regularly used to mark stratigraphic boundaries. The percentage of Cretaceous grains in QGTC averages 2-5% higher than QGTB, consistent with the regional definition for the Good Thunder 3 member. Below QGTC, the till matrix texture tends towards silt-loam and the Cretaceous percentage decreases, implying the presence of the Good Thunder 4 member (QGTD), which is approximately 22 ft (7 m) thick.

Silt and fine- to coarse-grained sand and gravel below the till represent the aquifer of interest. The upper 7.5 ft (2.5 m) of the aquifer is predominantly gray and does not effervesce when introduced to hydrochloric acid (HCl). The color gradually changes with depth to orange-brown and becomes calcareous with depth. The low percentage of carbonate and trace Cretaceous grains suggest a Rainy provenance for this material. Pisolitic conglomerate and angular saprolith clasts are also present in this sand and gravel, suggesting moderate incorporation of weathered bedrock. The sand and gravel is likely a glaciofluvial deposit, representing reworking of local weathered bedrock and possible Rainy-sourced material deposited during the early onset of Pleistocene glaciation. Non-reaction of the upper 7.5 ft (2.5 m) of sand and gravel to HCl suggests possible leaching, allowing for the potential that this is leached Winnipeg sourced sediment. Color differences from oxidized (orange-brown) to unoxidized (gray) portions of the aquifer could be due to texture variations, with the coarse-grained sand section primarily oxidized and the finer-grained section unoxidized. This aquifer is interpreted as undefined Pleistocene Sediment (QUPS), considering the uncertainty of origin.

UM Field Site

The cores from HB1-15 and HT-200 reveal a history of repeated advance and retreat of the LIS into central Minnesota, culminating with its eventual demise during the Late Wisconsinan (Figures 3E and 3F). The cores consist of significant deposits of till, outwash, and glaciolacustrine sediment recording several glacial and interglacial periods. Interbedded brown, fine- to coarse-grained, sand and gravel interpreted as outwash dominate the top 105 ft (32 m), with a roughly 10 ft (3 m) interval of mixed yellowish-brown (2.5Y 5/4) sandy loam diamict near the surface (between depths of 5-15 ft (1.5-4.6 m) (Figure 3). This near-surface mixed zone, interpreted as a debris flow deposit, is highly variable in grain size and is unlikely to form a pervasive aquitard. Beneath the outwash is a 102 ft (31.1 m) thick unit of brown (10YR 4/4) sandy loam diamict interpreted as till which extends down to a depth of 207 ft (63.1 m). The till and outwash deposits of the upper 207 ft (63.1 m) are interpreted as Hewitt Formation (QHWU) based on their textural and lithological properties. Hewitt Formation till is characterized by its sandy loam texture, moderate amount of carbonate clasts (approximately 10-25% in unleached areas), and the absence of shale. The Hewitt Formation largely represents the advance of the Wadena lobe from the north-northeast (Rainy provenance) and it is present at the surface throughout a large area of central Minnesota (Johnson et al., 2016).

Pre-Wisconsinan till and associated glaciolacustrine and outwash deposits are present in the core from 207 ft (63.1 m) to the top of Cretaceous bedrock at 475 ft (144.8 m). Pre-Wisconsinan material at the UM field site was observed exclusively in HB1-15, as HT-200 was only drilled to a depth of 200 ft (61 m). A dense loam paleosol underlies the Hewitt Formation till at 207 ft (63.1 m) along with approximately 9 ft (0.3 m) of glaciolacustrine fine-grained sand and gravel (207-216 ft / 631-62.8 m) that was likely deposited during the pre-Wisconsinan interglacial. This glaciolacustrine unit, together with an underlying outwash unit from 216 to 230 ft (65.9 to 70.1 m) constitutes the 23 ft (7 m) aquifer of interest at the site. The uppermost pre-Wisconsinan till between 230 and 250 ft (70.1 and 76.2 m) is assigned to the northwest sourced (Winnipeg provenance) Browerville Formation (QBVU), largely on the basis of its stratigraphic position, carbonate content (average of 25%) and moderate presence of Cretaceous grains (~20% in HB1-

15) (Figure 6). The Browerville Formation till is underlain by a relatively thick package of sandy loam to loam textured diamicton interpreted as till (between 250 and 359 ft / 76.2 and 109.5 m), with intervals of well-sorted glaciolacustrine sand and silt. This unit is assigned to the Lake Henry Formation and shares a similar northwest source area to the Browerville Formation. The Lake Henry Formation can be differentiated based on a considerably higher carbonate content (30-55%) and lack of Cretaceous shale. This formation is subdivided into two members; the younger Sauk Centre Member (QLHS) which, at this site, has less clay and contains more carbonate, and the older Meyer Lake Member (QLHM) which, in some places, is capped by an organic zone (Johnson et al., 2016). At this site, the Meyer Lake Member till is marked by a paleosol at 318.5 ft (97.1 m). Beneath the Meyer Lake Member is the northeast sourced (Superior provenance) St. Francis Formation (QSTF) till (between 359 and 389.5 ft / 109.5 and 118.8 m), which is a dense loam containing distinct red Superior provenance clasts. This overlies approximately 50 ft (15.2 m) of glaciolacustrine fine-grained sand and the lowermost till, interpreted to be the Elmdale Formation (QELU), which extends from 440 ft (134.1 m) to its contact with Cretaceous bedrock at 475 ft (144.8 m). This till was deposited by Winnipeg-sourced ice and contains low to moderate amounts of carbonate (5-15%) and very little, if any, red and shale grains. HB1-15 ends in 4 ft (1.2 m) of Cretaceous shale (between 475 and 479 ft / 144.8 and 146 m) overlying 11 ft (3.4 m) of white-green Precambrian saprolite between 479 ft and the end of the boring at 490 ft (146 to 149.4 m).

Acknowledgements

The authors gratefully acknowledge funding from the United States Geological Survey (USGS) via the Environment and Natural Resources Trust Fund as recommended by the Legislative and Citizen’s Commission on Minnesota Resources (LCCMR) for their support of this investigation. Meetings and informal discussions with Barb Lusardi and Alan Knaeble (MGS), Dr. William Simpkins and Alyssa Witt (Iowa State University), and Jared Trost and Jim Stark (USGS) helped guide the content of this report. Special thanks to Andy Berg of the USGS and Scott Alexander of the University of Minnesota for great field support.

References Cited

Clayton, L., and Moran, S.R. 1982. Chronology of late-Wisconsinan glaciation in middle North America. Quaternary Science Reviews, 1: 55-58.

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.

Hobbs, H.C., and Goebel, J.E. 1982. Geologic map of Minnesota, Quaternary geology. Minnesota Geological Survey State Map S-1, scale 1:500,000.

Jennings, C.E. 2006. Terrestrial ice streams - A view from the lobe. Geomorphology, 75(1-2): 100-124.

Jennings, C.E., Adams, R.S., Arends, H.E., Breckenridge, A., Friedrich, H.G., Gowan, A.S., Harris, K.L., Hobbs, H.C., Johnson, M.D., Knaeble, A.R., Larson, P., Lusardi, B.A., Meyer, G.N., Mooers, H.D., and Thorleifson, L.H. 2013. Deglacial margin chronology of Minnesota and implications. Canadian Quaternary Association and Canadian Geomorphology Research Group Conference, Edmonton, Alberta, Program and Abstracts: 134 p.

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, 68: 262 p.

Johnson, M.D., and Mooers, H.D. 1998. Ice-margin positions of the Superior lobe during Late Wisconsinan deglaciation. In: Patterson, C.J., and Wright, H.E., Jr. (eds.), Contributions to Quaternary studies in Minnesota. Minnesota Geological Survey Report of Investigations, 49: 7-14.

Kilgore, S.M., Bettis, E.A., III, and Quade, D.J. 2007. Age, distribution and lithology of the Sheldon Creek Formation, north central Iowa: Geological Society of America Abstracts with Programs, v. 39, no. 3, p. 12.

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, 6 pls., scale 1:100,000.

Knaeble, A.R. 2018 (*in Progress*). Quaternary stratigraphy, Geologic atlas of Hubbard County, Minnesota: Minnesota Geological Survey County Atlas, pt. A, scale 1:100,000.

Knaeble, A.R., and Hobbs, H.C. 2009a. Surficial geology, pl. 3 *of* Boerboom, T.J., project manager, Geologic atlas of Carlton County, Minnesota: Minnesota Geological Survey County Atlas C-19, 6 pls., scale 1:100,000.

Knaeble, A.R., and Hobbs, H.C. 2009b. Quaternary stratigraphy, pl. 4 *of* Boerboom, T.J., project manager, Geologic atlas of Carlton County, Minnesota: Minnesota Geological Survey County Atlas C-19, 6 pls., scale 1:100,000.

Lusardi, B.A., Nguyen, M.K., and Staley, A.E. 2018. Quaternary stratigraphy, pl. 4 *of* Lusardi, B.A., project manager, Geologic atlas of Cass County, Minnesota: Minnesota Geological Survey County Atlas, pt. A, scale 1:100,000.

Lusardi, B.A., Jennings, C.E., and Harris, K.L. 2011. Provenance of Des Moines lobe till records ice-stream catchment evolution during Laurentide deglaciation. Boreas, 40(4): 585-597.

Lusardi, B.A., Meyer, G.N., Knaeble, A.R., Gowan, A.S., and Jennings, C.E. 2012. Quaternary stratigraphy, pl. 4 *of* Geologic atlas of Sibley County, Minnesota: Minnesota Geological Survey County Atlas C-19, pt. A, 6 pls., scale 1:100,000.

Meyer, G.N. 2015a. Surficial geology, pl. 3 *of* Meyer, G.N., project manager, Geologic Atlas of Meeker County, Minnesota: Minnesota Geological Survey County Atlas C-35, pt. A, 5 pls., scale 1:100,000.

Meyer, G.N. 2015b. Quaternary stratigraphy, pl.4 *of* Meyer, G.N., project manager, Geologic Atlas of Meeker County, Minnesota: Minnesota Geological Survey County Atlas C-35, pt. A, 5 pls., scale 1:100,000.

O'Cofaigh, C., Evans, D.J.A., and Smith, I.R. 2010. Large-scale reorganization and sedimentation of terrestrial ice streams during Late Wisconsinan Laurentide Ice Sheet deglaciation. Geological Society of America Bulletin, 12: 743-756.

Patterson, C.J. 1997. Southern Laurentide ice lobes were created by ice streams: Des Moines Lobe in Minnesota, USA. Sedimentary Geology, 111: 249-261.

Ross, M., Campbell, J.E., Parent, M., and Adams, R.S. 2009. Palaeo-ice streams and the subglacial landscape mosaic of the North American mid-continental prairies. Boreas, 38: 421-439.

Williams, J.H., Lapham, and W.W. Barringer, T.H. 1993. Application of electromagnetic logging to contamination investigations in glacial sand-and-gravel-aquifers. Ground Water Monitoring and Remediation, v.13, no. 1: 129-138. Wright, H.E., Jr. 1972. Quaternary history of Minnesota. In: Sims, P.K., and Morey, G.B. (eds.), Geology of Minnesota—A centennial volume. Minnesota Geological Survey: 515-547.

Wright, H.E., Jr., and Rubin, M. 1956. Radiocarbon dates of Mankato drift in Minnesota. Science, 124(3223): 625-626.

Wright, H.E., Jr., Mattson, L.A., and Thomas, J.A. 1970. Geology of the Cloquet quadrangle, Carlton County, Minnesota. Minnesota Geological Survey Geologic Map, GM-3: 30 p.

Appendices

Appendix A. Analysis of core samples collected from LF01, LF02, CW02, MN OB-7 and HB1-15.

Characterization includes textural and lithological analysis of samples, reaction to hydrochloric acid ("calcareous"), color, and interpreted deposit type, formation, and associated provenance. Matrix texture (< 2 mm grain-size fraction) is expressed as relative proportions of sand, silt, and clay in percent. Gravel fraction is stated as percentage of bulk sample. The lithologic composition of the very coarse-grained sand fraction (1-2 mm) is expressed in percent as relative proportions of crystalline rock, carbonate rock, and shale fragments and relative proportions of Precambrian, Paleozoic, and Cretaceous rock. Unit abbreviations are as follows: QAIA, Alborn Member of the Aitkin Formation; QBVU, Browerville Formation; QCMU, Cromwell Formation; QELU, Elmdale Formation; QGTA, Good Thunder 1 member; QGTB, Good Thunder 2 member; QGTC, Good Thunder 3 member; QGTD, Good Thunder 4 member; QHWU, Hewitt Formation; QLHM, Meyer Lake Member of the Lake Henry Formation; QLHS, Sauk Centre Member of the Lake Henry Formation; QNUL, Villard Member of the New Ulm Formation; QNUM, Moland Member of the New Ulm Formation; QSTF, St. Francis Formation; QUPS, undefined Pleistocene sediment. Note that provenance abbreviations were used for space efficiency in the table and are as follows: WP – Winnipeg sourced, SP – Superior sourced, RM – Riding Mountain sourced.

CW02

Sample	Depth (ft)	Sand %	Silt %	Clay %	USDA Texture	Gravel Fraction	Precambrian %	Paleozoic %	Cretaceous %	Crystalline %	Carbonate %	Shale %	Calcareous	Wet Color	Deposit Type	Formation	Provenance
01B	1.00	50	41	9	loam	11	-	-	-	-	-	-	N	10YR 4/6	Soil Mod. Till	QAIA	WP, SP, RM
02B	4.00	22	58	20	silt loam	2	99	1	0	99	1	0	N	7.5Y R 4/6	Soil Mod. Till	QAIA	Superior
03B	8.50	95	5	0	sand	16	100	0	0	100	0	0	N	10YR 6/8	Outwash	QCMU	Superior
04B	15.00	95	5	0	sand	9	100	0	0	100	0	0	N	10YR 6/6	Outwash	QCMU	Superior
05B	19.00	91	9	0	sand	14	100	0	0	100	0	0	N	10YR 6/8	Outwash	QCMU	Superior
06B	22.00	97	3	0	sand	1	99	1	0	99	1	0	N	10YR 8/8	Outwash	QCMU	Superior
07B	27.00	99	1	0	sand	9	100	0	0	100	0	0	N	10YR 8/4	Outwash	QCMU	Superior
08B	44.00	53	38	9	sandy loam	15	100	0	0	100	0	0	Y	10YR 4/3	Till	QCMU	Superior
09B	48.50	53	37	10	sandy loam	9	96	4	0	96	4	0	Y	-	Till	QCMU	Superior
10B	54.00	56	36	8	sandy loam	9	-	-	-	-	-	-	Y	10YR 4/3	Till	QCMU	Superior
3	63.00	61	30	9	sandy loam	34	-	-	-	-	-	-	Y	5Y 4/4	Till	QCMU	Superior
11B	63.50	59	31	10	sandy loam	38	-	-	-	-	-	-	Y	10YR 4/3	Till	QCMU	Superior
12B	66.50	56	33	11	sandy loam	26	-	-	-	-	-	-	Y	10YR 4/3	Till	QCMU	Superior
13B	81.50	55	34	11	sandy loam	15	-	-	-	-	-	-	Y	10YR 4/3	Till	QCMU	Superior
14B	94.00	55	31	14	sandy loam	7	-	-	-	-	-	-	Y	10YR 4/3	Till	QCMU	Superior
15B	106.00	54	34	12	sandy loam	14	-	-	-	-	-	-	Y	5YR 5/3	Till	QCMU	Superior
16B	108.50	53	37	10	sandy loam	8	97	3	0	97	3	0	Y	5YR 5/3	Till	QCMU	Superior
17B	119.50	53	36	11	sandy loam	10	97	3	0	97	3	0	Y	5YR	Till	QCMU	Superior

														5/3		

LF01

Sample	Depth (ft)	Sand %	Silt %	Clay %	USDA Texture	Gravel Fraction	Precambrian %	Paleozoic %	Cretaceous %	Crystalline %	Carbonate %	Shale %	Calcareous	Wet Color	Deposit Type	Formation	Provenance
1	6.00	97	3	0	sand	0	-	-	-	-	-	-	N	2.5Y 7/8	Deltaic	QNUL	Riding Mtn.
2	10.00	97	3	0	sand	1	-	-	-	-	-	-	Y	2.5Y 7/8	Deltaic	QNUL	Riding Mtn.
3	13.00	76	24	0	loamy sand	0	-	-	-	-	-	-	Y	2.5Y 6/8	Deltaic	QNUL	Riding Mtn.
4	16.00	3	90	7	silt	0	-	-	-	-	-	-	Y	2.5Y 4/4	Glaciolacustrine	QNUL	Riding Mtn.
5	16.50	2	93	5	silt	0	-	-	-	-	-	-	Y	10YR 3/4	Glaciolacustrine	QNUL	Riding Mtn.
6	19.50	1	87	12	silt loam	0	-	-	-	-	-	-	Y	2.5Y 5/2	Glaciolacustrine	QNUL	Riding Mtn.
7	39.50	30	43	27	clay loam - loam	2	62	26	12	62	28	10	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
8	43.50	9	56	35	silty clay loam	3	-	-	-	-	-	-	Y	2.5Y 5/2	Ice Contact	QNUL	Riding Mtn.
9	46.00	52	35	13	loam	5	67	25	8	68	26	6	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
10	52.00	58	29	13	sandy loam	22	68	26	5	68	27	5	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
11	53.00	48	34	18	loam	6	58	24	18	58	24	17	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
12	55.00	46	34	20	loam	9	53	22	25	53	24	23	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
13	58.00	46	36	18	loam	3	51	23	26	52	26	22	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
14	62.00	45	36	19	loam	6	54	25	21	54	26	19	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
15	65.00	47	35	18	loam	10	46	33	21	47	33	20	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
16	72.00	47	32	21	loam	7	52	25	23	52	26	21	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
17	75.00	45	32	23	loam	8	50	25	25	50	27	23	Y	2.5Y 5/2	Till	QNUL	Riding Mtn.
18	78.00	65	27	8	sandy loam	2	-	-	-	-	-	-	Y	2.5Y 5/2	Lensoidal	QNUL	Riding Mtn.
19	80.50	85	9	6	loamy sand	7	-	-	-	-	-	-	Y	2.5Y 5/2	Glaciofluvial	QNUL	Riding Mtn.
20	81.50	88	8	4	sand	28	-	-	-	-	-	-	Y	2.5Y 5/4	Glaciofluvial	QNUL	Riding Mtn.
21	81.75	67	15	18	sandy loam	5	67	29	5	67	29	3	Y	2.5Y 5/2	Till	QNUM	Riding Mtn.
22	84.00	95	3	2	sand	0	-	-	-	-	-	-	Y	10YR 6/4	Glaciofluvial	QNUM	Riding Mtn.
23	84.25	56	29	15	sandy loam	3	64	33	3	64	34	2	Y	2.5Y 5/2	Till	QNUM	Riding Mtn.
24	90.00	53	33	14	sandy loam	5	54	44	2	54	44	2	Y	2.5Y 5/2	Till	QNUM	Riding Mtn.

LF02

Sample	Depth (ft)	Sand %	Silt %	Clay %	USDA Texture	Gravel Fraction	Precambrian %	Paleozoic %	Cretaceous %	Crystalline %	Carbonate %	Shale %	Calcareous	Wet Color	Deposit Type	Formation	Provenance
1	3.00	50	34	16	loam	5	71	24	6	71	24	6	Y	10YR 6/6	Till	QNUL	Riding Mtn.
2	6.50	47	33	20	loam	5	54	27	19	54	28	18	Y	10YR 6/6	Till	QNUL	Riding Mtn.
3	12.50	47	35	18	loam	5	56	29	15	56	29	14	Y	10YR 6/6	Till	QNUL	Riding Mtn.
4	16.50	44	36	20	loam	7	54	31	15	54	31	15	Y	2.5Y 4/4	Till	QNUL	Riding Mtn.
5	18.50	52	35	13	loam	0	-	-	-	-	-	-	Y	2.5Y 5/6	Lensoidal	QNUL	Riding Mtn.
6	21.00	45	34	21	loam	10	54	25	21	55	26	19	Y	2.5Y 4/4	Till	QNUL	Riding Mtn.
7	24.50	97	2	1	sand	1	-	-	-	-	-	-	Y	2.5Y 7/6	Glaciofluvial	QNUL	Riding Mtn.
8	27.00	91	8	1	sand	5	-	-	-	-	-	-	Y	2.5Y 5/4	Glaciofluvial	QNUL	Riding Mtn.
9	30.50	53	31	16	sandy loam	6	63	28	8	64	29	7	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
10	33.50	49	32	19	loam	5	54	29	16	55	30	15	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
11	38.00	50	32	18	loam	7	60	26	14	60	26	13	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
12	42.00	49	34	17	loam	7	58	29	13	58	30	12	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
13	46.50	46	33	21	loam	6	47	28	25	48	30	22	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
14	50.00	46	34	20	loam	28	53	25	22	53	26	21	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
15	54.00	46	36	18	loam	5	60	22	17	61	22	17	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
16	58.00	46	34	20	loam	4	48	29	23	48	29	22	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
17	61.00	47	31	22	loam	8	57	26	17	58	26	16	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
18	65.00	50	32	18	loam	11	44	30	26	44	33	23	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
19	68.00	47	33	20	loam	6	53	24	23	53	24	23	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
20	73.00	64	27	9	sandy loam	8	65	22	13	65	26	8	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
21	75.50	53	32	15	sandy loam	7	53	37	10	53	38	8	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
22	80.50	48	34	18	loam	11	61	22	17	61	23	16	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
23	84.50	47	32	21	loam	5	51	26	23	51	26	23	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
24	88	47	36	17	loam	4	52	31	17	52	32	16	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
25	93	47	34	19	loam	3	57	28	15	57	28	15	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
26	97.5	48	31	21	loam	4	58	22	20	58	24	18	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
27	102	44	35	21	loam	4	52	26	22	52	26	22	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
28	106	47	34	19	loam	7	49	30	22	49	31	21	Y	2.5Y 4/2	Till	QNUL	Riding Mtn.
29	107.25	87	8	5	loamy sand	58	-	-	-	-	-	-	Y	2.5Y 6/2	Glaciofluvial	QNUL	Riding Mtn.
30	112	58	29	13	sandy loam	6	68	26	6	68	27	5	Y	2.5Y 4/2	Till	QNUM	Riding Mtn.

OB-7

Sample	Depth (ft)	Sand %	Silt %	Clay %	USDA Texture	Gravel Fraction	Precambrian %	Paleozoic %	Cretaceous %	Crystalline %	Carbonate %	Shale %	Calcareous	Wet Color	Deposit Type	Formation	Provenance
1	9.00	60	25	15	sandy loam	26	57	29	14	57	30	13	Y	2.5Y 5/4	Stream Deposit	Holocene	n/a
2	12.50	73	23	4	sandy loam	3	75	25	0	75	25	0	Y	2.5Y 6/4	Stream Deposit	Holocene	n/a
3	14.50	35	44	21	loam	4	51	49	0	51	49	0	Y	2.5Y 7/4	Till	QLHS/ QGTA	Winnipeg
4	18.00	45	38	17	loam	5	34	65	1	34	66	0	Y	2.5Y 6/2	Till	QLHS/ QGTA	Winnipeg
5	21.00	53	35	12	sandy loam	9	51	48	0	51	48	0	Y	2.5Y 7/4	Till	QLHS/ QGTA	Winnipeg
6	26.25	36	35	29	clay loam	4	52	45	3	52	46	2	Y	10YR 7/1	Till	QGTB	Winnipeg
7	29.75	36	42	22	loam	9	41	56	2	41	58	1	Y	5Y 6/1	Till	QGTB	Winnipeg
8	33.00	35	38	27	clay loam - loam	4	45	51	4	45	52	3	Y	5Y 5/2	Till	QGTB	Winnipeg
9	39.00	35	37	28	clay loam	5	45	51	5	45	53	3	Y	5Y 6/2	Till	QGTB	Winnipeg
10	41.00	93	1	6	sand	36	41	59	0	41	59	0	Y	5Y 8/3	Glaciofluvial	QGTC	Winnipeg
11	43.00	34	37	29	clay loam	7	50	45	5	50	48	2	Y	5Y 5/2	Till	QGTC	Winnipeg
12	46.00	35	38	27	clay loam - loam	14	41	54	4	42	57	2	Y	5Y 5/2	Till	QGTC	Winnipeg
13	52.00	33	37	30	clay loam	8	55	40	4	56	42	2	Y	5Y 6/2	Till	QGTC	Winnipeg
14	57.00	36	38	26	loam	12	42	54	4	42	55	3	Y	5Y 6/2	Till	QGTC	Winnipeg
15	62.00	31	42	27	clay loam - loam	3	38	59	3	38	60	2	Y	5Y 5/2	Till	QGTC	Winnipeg
16	67.00	37	39	24	loam	7	45	53	1	45	54	1	Y	5Y 5/2	Till	QGTC	Winnipeg
17	73.00	36	39	25	loam	8	44	54	3	44	55	1	Y	5Y 5/3	Till	QGTC	Winnipeg
18	78.00	33	39	28	clay loam	7	41	55	4	41	58	1	Y	5Y 5/3	Till	QGTC	Winnipeg
19	82.50	32	40	28	clay loam	6	37	63	0	37	63	0	Y	2.5Y 6/2	Till	QGTC	Winnipeg
20	86.00	33	43	24	loam	6	36	60	3	36	61	2	Y	2.5Y 6/2	Till	QGTC	Winnipeg
22	87.25	34	42	24	loam	0	8	92	0	8	92	0	Y	5Y 4/2	Glaciolacustrine	QGTC	Winnipeg
21	89.00	30	43	27	clay loam - loam	5	46	48	5	46	50	4	Y	5Y 4/2	Till	QGTC	Winnipeg
23	93.00	31	43	26	loam	4	40	54	6	40	56	4	Y	5Y 4/2	Till	QGTC	Winnipeg
24	97.00	29	43	28	clay loam	13	37	58	5	37	60	3	Y	5Y 4/2	Till	QGTC	Winnipeg
25	99.00	33	44	23	loam	8	39	52	8	39	55	6	Y	5Y 4/2	Till	QGTC	Winnipeg
26	103.00	32	45	23	loam	4	44	47	9	44	50	6	Y	5Y 4/2	Till	QGTC	Winnipeg
27	107.50	38	39	23	loam	3	50	46	4	50	48	2	Y	5Y 4/2	Till	QGTC	Winnipeg
28	109.25	49	35	16	loam	25	38	49	13	38	56	6	Y	5Y 4/2	Till	QGTC	Winnipeg
29	113.00	50	34	16	loam	7	40	49	10	40	54	6	Y	5Y 4/2	Till	QGTC	Winnipeg
30	114.50	42	35	23	loam	3	42	50	8	43	53	4	Y	5Y 4/2	Till	QGTC	Winnipeg
31	117.00	86	10	4	loamy sand	0	46	46	9	46	47	7	Y	5Y 4/2	Glaciofluvial	QGTC	Winnipeg
32	118.00	35	38	27	clay loam - loam	6	47	40	12	48	45	7	Y	5Y 4/2	Till	QGTC	Winnipeg
33	121.00	35	37	28	clay loam	3	50	43	7	51	45	4	Y	5Y 4/2	Till	QGTC	Winnipeg
34	123.50	36	37	27	clay loam - loam	3	52	41	7	52	43	5	Y	5Y 4/2	Till	QGTC	Winnipeg
35	127.50	36	38	26	loam	2	48	47	4	48	50	1	Y	5Y 4/2	Till	QGTC	Winnipeg
36	130.00	36	36	28	clay loam	15	47	50	3	47	52	2	Y	5Y 4/2	Till	QGTC	Winnipeg

38	135.00	34	41	25	loam	3	54	44	2	54	44	2	Y	5Y 4/2	Till	QGTC	Winnipeg
38	140.00	34	39	27	clay loam - loam	7	49	49	2	49	51	0	Y	5Y 4/2	Till	QGTC	Winnipeg
39	141.75	29	40	31	clay loam	3	40	59	1	40	59	0	Y	5Y 5/6	Till	QGTC	Winnipeg
40	143.25	34	36	30	clay loam	4	47	48	5	47	50	3	Y	5Y 4/2	Till	QGTC	Winnipeg
41	146.00	33	41	26	loam	2	48	47	5	48	49	3	Y	5Y 4/2	Till	QGTC	Winnipeg
42	150.00	34	41	25	loam	3	46	51	3	46	53	1	Y	5Y 4/2	Till	QGTC	Winnipeg
43	153.00	78	17	5	loamy sand	0	27	73	0	27	73	0	Y	5Y 5/3	Glaciofluvial	QGTC	Winnipeg
44	155.00	41	41	18	loam	2	48	45	7	48	50	2	Y	5Y 4/2	Till	QGTC	Winnipeg
45	157.00	48	29	23	loam	4	44	45	10	44	52	4	Y	5Y 4/2	Till	QGTC	Winnipeg
46	160.00	28	46	26	loam	4	53	44	2	53	44	2	Y	5Y 5/3	Till	QGTD	Winnipeg
47	161.25	88	12	0	sand	1	34	60	6	34	60	6	Y	2.5Y 6/4	Glaciofluvial	QGTD	Winnipeg
48	163.00	26	50	24	silt loam - loam	8	46	51	3	46	52	1	Y	5Y 5/3	Till	QGTD	Winnipeg
49	164.00	20	51	29	silty clay loam	11	39	58	3	39	59	1	Y	5Y 5/3	Till	QGTD	Winnipeg
50	167.00	12	62	26	silt loam	9	48	49	3	48	51	1	Y	5Y 5/3	Till	QGTD	Winnipeg
51	171.00	18	54	28	silty clay loam	5	46	52	1	46	54	0	Y	5Y 5/3	Till	QGTD	Winnipeg
52	176.00	14	60	26	silt loam	1	45	54	1	45	55	0	Y	5Y 4/2	Till	QGTD	Winnipeg
53	177.00	14	61	25	silt loam	1	45	54	1	45	55	0	Y	5Y 5/3	Till	QGTD	Winnipeg
54	178.00	10	61	29	silty clay loam	5	49	49	2	49	51	0	Y	5Y 4/2	Till	QGTD	Winnipeg
55	179.50	12	58	30	silty clay loam	2	44	55	1	44	56	0	Y	5Y 4/2	Till	QGTD	Winnipeg
56	181.00	7	72	21	silt loam	0	58	38	4	61	39	0	N	10YR 3/2	Glaciolacustrine	QUPS	Rainy?
57	181.50	32	48	20	loam	0	97	3	0	97	3	0	N	5Y 4/2	Glaciolacustrine	QUPS	Rainy?
58	182.75	87	10	3	sand	0	96	4	0	96	4	0	N	5Y 5/3	Glaciofluvial	QUPS	Rainy?
59	186.00	90	9	1	sand	0	92	8	0	92	8	0	N	5Y 5/3	Glaciofluvial	QUPS	Rainy?
60	188.00	8	92	0	silt	1	98	2	0	98	2	0	Y	10YR 4/6	Glaciolacustrine	QUPS	Rainy?
61	192.00	95	5	0	sand	7	94	6	0	94	6	0	Y	10YR 6/8	Glaciofluvial	QUPS	Rainy?
62	198.00	96	3	1	sand	2	84	15	1	84	16	0	Y	10YR 6/8	Glaciofluvial	QUPS	Rainy?
63	203.00	91	5	4	sand	1	87	13	0	87	13	0	Y	10YR 6/8	Glaciofluvial	QUPS	Rainy?
64	206.25	74	23	3	loamy sand	0	95	5	0	95	5	0	Y	10R 5/8	Glaciofluvial	QUPS	Rainy?
65	207.00	92	6	2	sand	1	97	3	1	97	3	0	Y	10YR 5/8	Glaciofluvial	QUPS	Rainy?
66	208.00	93	5	2	sand	5	93	7	0	93	7	0	Y	10YR 4/6	Glaciofluvial	QUPS	Rainy?
67	211.00	90	10	0	sand	8	97	3	0	97	3	0	Y	10YR 6/8	Glaciofluvial	QUPS	Rainy?
68	218.00	93	6	1	sand	16	94	6	0	94	6	0	Y	10YR 6/8	Glaciofluvial	QUPS	Rainy?
69	222.00	97	1	2	sand	0	93	7	0	93	7	0	Y	10YR 7/6	Glaciofluvial	QUPS	Rainy?
70	227.00	95	5	0	sand	33	89	11	0	89	11	0	Y	10YR 6/8	Glaciofluvial	QUPS	Rainy?

HB1-15

Sample	Depth (ft)	Sand %	Silt %	Clay %	USDA Texture	Gravel Fraction	Precambrian %	Paleozoic %	Cretaceous %	Crystalline %	Carbonate %	Shale %	Calcareous	Wet Color	Deposit Type	Formation	Provenance
1	3	88	10	2	sand	13	100	0	0	100	0	0	N	10YR 4/6	Glaciofluvial	QHWU	Winnipeg
2	4	95	3	2	sand	12	100	0	0	100	0	0	N	10YR 5/8	Glaciofluvial	QHWU	Winnipeg
3	6	50	32	18	loam	9	100	0	0	100	0	0	N	2.5Y 5/4	Till	QHWU	Winnipeg
4	11	39	46	15	loam	8	100	0	0	100	0	0	N	2.5Y 5/6	Till	QHWU	Winnipeg
5	14	81	12	7	loamy sand	18	100	0	0	100	0	0	N	2.5Y 5/6	Till	QHWU	Winnipeg
6	20	94	4	2	sand	16	93	7	0	93	7	0	Y	2.5Y 6/8	Glaciofluvial	QHWU	Winnipeg
7	26	95	5	0	sand	1	88	12	0	88	12	0	Y	2.5Y 6/8	Glaciofluvial	QHWU	Winnipeg
8	32	99	1	0	sand	28	91	9	0	91	9	0	Y	2.5Y 7/4	Glaciofluvial	QHWU	Winnipeg
9	37	99	1	0	sand	16	89	11	0	89	11	0	Y	2.5Y 8/6	Glaciofluvial	QHWU	Winnipeg
10	43	98	2	0	sand	3	91	9	0	91	9	0	Y	2.5Y 7/4	Glaciofluvial	QHWU	Winnipeg
11	48	96	4	0	sand	0	95	5	0	95	5	0	Y	2.5Y 8/6	Glaciofluvial	QHWU	Winnipeg
12	54	98	2	0	sand	0	87	13	0	87	13	0	Y	2.5Y 7/2	Glaciofluvial	QHWU	Winnipeg
13	59	93	7	0	sand	1	97	3	0	97	3	0	Y	10YR 6/4	Glaciofluvial	QHWU	Winnipeg
14	65	99	1	0	sand	4	92	8	0	92	8	0	Y	2.5Y 8/4	Glaciofluvial	QHWU	Winnipeg
15	70	89	9	2	sand	0	100	0	0	100	0	0	Y	10YR 7/6	Glaciofluvial	QHWU	Winnipeg
16	75	97	3	0	sand	7	94	6	0	94	6	0	Y	2.5Y 8/4	Glaciofluvial	QHWU	Winnipeg
17	80	98	1	1	sand	0	100	0	0	100	0	0	Y	2.5Y 8/6	Glaciofluvial	QHWU	Winnipeg
18	85	99	1	0	sand	37	96	4	0	96	4	0	Y	10YR 7/6	Glaciofluvial	QHWU	Winnipeg
19	91	98	2	0	sand	0	95	5	0	95	5	0	Y	2.5Y 8/6	Glaciofluvial	QHWU	Winnipeg
20	100	99	1	0	sand	1	90	10	0	90	10	0	Y	2.5Y 8/2	Glaciofluvial	QHWU	Winnipeg
21	103	99	1	0	sand	11	93	7	0	93	7	0	Y	2.5Y 8/2	Glaciofluvial	QHWU	Winnipeg
22	106	70	22	8	sandy loam	4	95	5	0	95	5	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
23	111	73	18	9	sandy loam	3	95	5	0	95	5	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
24	116	70	19	11	sandy loam	8	95	5	0	95	5	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
25	120	70	19	11	sandy loam	7	95	5	0	95	5	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
26	122	64	23	13	sandy loam	5	93	7	0	93	7	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
27	124	73	18	9	sandy loam	8	96	4	0	96	4	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
28	126	78	13	9	sandy loam	11	96	4	0	96	4	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
29	129	71	19	10	sandy loam	5	93	7	0	93	7	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg

30	135	66	21	13	sandy loam	10	95	5	0	95	5	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
31	138	67	23	10	sandy loam	4	94	6	0	94	6	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
32	140	66	22	12	sandy loam	4	94	6	0	94	6	0	Y	10YR 6/2	Till	QHWU	Winnipeg
33	141	68	20	12	sandy loam	11	95	5	0	95	5	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
34	142	51	32	17	loam	4	99	1	0	99	1	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
35	143	49	32	19	loam	6	100	0	0	100	0	0	Y	2.5Y 5/2	Till	QHWU	Winnipeg
36	145	17	73	10	silt loam	4	100	0	0	100	0	0	N	10YR 5/6	Till	QHWU	Winnipeg
37	146	84	10	6	loamy sand	18	100	0	0	100	0	0	N	10YR 5/6	Till	QHWU	Winnipeg
38	148	83	10	7	loamy sand	11	100	0	0	100	0	0	N	10YR 5/8	Till	QHWU	Winnipeg
39	150	71	19	10	sandy loam	3	100	0	0	100	0	0	N	10YR 5/6	Till	QHWU	Winnipeg
40	152	72	16	12	sandy loam	5	100	0	0	100	0	0	N	10YR 5/6	Till	QHWU	Winnipeg
41	156	71	18	11	sandy loam	5	100	0	0	100	0	0	N	10YR 5/6	Till	QHWU	Winnipeg
42	160	66	23	11	sandy loam	11	100	0	0	100	0	0	N	10YR 6/8	Till	QHWU	Winnipeg
43	165	71	19	10	sandy loam	3	100	0	0	100	0	0	N	10YR 6/6	Till	QHWU	Winnipeg
44	170	71	18	11	sandy loam	5	100	0	0	100	0	0	N	10YR 6/6	Till	QHWU	Winnipeg
45	174	73	19	8	sandy loam	5	100	0	0	100	0	0	N	10YR 5/6	Till	QHWU	Winnipeg
46	180	63	28	9	sandy loam	3	100	0	0	100	0	0	N	10YR 5/6	Till	QHWU	Winnipeg
47	181	54	26	20	sandy loam - sandy clay loam	7	99	1	0	99	1	0	N	10YR 5/4	Till	QHWU	Winnipeg
48	182	74	18	8	sandy loam	5	98	2	0	98	2	0	Y	2.5Y 6/8	Till	QHWU	Winnipeg
49	186	73	19	8	sandy loam	5	95	5	0	95	5	0	Y	2.5Y 6/8	Till	QHWU	Winnipeg
50	189	62	26	12	sandy loam	3	96	4	0	96	4	0	Y	2.5Y 5/6	Till	QHWU	Winnipeg
51	194	74	18	8	sandy loam	4	96	4	0	96	4	0	Y	10YR 5/6	Till	QHWU	Winnipeg
52	198	68	22	10	sandy loam	4	97	3	0	97	3	0	Y	2.5Y 6/6	Till	QHWU	Winnipeg
53	202	72	18	10	sandy loam	4	94	6	0	94	6	0	Y	2.5Y 6/4	Till	QHWU	Winnipeg
54	205	73	19	8	sandy loam	4	98	2	0	98	2	0	Y	10YR 6/6	Till	QHWU	Winnipeg
55	207	76	15	9	sandy loam	7	93	7	0	93	7	0	Y	2.5Y 5/6	Till	QHWU	Winnipeg
56	208	31	45	24	loam	0	100	0	0	100	0	0	N	2.5Y 5/2	Glaciolacustrine	QBVU	Winnipeg
57	209	76	14	10	sandy loam	0	100	0	0	100	0	0	N	2.5Y 5/4	Glaciolacustrine	QBVU	Winnipeg
58	211	72	16	12	sandy loam	0	90	10	0	90	10	0	N	2.5Y 5/4	Glaciolacustrine	QBVU	Winnipeg
59	215	96	4	0	sand	1	98	2	0	98	2	0	N	2.5Y 7/4	Glaciolacustrine	QBVU	Winnipeg
60	220	100	0	0	sand	9	100	0	0	100	0	0	N	5Y 7/6	Glaciofluvial	QBVU	Winnipeg

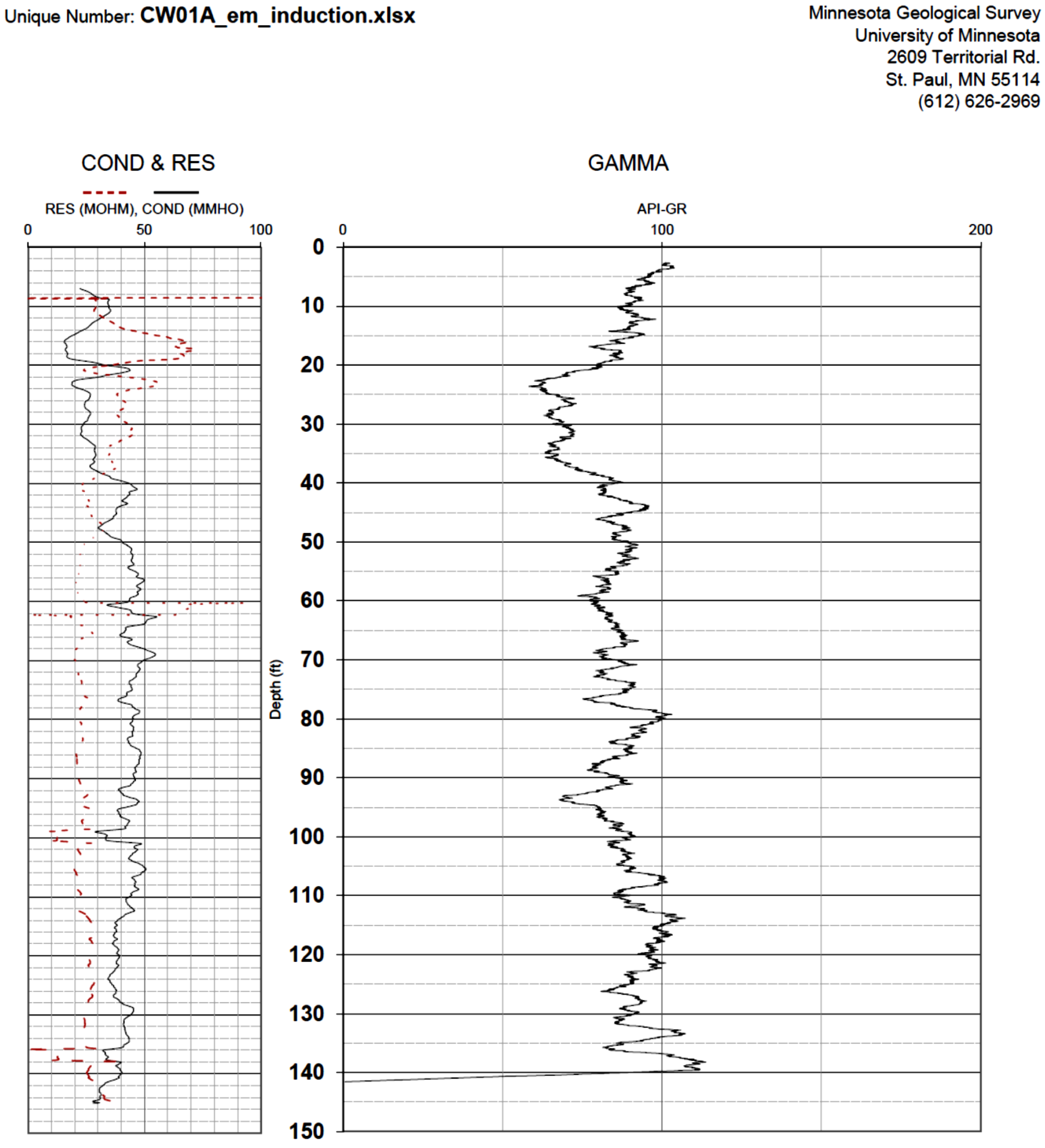
61	225	100	0	0	sand	17	80	19	1	80	20	0	Y	2.5Y 7/2	Glaciofluvial	QBVU	Winnipeg
62	229	89	7	4	sand	5	72	24	4	72	27	1	Y	10YR 4/2	Glaciofluvial	QBVU	Winnipeg
63	230	41	44	15	loam	7	55	26	19	56	33	10	Y	10YR 4/1	Till	QBVU	Winnipeg
64	231	27	42	31	clay loam	3	61	24	16	61	30	9	Y	10YR 4/1	Till	QBVU	Winnipeg
65	236	31	43	26	loam	3	51	25	24	51	32	17	Y	10YR 4/1	Till	QBVU	Winnipeg
66	240	35	42	23	loam	5	57	27	16	57	34	9	Y	10YR 4/1	Till	QBVU	Winnipeg
67	241	31	38	31	clay loam	2	61	26	13	62	33	5	Y	10YR 4/1	Till	QBVU	Winnipeg
68	246	36	38	26	loam	4	60	26	14	60	35	5	Y	10YR 4/1	Till	QBVU	Winnipeg
69	250	25	44	31	clay loam	3	49	22	29	49	34	16	Y	10YR 4/1	Till	QBVU	Winnipeg
70	251	52	40	8	loam	2	56	43	1	56	43	1	Y	2.5Y 6/2	Till	QLHS	Winnipeg
71	251	97	3	0	sand	5	68	32	0	68	32	0	Y	2.5Y 7/4	Slough	QLHS	Winnipeg
72	253	45	41	14	loam	2	65	35	0	65	35	0	Y	2.5Y 5/2	Till	QLHS	Winnipeg
73	255	44	44	12	loam	2	60	40	0	60	40	0	Y	2.5Y 5/2	Till	QLHS	Winnipeg
74	259	33	50	17	silt loam - loam	1	61	36	3	61	37	2	Y	2.5Y 5/2	Till	QLHS	Winnipeg
75	263	13	69	18	silt loam	0	59	40	2	59	41	0	Y	10YR 3/3	Till	QLHS	Winnipeg
76	266	11	71	18	silt loam	0	64	33	3	64	33	3	Y	10YR 3/3	Glaciolacustrine	QLHS	Winnipeg
77	270	0	78	22	silt loam	0	-	-	-	-	-	-	Y	10YR 4/3	Glaciolacustrine	QLHS	Winnipeg
78	276	94	6	0	sand	0	100	0	0	100	0	0	Y	10YR 6/6	Glaciolacustrine	QLHS	Winnipeg
79	278	93	7	0	sand	0	78	22	0	78	22	0	Y	10YR 6/6	Glaciolacustrine	QLHS	Winnipeg
80	284	93	7	0	sand	0	46	54	0	46	54	0	Y	10YR 6/6	Glaciolacustrine	QLHS	Winnipeg
81	286	33	50	17	silt loam - loam	8	47	53	0	47	53	0	Y	2.5Y 6/4	Till	QLHS	Winnipeg
82	289	39	44	17	loam	4	53	46	1	53	47	0	Y	2.5Y 6/4	Till	QLHS	Winnipeg
83	294	38	43	19	loam	4	55	44	0	55	45	0	Y	2.5Y 6/4	Till	QLHS	Winnipeg
84	296	39	42	19	loam	4	49	51	0	49	51	0	Y	2.5Y 5/2	Till	QLHS	Winnipeg
85	302	38	42	20	loam	8	51	49	0	51	49	0	Y	-	Till	QLHS	Winnipeg
86	306	45	38	17	loam	5	59	40	1	59	41	1	Y	-	Till	QLHS	Winnipeg
87	310	33	47	20	loam	2	50	50	0	50	50	0	Y	2.5Y 5/2	Till	QLHS	Winnipeg
88	314	32	52	16	silt loam	2	70	29	1	70	29	1	Y	2.5Y 5/4	Till	QLHM	Winnipeg
89	321	41	29	30	clay loam	0	63	37	0	63	37	0	Y	7.5YR 5/6	Glaciolacustrine	QLHM	Winnipeg
90	330	28	53	19	silt loam	3	84	15	1	85	15	0	Y	10YR 5/4	Till	QLHM	Winnipeg
91	337	34	46	20	loam	2	66	34	0	66	34	0	Y	2.5Y 5/2	Till	QLHM	Winnipeg
92	339	37	40	23	loam	4	63	36	1	63	37	0	Y	2.5Y 5/2	Till	QLHM	Winnipeg

93	346	37	42	21	loam	4	61	39	0	61	39	0	Y	2.5Y 5/2	Till	QLHM	Winnipeg
94	346	37	40	23	loam	3	65	35	0	65	35	0	Y	2.5Y 5/2	Till	QLHM	Winnipeg
95	349	33	41	26	loam	4	67	32	1	67	33	0	Y	2.5Y 5/2	Till	QLHM	Winnipeg
96	353	33	44	23	loam	2	50	49	1	50	50	0	Y	2.5Y 5/2	Till	QLHM	Winnipeg
97	357	29	45	26	loam	2	52	48	0	52	48	0	Y	2.5Y 5/2	Till	QLHM	Winnipeg
98	360	54	35	11	sandy loam	13	90	9	1	90	9	0	Y	10YR 3/3	Till	QSTF	Superior
99	361	83	15	2	loamy sand	9	89	10	1	89	10	0	Y	10YR 5/6	Glaciofluvial	QSTF	Superior
100	362	49	31	20	loam	12	93	7	0	93	7	0	Y	10YR 4/3	Till	QSTF	Superior
101	366	47	28	25	loam	5	84	16	0	84	16	0	Y	10YR 4/3	Till	QSTF	Superior
102	370	42	32	26	loam	7	83	15	2	83	16	0	Y	10YR 4/3	Till	QSTF	Superior
103	374	44	31	25	loam	4	89	9	2	89	10	1	Y	10YR 4/3	Till	QSTF	Superior
104	379	42	31	27	clay loam - loam	8	86	13	1	86	14	0	Y	10YR 4/3	Till	QSTF	Superior
105	381	41	31	28	clay loam	9	84	15	0	84	16	0	Y	10YR 4/3	Till	QSTF	Superior
106	385	45	34	21	loam	5	86	13	1	86	13	1	Y	10YR 4/3	Till	QSTF	Superior
107	388	40	41	19	loam	6	84	14	2	84	16	0	Y	10YR 4/3	Till	QSTF	Superior
108	390	93	5	2	sand	0	91	9	0	91	9	0	Y	2.5Y 6/6	Glaciolacustrine	QELU	Winnipeg
109	395	90	8	2	sand	0	-	-	-	-	-	-	Y	2.5Y 6/8	Glaciolacustrine	QELU	Winnipeg
110	400	95	1	4	sand	0	57	0	43	100	0	0	Y	2.5Y 5/6	Glaciolacustrine	QELU	Winnipeg
111	403	95	3	2	sand	0	-	-	-	-	-	-	Y	2.5Y 7/8	Glaciolacustrine	QELU	Winnipeg
112	406	3	85	12	silt loam	0	-	-	-	-	-	-	Y	10YR 4/2	Glaciolacustrine	QELU	Winnipeg
113	410	1	67	32	silty clay loam	0	-	-	-	-	-	-	Y	10YR 4/2	Glaciolacustrine	QELU	Winnipeg
114	415	1	35	64	clay	0	-	-	-	-	-	-	Y	10YR 4/2	Glaciolacustrine	QELU	Winnipeg
115	419	1	23	76	clay	0	-	-	-	-	-	-	Y	2.5Y 4/2	Glaciolacustrine	QELU	Winnipeg
116	423	1	17	82	clay	0	100	0	0	100	0	0	Y	2.5Y 4/2	Glaciolacustrine	QELU	Winnipeg
117	427	1	24	75	clay	0	-	-	-	-	-	-	Y	2.5Y 4/2	Glaciolacustrine	QELU	Winnipeg
118	431	3	69	28	silty clay loam	0	-	-	-	-	-	-	Y	10YR 3/2	Glaciolacustrine	QELU	Winnipeg
119	436	3	79	18	silt loam	0	100	0	0	100	0	0	Y	10YR 3/2	Glaciolacustrine	QELU	Winnipeg
120	440	8	68	24	silt loam	1	74	17	9	78	22	0	Y	10YR 3/2	Glaciolacustrine	QELU	Winnipeg
121	441	40	36	24	loam	8	76	15	9	77	22	1	Y	2.5Y 3/2	Till	QELU	Winnipeg
122	445	49	30	21	loam	5	89	9	2	91	9	0	Y	2.5Y 4/2	Till	QELU	Winnipeg
123	449	45	30	25	loam	5	91	8	1	92	8	0	Y	2.5Y 4/2	Till	QELU	Winnipeg

124	452	50	29	21	loam	3	92	7	1	92	7	0	Y	2.5Y 4/2	Till	QELU	Winnipeg
125	456	46	30	24	loam	7	89	10	2	90	10	0	Y	2.5Y 4/2	Till	QELU	Winnipeg
126	460	38	32	30	clay loam	6	87	12	1	87	12	0	Y	2.5Y 4/2	Till	QELU	Winnipeg
127	464	46	32	22	loam	5	90	8	2	90	10	0	Y	2.5Y 4/2	Till	QELU	Winnipeg
128	467	46	29	25	loam	5	91	7	2	92	8	0	Y	2.5Y 5/2	Till	QELU	Winnipeg
129	471	4	84	12	silt loam	1	95	4	1	95	5	0	Y	2.5Y 5/2	Glaciolacustrine	QELU	Winnipeg
130	474	51	30	19	loam	6	94	5	1	94	5	0	Y	2.5Y 5/2	Till	QELU	Winnipeg
131	476	2	45	53	-	0	100	0	0	100	0	0	N	2.5Y 3/2	Bedrock		

Appendix B. Borehole geophysical logs.

EM Induction Log – CW01A



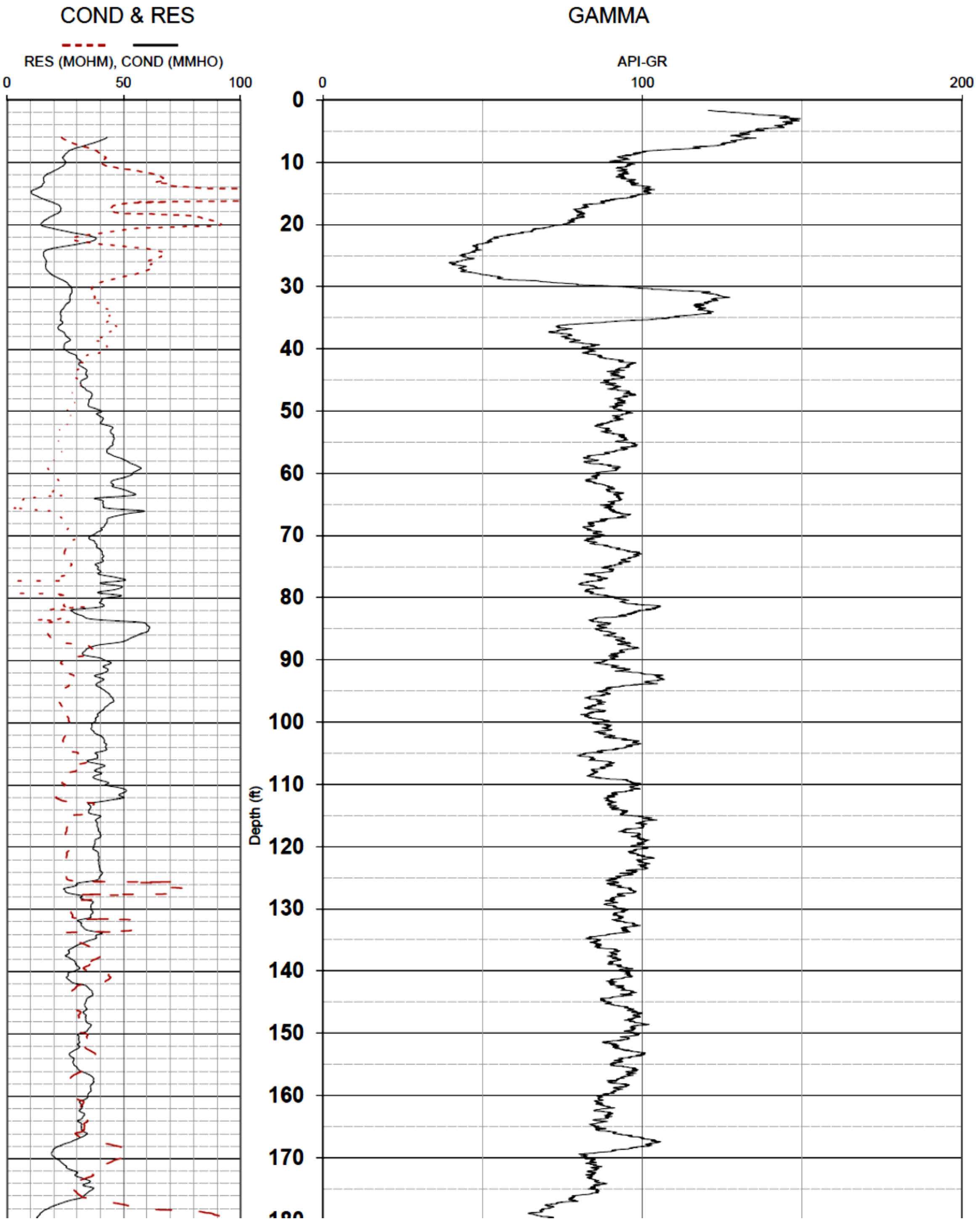
Unique Number: **CW01A_em_induction.xlsx**

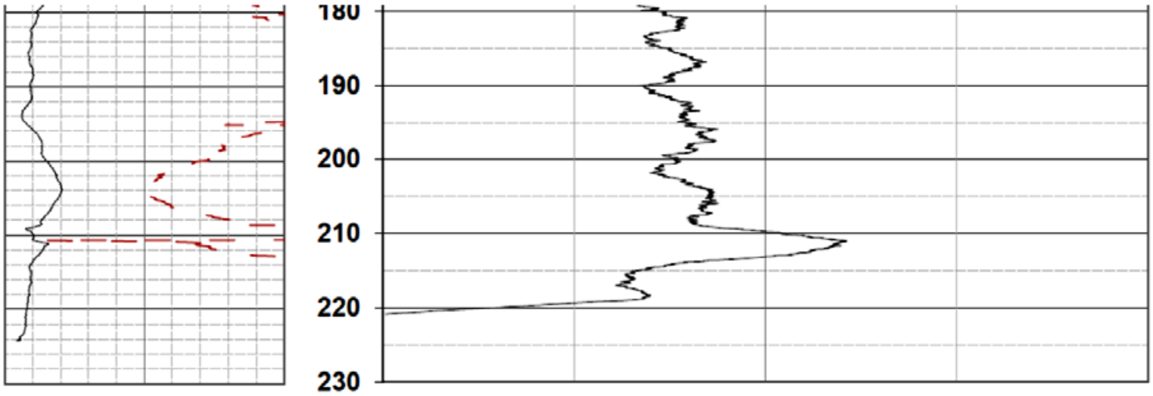
Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969

EM Induction Log – CW01B

Unique Number: **CW01B_em_induction.xlsx**

Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969

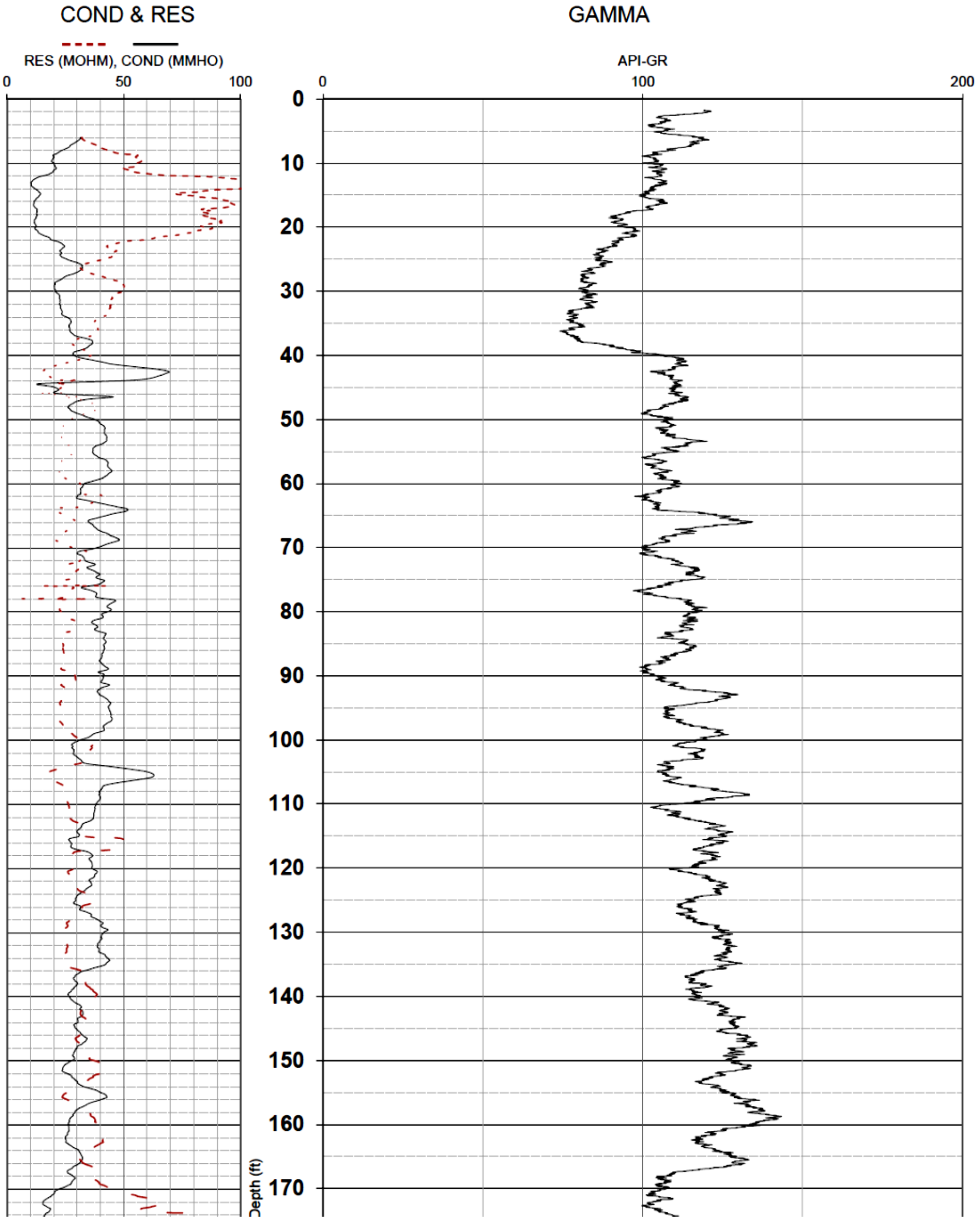


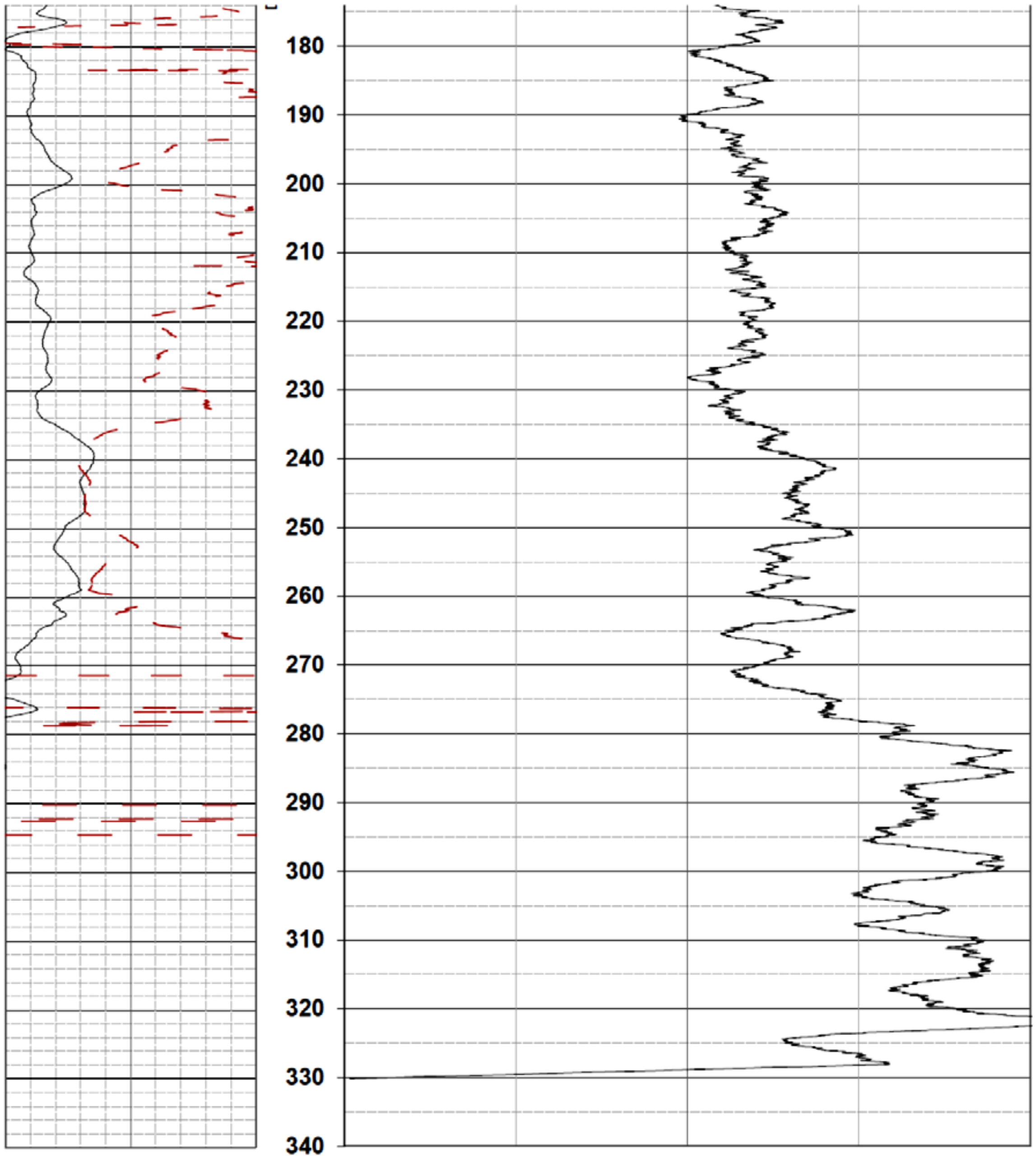

180
190
200
210
220
230

EM Induction Log – CW01C

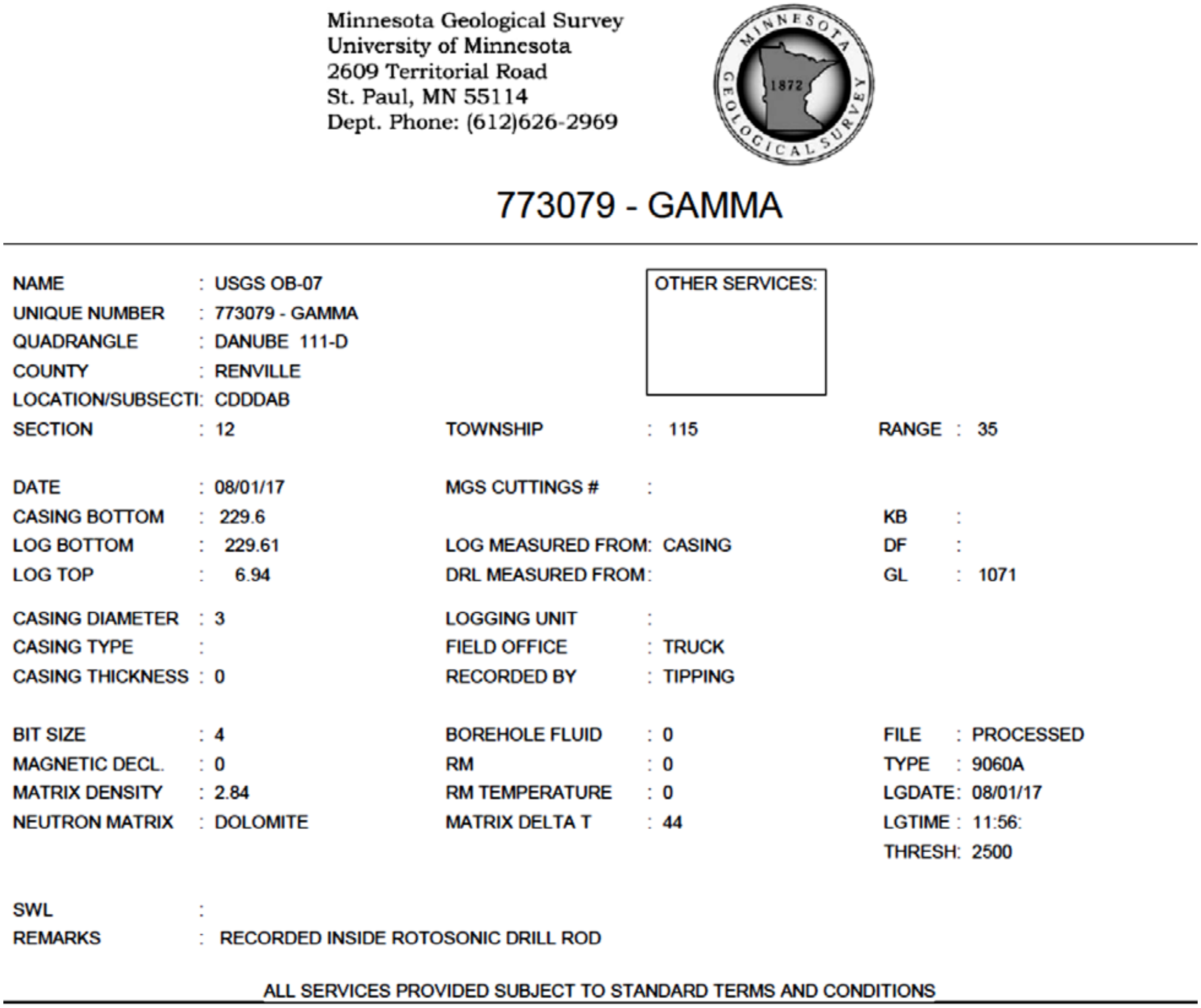
Unique Number: **CW01C_em_induction.xlsx**

Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969




180
190
200
210
220
230
240
250
260
270
280
290
300
310
320
330
340

Gamma, spontaneous potential and resistivity logs – MN OB-7

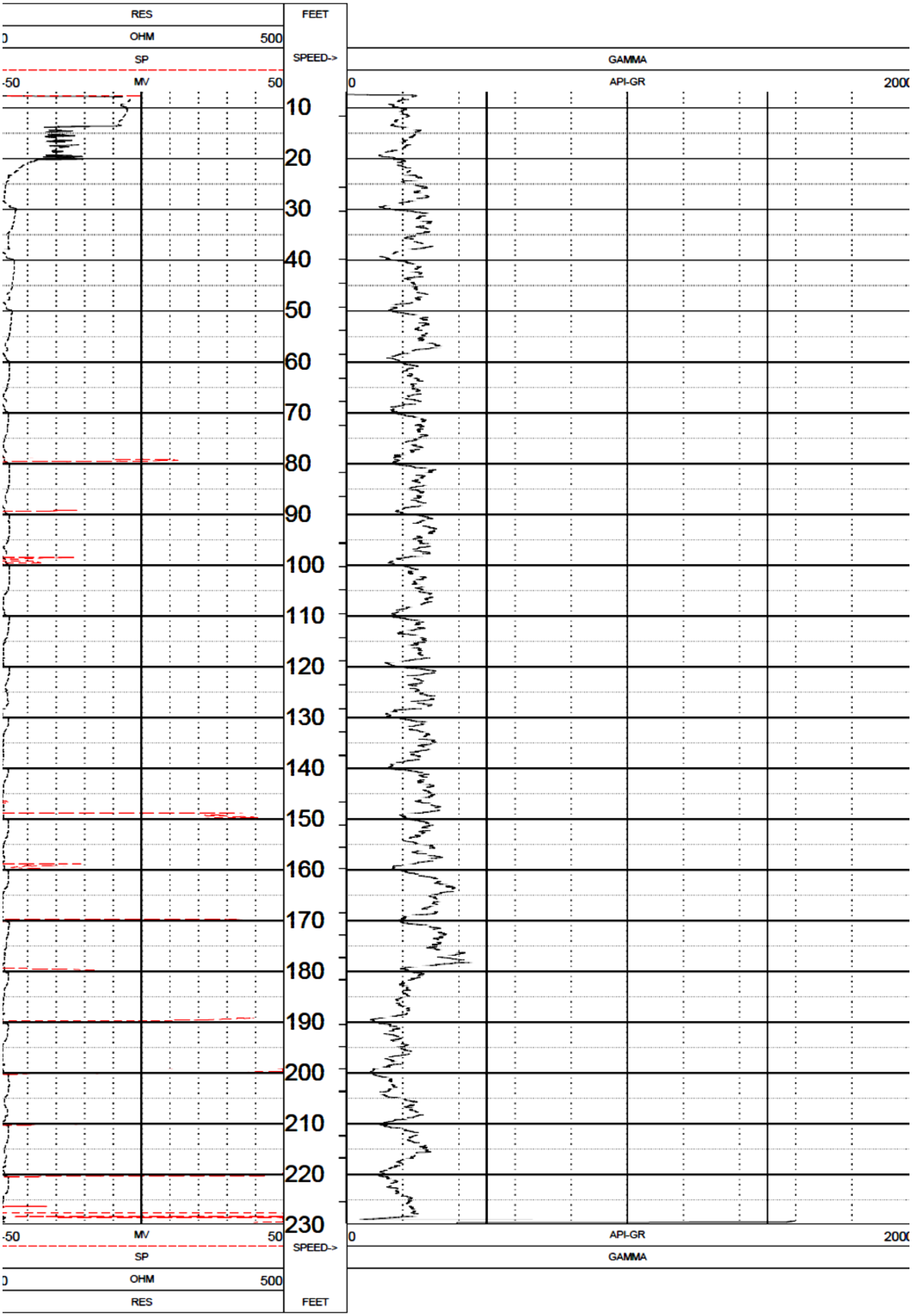


Minnesota Geological Survey
University of Minnesota
2609 Territorial Road
St. Paul, MN 55114
Dept. Phone: (612)626-2969

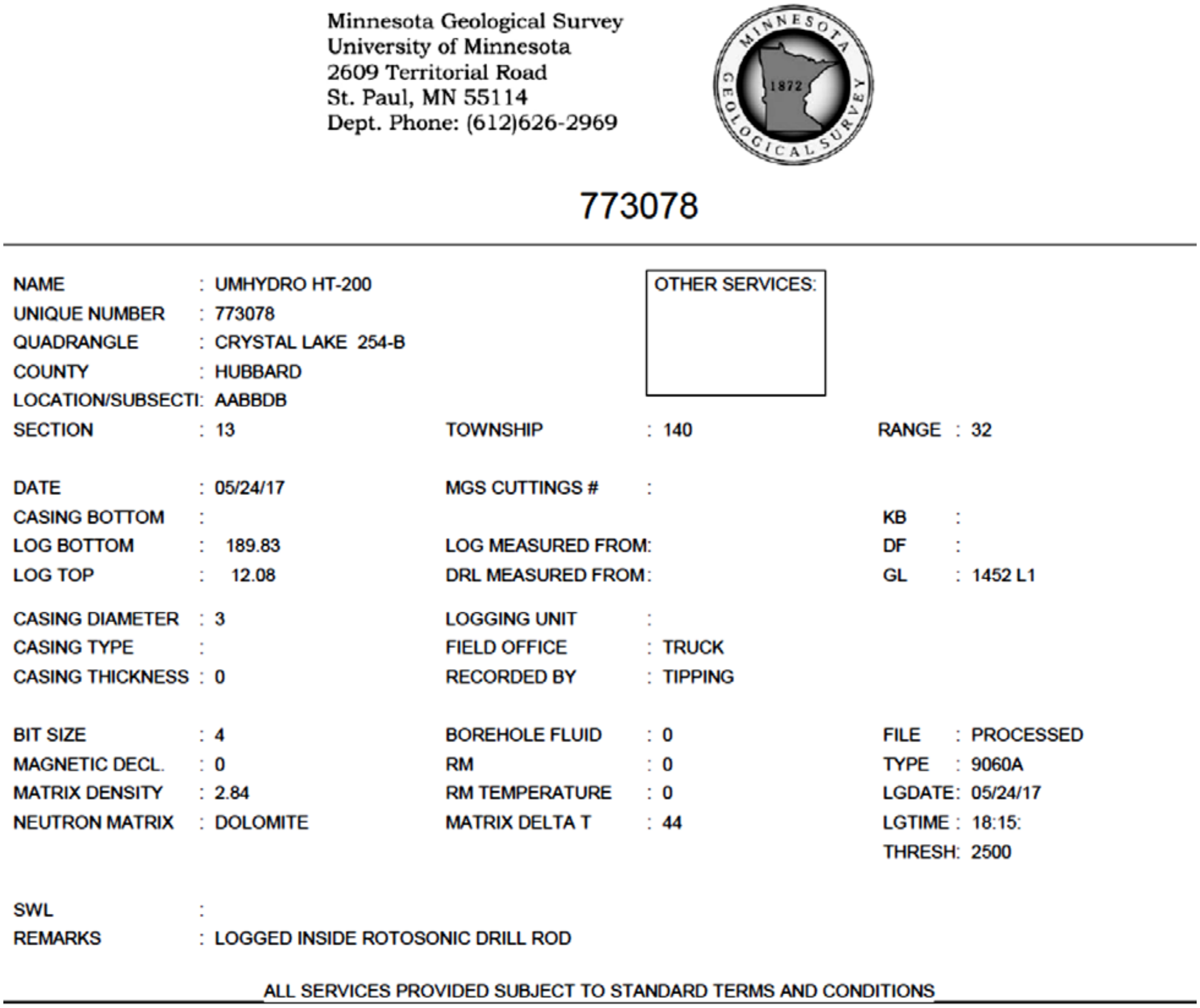
773079 - GAMMA

NAME	: USGS OB-07	OTHER SERVICES:			
UNIQUE NUMBER	: 773079 - GAMMA				
QUADRANGLE	: DANUBE 111-D				
COUNTY	: RENVILLE				
LOCATION/SUBSECTI:	CDDDAB				
SECTION	: 12	TOWNSHIP	: 115	RANGE	: 35
DATE	: 08/01/17	MGS CUTTINGS #	:		
CASING BOTTOM	: 229.6			KB	:
LOG BOTTOM	: 229.61	LOG MEASURED FROM:	CASING	DF	:
LOG TOP	: 6.94	DRL MEASURED FROM:		GL	: 1071
CASING DIAMETER	: 3	LOGGING UNIT	:		
CASING TYPE	:	FIELD OFFICE	: TRUCK		
CASING THICKNESS	: 0	RECORDED BY	: TIPPING		
BIT SIZE	: 4	BOREHOLE FLUID	: 0	FILE	: PROCESSED
MAGNETIC DECL.	: 0	RM	: 0	TYPE	: 9060A
MATRIX DENSITY	: 2.84	RM TEMPERATURE	: 0	LGDATE:	08/01/17
NEUTRON MATRIX	: DOLOMITE	MATRIX DELTA T	: 44	LGTIME :	11:56:
				THRESH:	2500
SWL	:				
REMARKS	: RECORDED INSIDE ROTOSONIC DRILL ROD				

ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS


RES
OHM
0
500
SP
-50
MV
50
FEET
SPEED->
GAMMA
API-GR
0
200
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230

Gamma, spontaneous potential and resistivity logs – HT-200

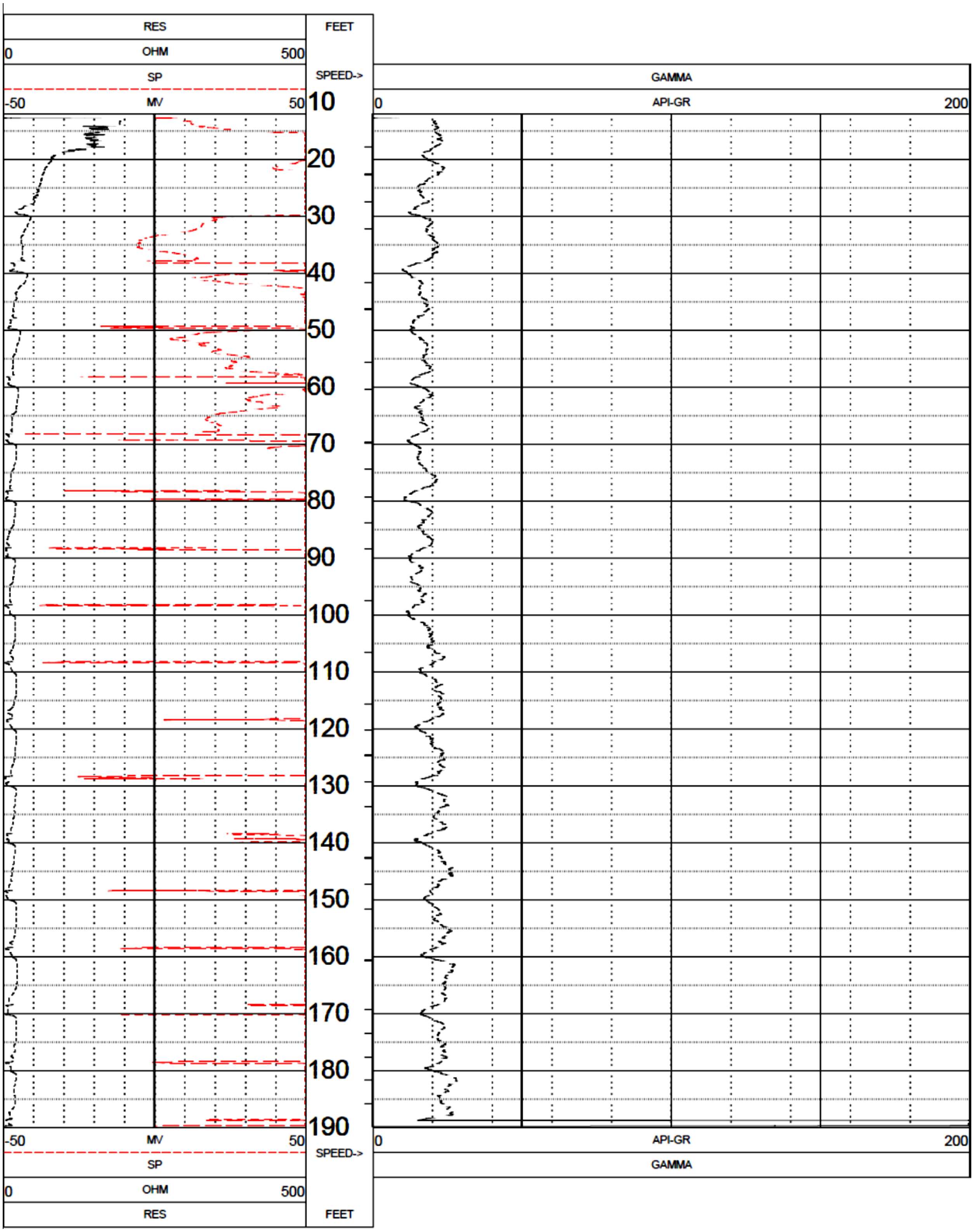


Minnesota Geological Survey
University of Minnesota
2609 Territorial Road
St. Paul, MN 55114
Dept. Phone: (612)626-2969

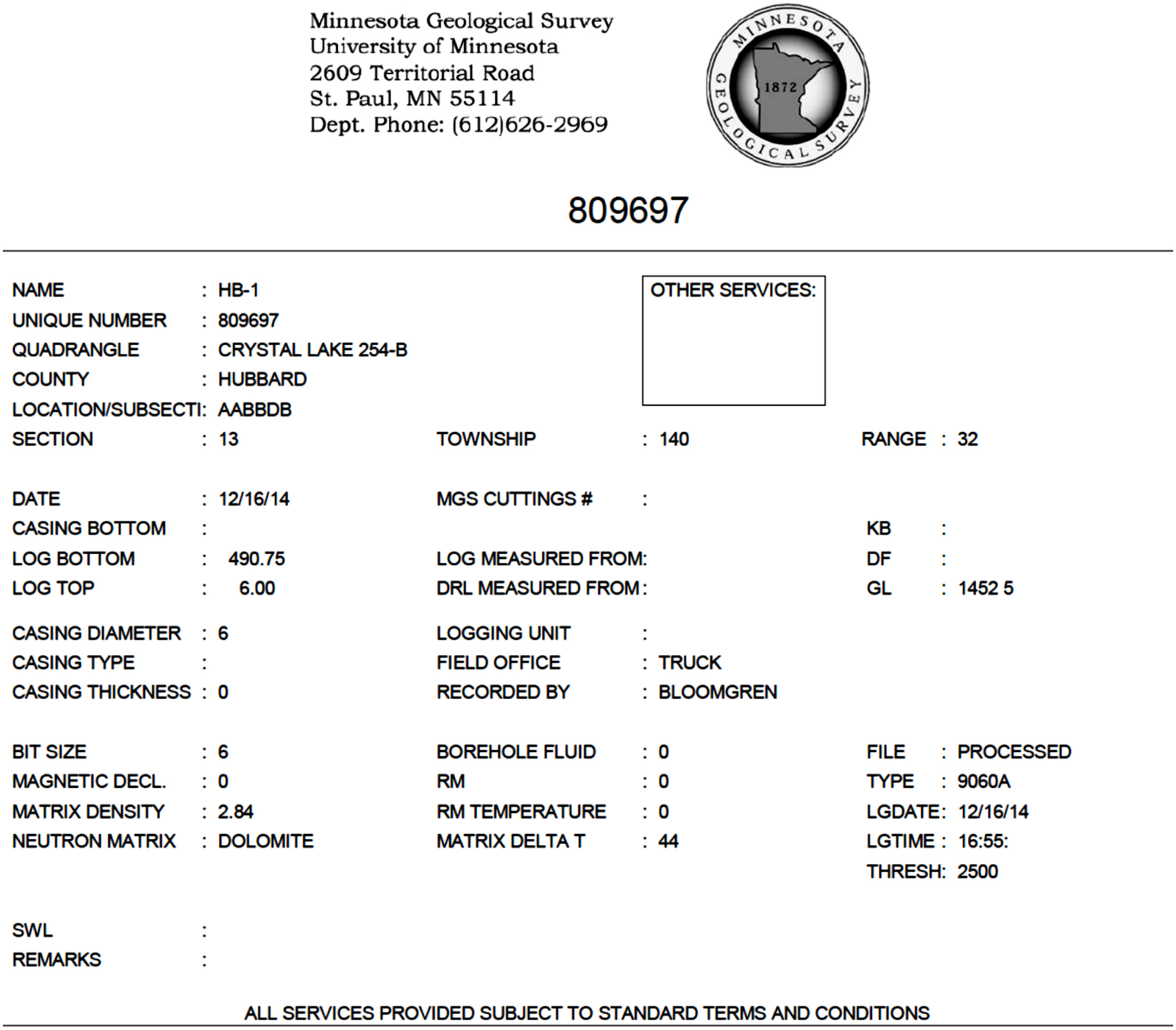
773078

NAME	: UMHYDRO HT-200	OTHER SERVICES:			
UNIQUE NUMBER	: 773078				
QUADRANGLE	: CRYSTAL LAKE 254-B				
COUNTY	: HUBBARD				
LOCATION/SUBSECTI:	AABBDB				
SECTION	: 13	TOWNSHIP	: 140	RANGE	: 32
DATE	: 05/24/17	MGS CUTTINGS #	:		
CASING BOTTOM	:			KB	:
LOG BOTTOM	: 189.83	LOG MEASURED FROM:		DF	:
LOG TOP	: 12.08	DRL MEASURED FROM:		GL	: 1452 L1
CASING DIAMETER	: 3	LOGGING UNIT	:		
CASING TYPE	:	FIELD OFFICE	: TRUCK		
CASING THICKNESS	: 0	RECORDED BY	: TIPPING		
BIT SIZE	: 4	BOREHOLE FLUID	: 0	FILE	: PROCESSED
MAGNETIC DECL.	: 0	RM	: 0	TYPE	: 9060A
MATRIX DENSITY	: 2.84	RM TEMPERATURE	: 0	LGDATE:	05/24/17
NEUTRON MATRIX	: DOLOMITE	MATRIX DELTA T	: 44	LGTIME :	18:15:
				THRESH:	2500
SWL	:				
REMARKS	: LOGGED INSIDE ROTOSONIC DRILL ROD				

ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS


RES
FEET
0
OHM
500
SP
SPEED->
-50
MV
50
GAMMA
0
API-GR
200
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
-50
MV
50
SPEED->
0
API-GR
200
GAMMA
SP
0
OHM
500
RES
FEET

Gamma, spontaneous potential and resistivity logs –HB1-15

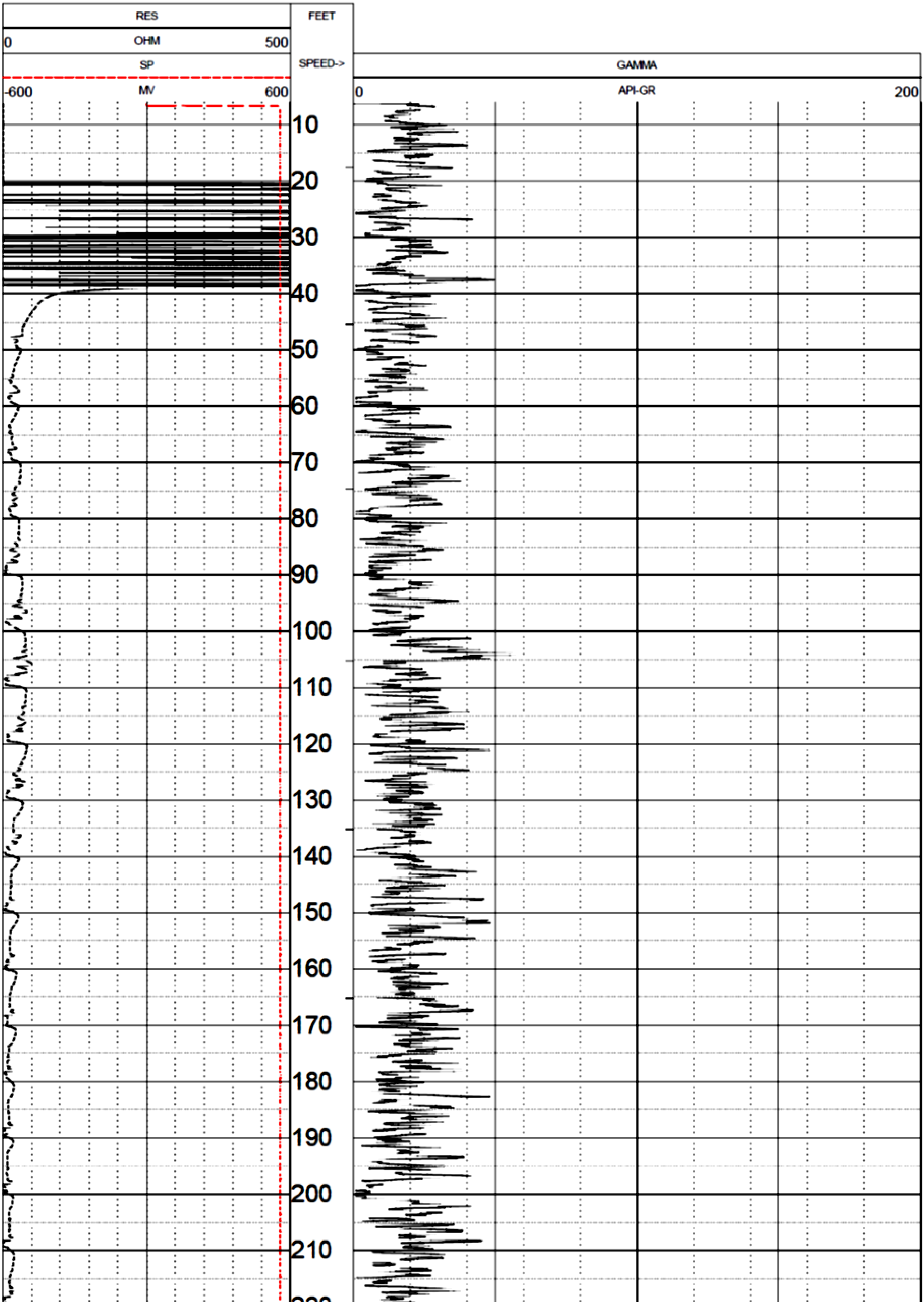


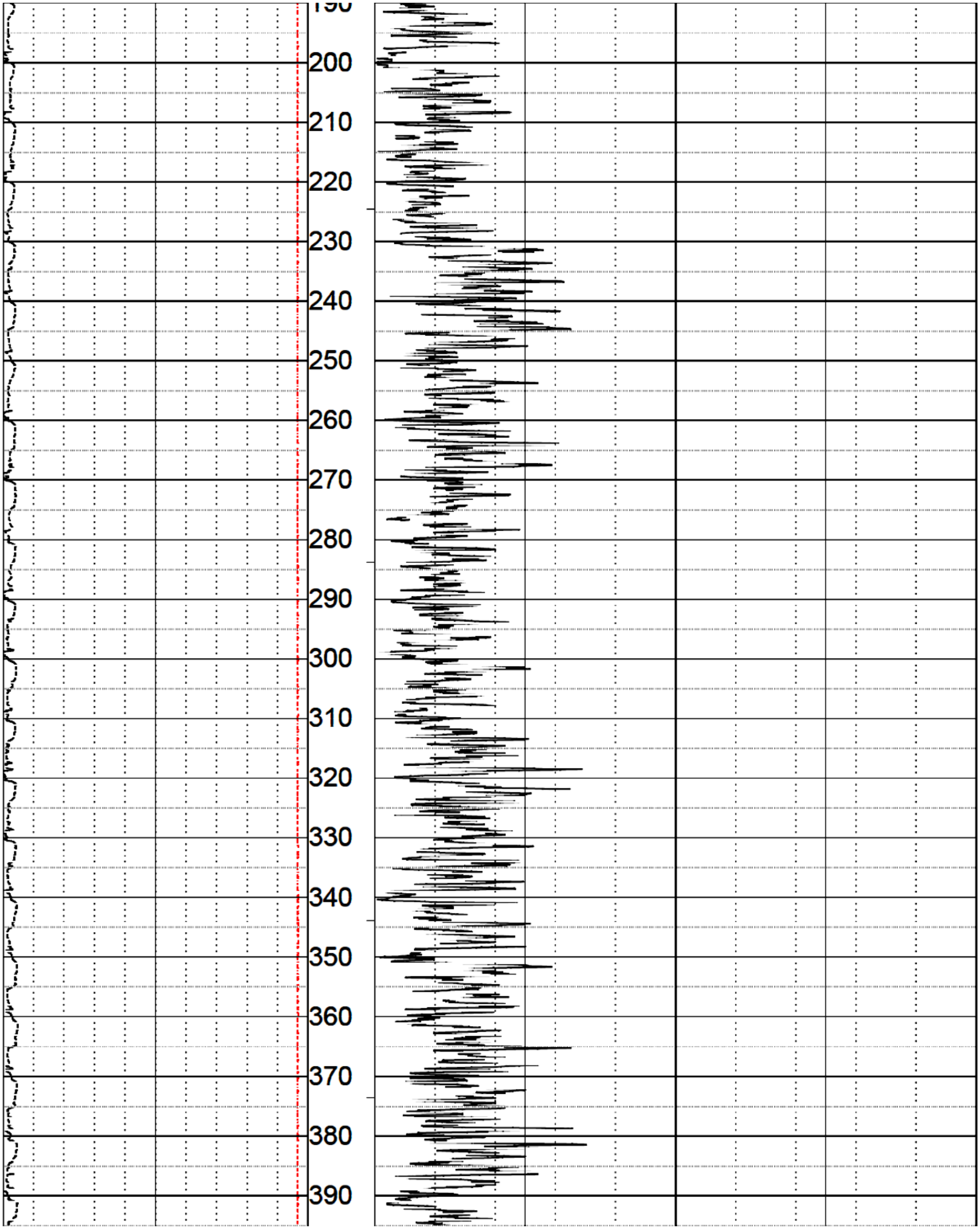
Minnesota Geological Survey
University of Minnesota
2609 Territorial Road
St. Paul, MN 55114
Dept. Phone: (612)626-2969

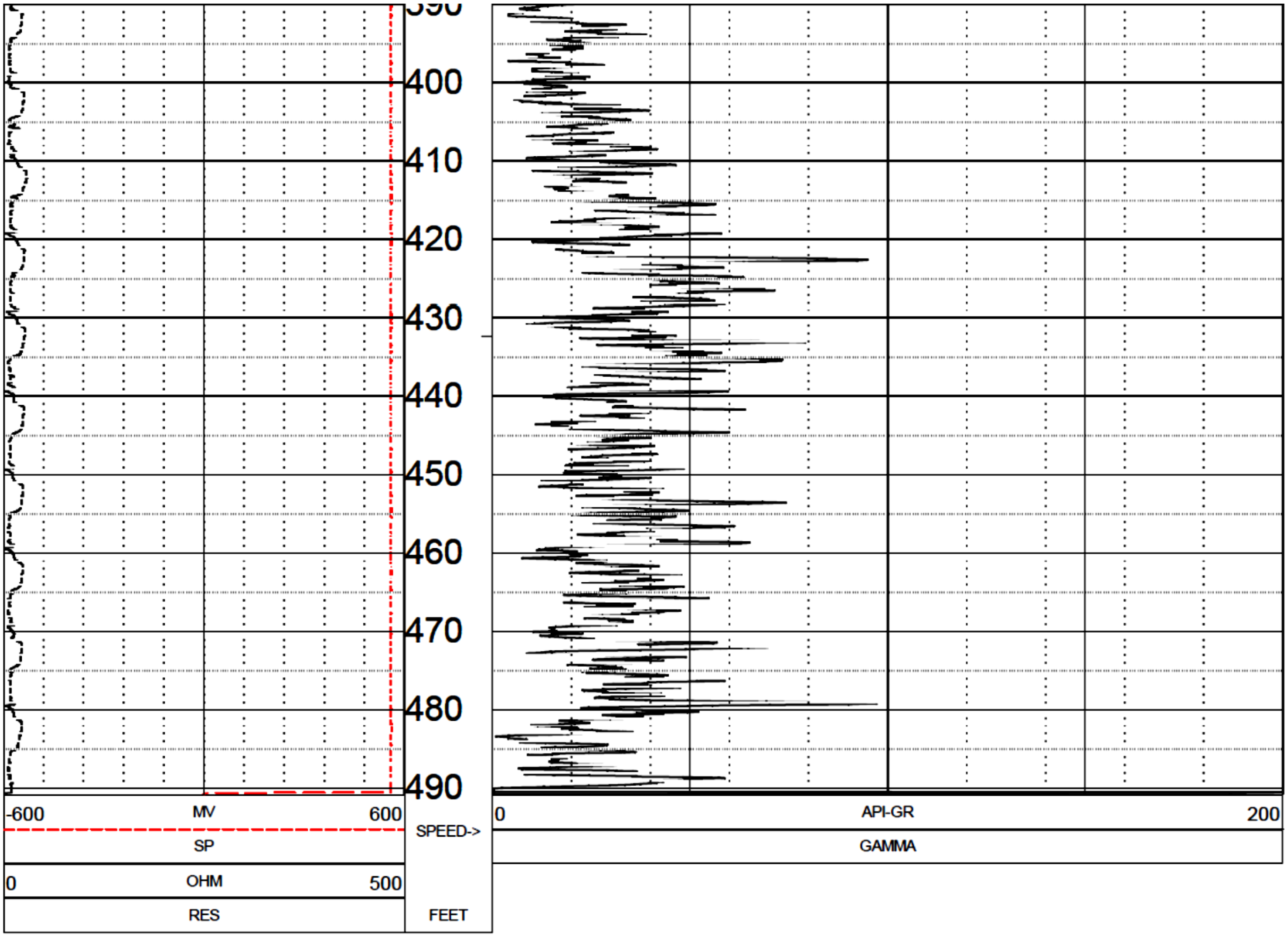
809697

NAME	:	HB-1				OTHER SERVICES:	
UNIQUE NUMBER	:	809697					
QUADRANGLE	:	CRYSTAL LAKE 254-B					
COUNTY	:	HUBBARD					
LOCATION/SUBSECTI:		AABBDB					
SECTION	:	13	TOWNSHIP	:	140	RANGE :	32
DATE	:	12/16/14	MGS CUTTINGS #	:			
CASING BOTTOM	:					KB :	
LOG BOTTOM	:	490.75	LOG MEASURED FROM:			DF :	
LOG TOP	:	6.00	DRL MEASURED FROM:			GL :	1452 5
CASING DIAMETER	:	6	LOGGING UNIT	:			
CASING TYPE	:		FIELD OFFICE	:	TRUCK		
CASING THICKNESS	:	0	RECORDED BY	:	BLOOMGREN		
BIT SIZE	:	6	BOREHOLE FLUID	:	0	FILE :	PROCESSED
MAGNETIC DECL.	:	0	RM	:	0	TYPE :	9060A
MATRIX DENSITY	:	2.84	RM TEMPERATURE	:	0	LGDATE:	12/16/14
NEUTRON MATRIX	:	DOLOMITE	MATRIX DELTA T	:	44	LGTIME :	16:55:
						THRESH:	2500
SWL	:						
REMARKS	:						

ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS


RES
0
OHM
500
SP
-600
MV
600
FEET
SPEED->
GAMMA
0
API-GR
200
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210


200
210
220
230
240
250
260
270
280
290
300
310
320
330
340
350
360
370
380
390


400
410
420
430
440
450
460
470
480
490
-600
MV
600
SP
0
OHM
500
RES
SPEED->
FEET
0
API-GR
200
GAMMA