UNIVERSITY OF MINNESOTA

Minnesota Geological Survey

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CORE DESCRIPTIONS AND BOREHOLE GEOPHYSICS IN SUPPORT OF USGS HYDROLOGIC PROPERTIES OF TILL INVESTIGATION,

LITCHFIELD AND CROMWELL, MINNESOTA

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Contents

Executive summary

This report summarizes the contributions of the Minnesota Geological Survey to Phase I of an ongoing study – Environmental and Natural Resources Trust Fund (ENRTF), M.L. 2014, Chp. 226, Sec. 2, Subd. 03h, 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. Geologic cores from sites in Litchfield and Cromwell Minnesota were described both in the field and in the laboratory, and then archived at the Minnesota Department of Natural Resources core repository in Hibbing, Minnesota. Core sediments were described systematically in terms of grain size and sorting, texture, structure, Munsell color, level of consolidation, carbonate content of matrix, and clast lithological assemblage. Textural characterization included collection of 72 bulk sediment samples for particle-size analysis from the three cores at approximate 4' intervals to detect textural deviations between core sediments at each site, and to determine the degree of internal compositional variation. Borehole geophysical logs were collected for all drill holes of adequate diameter, including gamma, electromagnetic induction, spontaneous potential and resistivity logs.

Sediments 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. 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, colour and visible clast lithologies documented down-core in LF01 and LF02. In Cromwell, core materials recovered from CW02 detail lobate interactions of the LIS in north-eastern Minnesota throughout the Late Wisconsinan glacial episode. Glacial tills and associated glaciolacustrine and glaciofluvial 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).

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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 glacial tills and fine-grained glaciolacustrine sediments (i.e., potential aquitards) which overlie and/or encompass high permeability glaciofluvial outwash sands and gravels (i.e., potential aquifers). Confining units 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 to Phase I of an ongoing study, led by the United States Geological Survey 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.

Methods

Texture data and core analysis

Unlithified Quaternary age sediments were collected on-site between 06/09/2015 and 06/26/2015 at Litchfield (cores LF01, LF02) and Cromwell, MN (core CW02) by hollow-stem coring and extruded into polyethelene casing and transported to Minnesota Geological Survey (MGS) facilities for cutting, description, sampling, and packaging. Each 5’ 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 were shipped to the DNR Drill Core Library at Hibbing, MN for archiving. Core sediments were described systematically in terms of grain size and sorting, texture, structure, Munsell color, level of consolidation, carbonate content of matrix, and clast lithological assemblage.

72 bulk sediment samples were collected for particle-size analysis from the three cores at approximate 4’ intervals, with higher sampling density near lithostratigraphic contacts, in order to detect textural deviations between core sediments at each site, and to determine the degree of internal compositional variation. Individual bulk sediment samples ranged in mass between ~150 and 200 g. Particle-size analysis was carried out by laboratory staff at MGS facilities and was conducted in two stages, broadly following ASTM D 422 procedural standards (Standard Test Method for Particle-Size Analysis of Soils): Dry sieving of the $< 4.0\ \varphi$ (> 0.63 mm) fraction, and hydrometer analysis of the $> 4.0\ \varphi$ (< 0.63 mm) fraction.

Prior to fines separation, samples were manually crushed, and 50 g of the > 4.0 φ (< 0.63 mm) fraction from each sample (in batches of 20) was weighed and placed into a 250 mL beaker, and the remaining portion of the raw sample archived. 150 mL of 40 g/L sodium pyrophosphate dispersant solution was added to each beaker and the slurries were stirred using a metal spatula and left to settle for 24 hours. A 1 L control cylinder was prepared for each test with 150 mL of 40 g/L sodium pyrophosphate and 850 mL of deionized water. Sediment mixtures were washed from 250 mL beakers into metal stirring cups using deionized water and placed on a mechanical mixer for 1 minute. After mixing, each sample was transferred to a 1 L settling cylinder and deionized water was added to make up the slurry to 1 L. ASTM 152H hydrometers were placed in both sample settling cylinders and the blank cylinder, and the meniscus correction factor calculated for each apparatus. Prior to measurement, samples were mixed and re-suspended for 1 minute using a metal plunger. Thermometers were placed in each cylinder, and temperature and hydrometer readings taken from both the blank and sample cylinders at 2 minutes following re-suspension, and thereafter at 2 hours. Wet Munsell color was obtained from each cylinder during particle sedimentation. The rate of particle settling was estimated using Stokes Law, which assumes that a solid, perfectly spherical particle of radius r and density ρs will settle downward through a fluid of density ρl at a calculable rate.

Following hydrometer testing, the < 4.0 φ (> 0.63 mm) sample fraction was isolated and retained by wet sieving. Retained fractions were transferred to beakers for drying on a hot plate. Dry sieving was then carried out using a stack of mesh sieves with apertures ranging from -1.0 φ (2 mm) to 4.0 φ (0.63 mm) (US Mesh #10 – 230). Dried samples were transferred to a sieve stack, loaded onto a RoTap® sieve-shaker, and mechanically agitated for 5 minutes to facilitate particle sorting. After shaking, the contents of each sieve were collected and their mass measured to three decimal places using a digital weigh scale. Percentages derived from hydrometer readings for particle fractions up to 4.0 φ (0.63 mm) were combined with dry sieving data for the 0 – 4.0 φ range, which returned baseline textural profiles for each sample.

Borehole geophysics

Litchfield observation wells LFO1-F and LFO2-F were logged using EM-Induction and Gamma sondes on June 24, 2015. Litchfield LFO2-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 CWO1-A, CWO1-B, and CWO1-C were logged using EM-Induction and Gamma sondes on August 13, 2015. Logging was conducted in holes having 2 inch diameter plastic casing inserted into 6 inch diameter holes. Fluid in the holes was aquifer water. 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 Litchfield and Cromwell borehole geophysical logs.

Hole name	**EM-Induction rate (ft/min)**	**Gamma rate (ft/min)**
Litchfield LFO1-F	5	10
Litchfield LFO2-F	5	15
Cromwell CWO1-A	16	22
Cromwell CWO1-B	16	16
Cromwell CWO1-C	15	15

Results

Core descriptions and textural analysis

Logging and analysis of core materials revealed interpretable successions of glacially-derived sediments at each of the three sites (Appendix A). Core CW02 is capped by ~ 5.5’ of Alborn Member diamicton (*Qat*) of the Aitkin Formation (*QAIA*), overlying ~ 20’ of Cromwell Formation (*QCMU*) sand and gravel and ~ 76.5’ of subjacent *QCMU* diamicton. ~ 7.5’ of sand and gravelly sand overlies ~ 8.5’ of finer-grained sand and silt at surface in core LF01, all of which rests on ~ 70’ of alternating sandy loam (*Nva*), to loam (*Nvt*) textured diamicton of the Villard Member, New Ulm Formation (*QNVT*). Similarly, core LF02 is comprised of a thick (~ 113.5’) package of unsorted sediments with variable textures (*Nva*, *Nvt*), intercalated with thin (≤ 7.5’) glaciofluvial sequences and occasional sand stringers, flow noses and lenses. Bulk sample grain size distributions are presented in Table 2. See Appendix A for sample stratigraphic context.

Table 2. Bulk grain size distributions for Cromwell and New Ulm Tills from cores LF01, LF02 and CW02.

	Cromwell Till (QCMU)			**New Ulm Till (QNVT)**			**All**		
	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
Mean	0.57	0.31	0.13	0.49	0.33	0.18	0.5	0.32	0.17
Median	0.56	0.31	0.13	0.47	0.33	0.18	0.48	0.33	0.18
Mode	0.56	0.33	0.14	0.47	0.34	0.18	0.47	0.33	0.18
St. Dev	0.03	0.02	0.02	0.06	0.04	0.03	0.06	0.04	0.04

Sample values are plotted in terms of their relative proportions of sand (0.063 – 2.00 mm), silt (0.002 – 0.063 mm), and clay (< 0.002 mm) for grouped units interpreted as glacial till, glaciolacustrine, and fine-grained ice-contact deposits (i.e., potential aquitards, *Group A*) in Fig.1[A], and grouped proglacial deltaic, outwash, and undifferentiated glaciofluvial deposits (i.e., potential aquifers, *Group B*) in Fig.1[B]. *QCMU* units within *Group A* (retrieved from core CW02) are relatively coarse-grained and exclusively exhibit sandy loam matrix textures.

Conversely, *QNVT* units within *Group A* (retrieved from cores LF01 and LF02) are, on average, finer-grained, and display predominantly loam, with minor skew towards sandy loam, matrix textures. *QCMU* units within *Group B* also plot with higher sand proportions and appear better-sorted than those of *QNVT*.

Comparison of grain size distributions (Fig.2) for *till samples only* confirms the existence of two separate populations, correlative with formations *QCMU* vs. *QNVT*. Density plots (shown along the diagonal in Fig.2) indicate that most of the variability between sampled tills is contained within the clay component (both within and between formations), though significant overlap occurs within the silt size-fraction. High negative correlation exists between sand and clay fractions within the sample distribution (as evidenced by the tightly-constrained negative slope on the sand vs. clay cross-plot), implying sufficient mixing and homogenization (i.e., a lack of bimodal till texture). *QNVT* tills exhibit slightly greater proportions of silt and clay, but moderately lesser proportions of sand compared to *QCMU* tills, in terms of all three measures of central tendency (Fig.3).

12 of 17 samples collected from core CW02 returned textural profiles inconsistent with their logged deposit-type (see Appendix A.1). Six of these samples (CW02/02-07) extracted in sequence from intervals logged as proglacial outwash (with the exception of CW02/02, interpreted as Alborn Member till of the Aitkin Formation) yielded uncharacteristically loamy textures, whereas 6 samples (CW02/10-15) obtained from intervals logged as glacial till yielded anomalously high sand and low fines percentages (with the exception of CW02/10 which ran high silt and clay). Our best judgment determined that samples were misordered at some unidentified stage during texture processing, and further, that interval CW02/2-07 corresponds to CW02/12-15 and *vice versa*. Samples are treated as such in all analyses presented here. Resampling of the archived core split has been completed and sample reprocessing for grain-size analysis is currently underway.

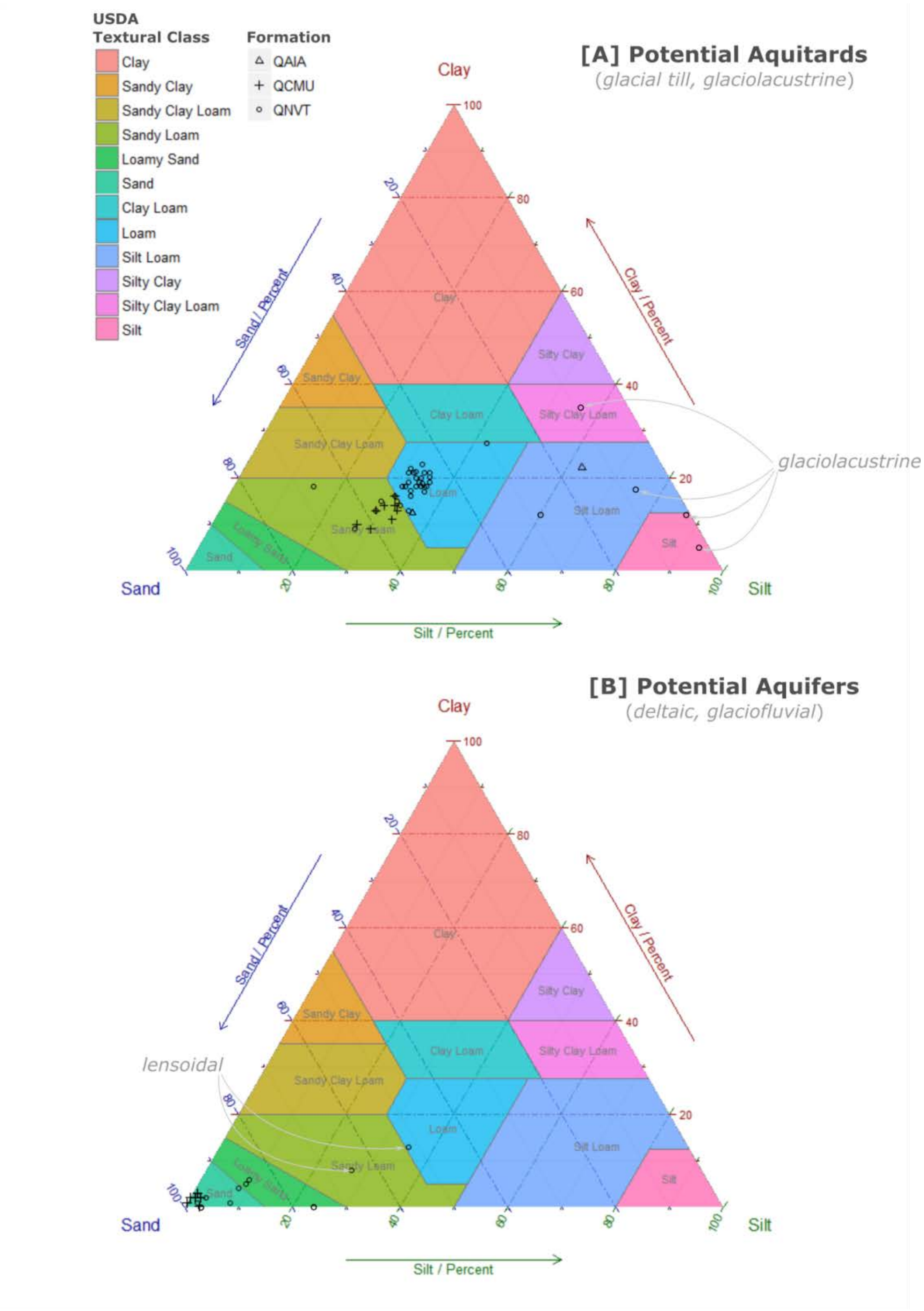


Figure 1. Ternary diagrams showing results of sample particle-size analysis from cores LF01, LF02, and CW02 for grouped units interpreted as: [A] glacial till, glaciolacustrine, and fine-grained ice-contact deposits (i.e., potential aquitards), and [B] grouped proglacial deltaic, outwash, and undifferentiated glaciofluvial deposits (i.e., potential aquifers). Classification and nomenclature follows United States Department of Agriculture (USDA) textural soil classification. QAIA = Aitkin Formation, Alborn Member, QCMU = Cromwell Formation, QNVT = New Ulm Formation, Villard Member.

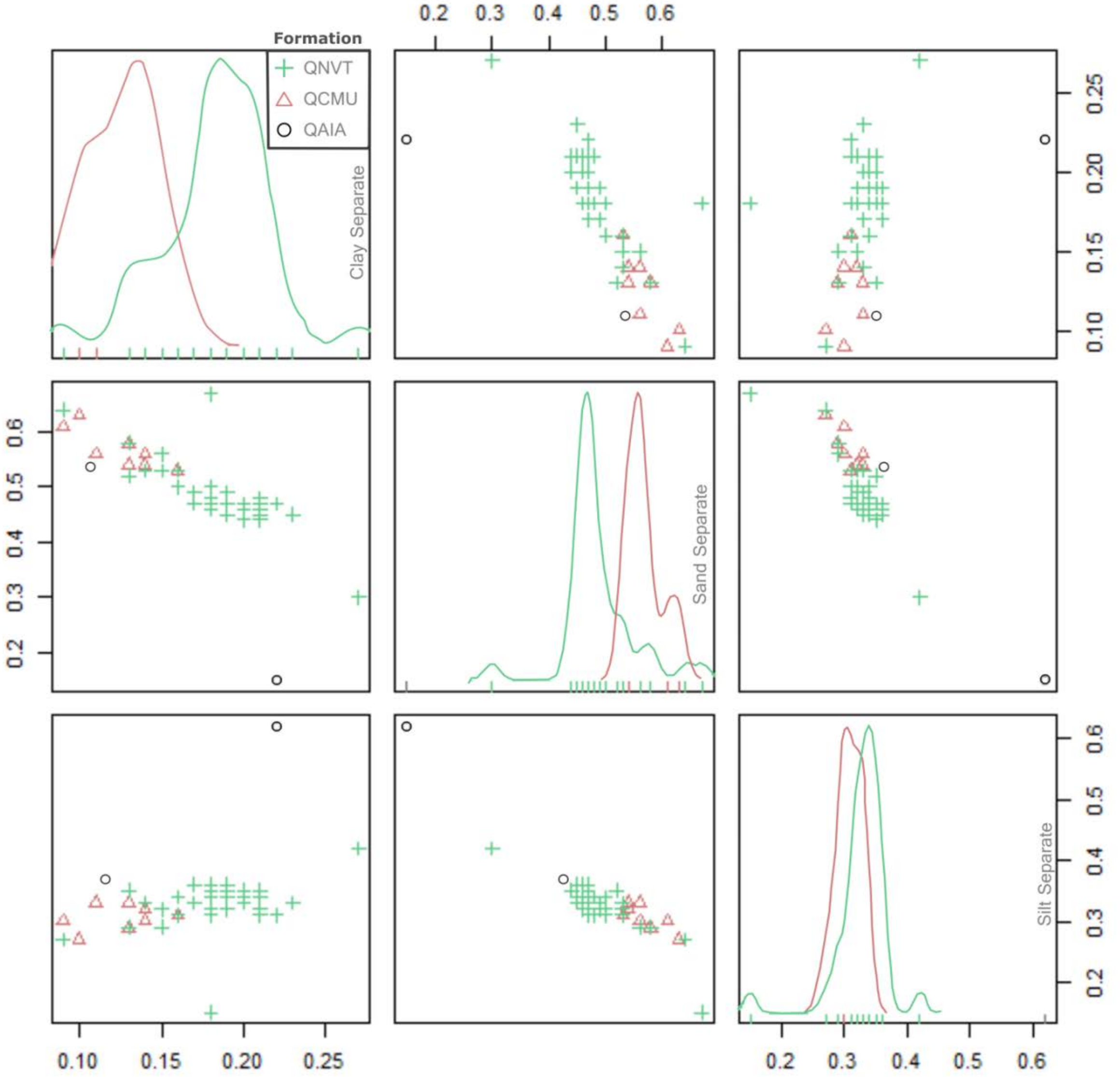
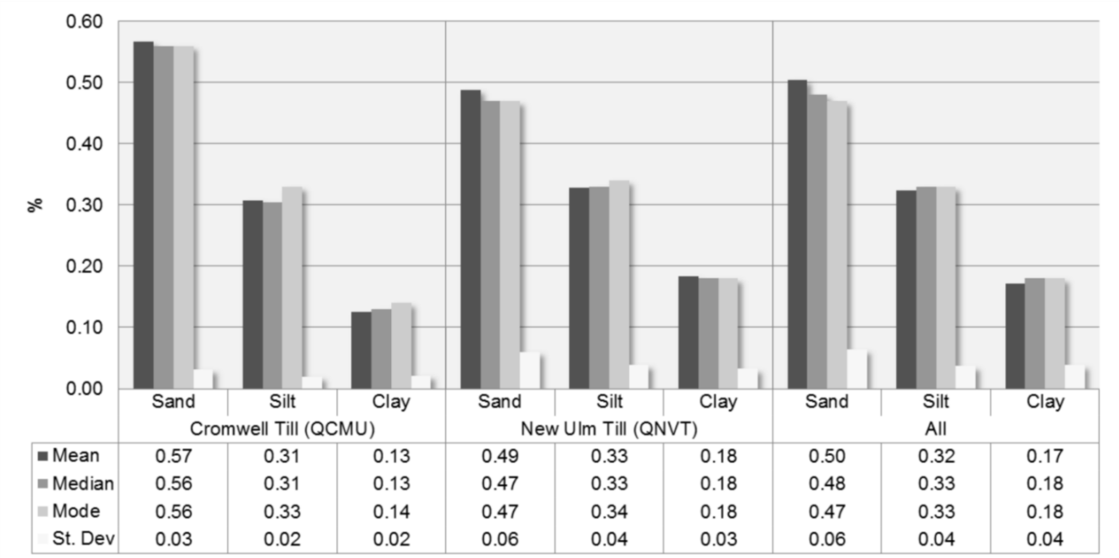


Figure 2. Scatterplot matrix depicting the relationship between sand, silt, and clay separates for till samples obtained from cores LF01, LF02, and CW02, grouped by lithostratigraphic formation. Sample density by particle-size fraction is shown along the diagonal for clay (left column), sand (middle column), and silt (right column). QAIA = Aitkin Formation, Alborn Member, QCMU = Cromwell Formation, QNVT = New Ulm Formation, Villard Member.



	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
	Cromwell Till (QCMU)			New Ulm Till (QNVT)			All		
■ Mean	0.57	0.31	0.13	0.49	0.33	0.18	0.50	0.32	0.17
■ Median	0.56	0.31	0.13	0.47	0.33	0.18	0.48	0.33	0.18
■ Mode	0.56	0.33	0.14	0.47	0.34	0.18	0.47	0.33	0.18
□ St. Dev	0.03	0.02	0.02	0.06	0.04	0.03	0.06	0.04	0.04

Figure 3. Central tendency statistics for sand, silt, and clay separates of till samples obtained from cores LF01, LF02, and CW02, grouped by lithostratigraphic formation. Two samples of the Alborn Member of the Aitkin Formation collected from core CW02 are not shown. * = sample has been reassigned to an interpreted depth due to inconsistency between texture result and sampled deposit-type. See Results section for details.

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 logged using the EM-Induction sonde as part of this investigation have similar patterns in conductivity and gamma logs; 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 4) and Litchfield observation wells LFO1-F and LFO2-F (Figure 5) identify zones where changing dissolved solids concentrations may be occurring. Wells in Cromwell observation cluster 1 are closely spaced and deviation depth intervals roughly correspond in the upper 100 feet, particularly at depths 18 to 26 feet bgs and 60 to 70 feet bgs.(Figure 4). Deviation depth intervals in Litchfield LFO1-F and LFO2-F correspond to thick sand and gravel intervals in the bottom of the holes (Figure 5) and likely represent water chemistry differences in the confined aquifer from water in overlying fine-grained sediment.

During the June 24, 2015 logging of LFO2-F, the EM-Induction sonde stopped at 153 feet below the ground surface prior to logging, approximately 10 feet 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. LFO2-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 feet below the ground surface,

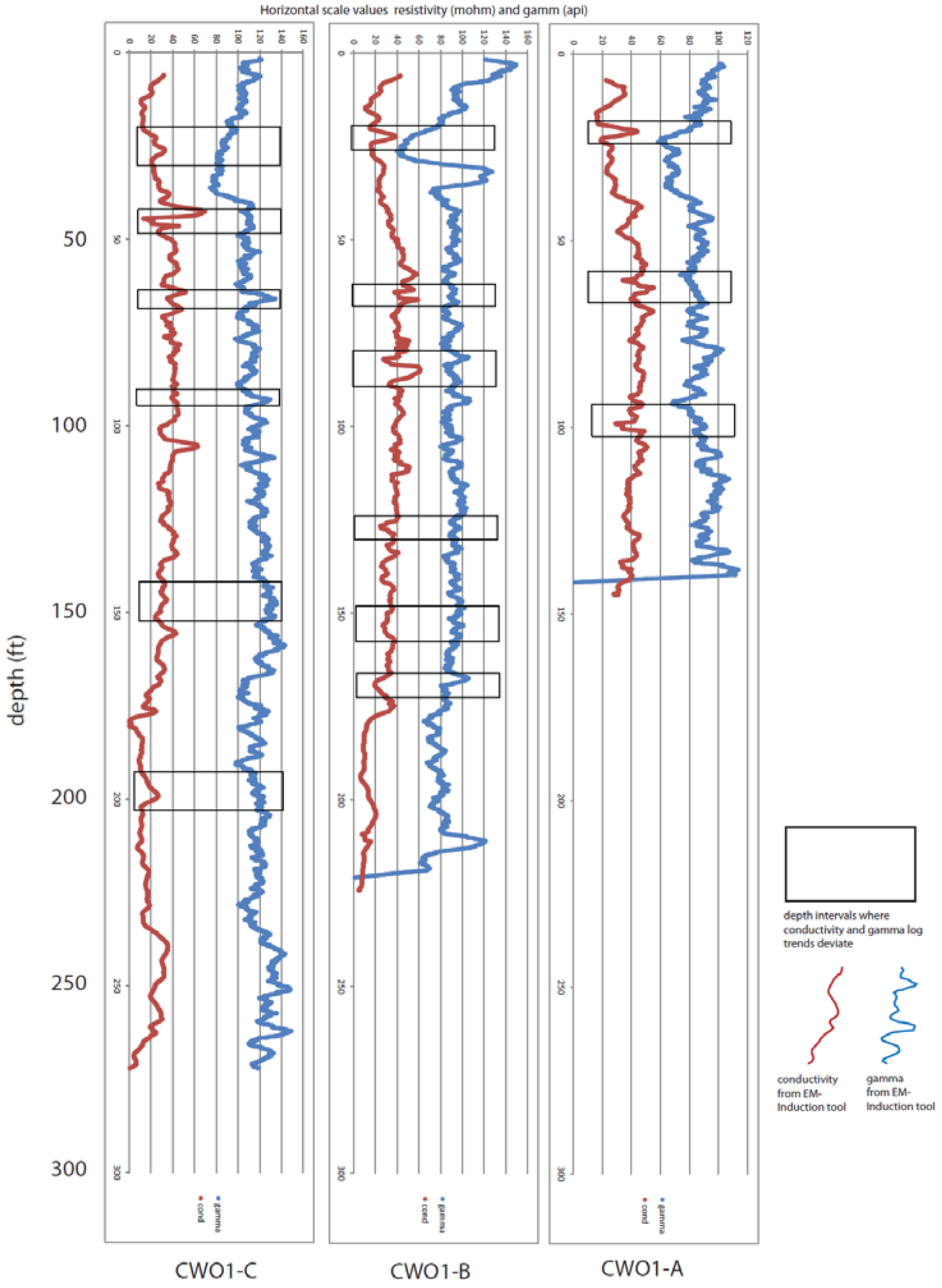


Figure 4. Qualitative identification of depth intervals where conductivity and gamma trends deviate, Cromwell observation well cluster 1. Rock-water conductivity measurements typically track gamma logs, with increasing conductivity associated with increased clay or silt content. Deviations from these trends may indicate changes in fluid conductivity due to changes in water chemistry. Both logs from EM-Induction sonde.

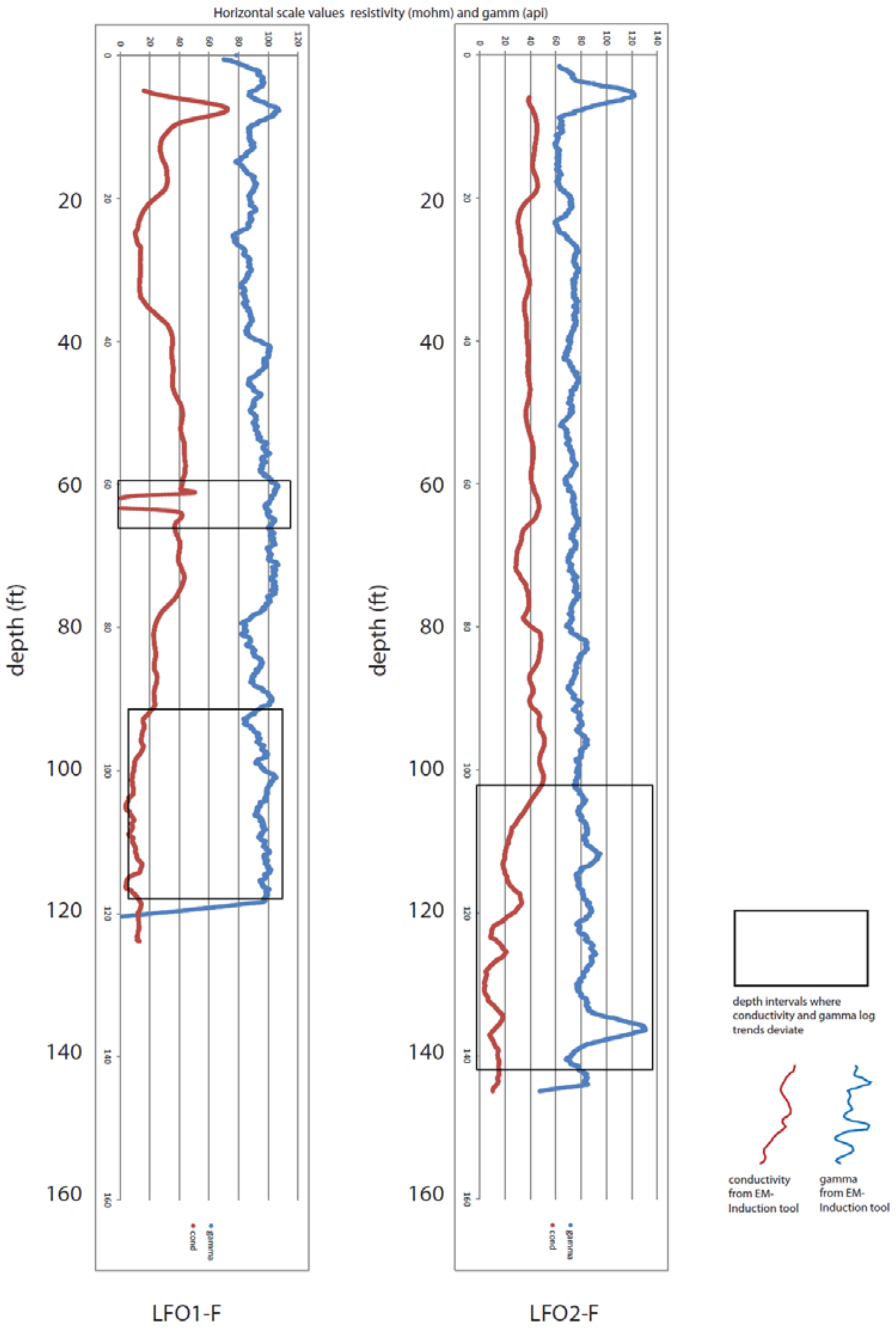


Figure 5. Qualitative identification of depth intervals where conductivity and gamma trends deviate, Litchfield observation wells LFO1-F and LFO2-F. Rock-water conductivity measurements typically track gamma logs, with increasing conductivity associated with increased clay or silt content. Deviations from these trends may indicate changes in fluid conductivity due to changes in water chemistry. Both logs from EM-Induction sonde.

resulting in no EM-induction record for the lower 10 feet of LFO2-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 qualitative, and would benefit from review by USGS staff more familiar with EM-Induction logs. We see value in continued use of this sonde, recognizing casing material restrictions.

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 (*QNVT*) predominantly reflects a mixed Winnipeg provenance. Within the geographic boundaries of its occurrence, 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 (the surface unit as little as 5 miles south and west of Litchfield (Meyer, 2015a)) – suggests that multiple ice sheds contributed distinctive lithological signatures to tills of the Des Moines Lobe, and 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, shifting ice flow towards the northeast across most of Meeker County, and enabling ice to overtop the St. Croix moraine, thus 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 event 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 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, colour and visible clast lithologies documented here down-core in LF01 and LF02. The observed increase in felsic igneous lithologies, the introduction of sparse Late Precambrian North Shore Volcanic Group (NSVG) red volcanics, and the associated proportional reduction of carbonates (Paleozoic limestone and dolostone) incorporated as clasts within till at the base of both cores, indicate local incorporation of older Rainy provenance materials, most likely till and/or outwash of the underlying Hewitt Formation (including deposits of the Alexandria moraine complex) deposited by the Wadena Lobe early in the Late Wisconsinan. The sustained presence of Cretaceous shale corroborates that this is indeed a mixed-provenance unit, as the pure Hewitt Formation is devoid of this lithology. At both sites, it is inferred that all changes in the nature of the tills reflect variability within a single member (i.e., units *nvt*, *nva* of the Villard Member) of the New Ulm formation 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 *QNVT* tills shown here 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). Systematic counts of the very coarse sand (1-2 mm) fraction were not completed for this study, but would be the preferred method of establishing a basis for this argument, as 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 (Harris, 1998). 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. 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 (GLL II) (represented in the sediment archive in LF01 from 12-20.5'), 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' 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.), the latter boring is sited on a till knob which evidently escaped inundation by the lake body, suggesting GLL II was relatively shallow and possibly short-lived.

Cromwell

Core materials recovered from CW02 detail lobate interactions of the LIS in north-eastern Minnesota throughout 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) ~13.5 – 14 ka cal yr BP, which generated the Mille Lacs Moraine along its westernmost extent (Wright, 1972).

Glacial tills and associated glaciolacustrine and glaciofluvial meltwater deposits of the St. Croix and Automba phases of the Superior Lobe are lithostratigraphically assigned to the Cromwell Formation (*QCMU*; Wright et al., 1970; Johnson et al., 2016). Materials of this formation are present in core CW02 from 8.5’ through to the base (120’), and consist of ~ 76.5’ of subglacial till overlain by a ~ 20’ sequence of variously graded and stratified proglacial outwash. Large (≤ 17 ft.) 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. This difficulty is exacerbated by a lack of confidence in sample texture results (see Results above). Though no formal assignment is offered here, the entire package of sediments below 8.5’ is assumed Automba Phase in origin, in keeping with more regional subsurface mapping completed by the MGS for the Carlton County Geologic Atlas (Hobbs and Knaeble, 2009; Knaeble and Hobbs, 2009), including description of a rotary-sonic core (Unique #: 257600) drilled to 162 ft. depth 2.5 miles 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. Assuming correct reassignment of misordered samples to depth, mean sand proportions of *QCMU* tills derived here are within 2 standard deviations, silt proportions within 3 standard deviations, and clay values equivalent to those reported by Hobbs and Knaeble (2009).

The Cromwell Formation in CW02 is capped by ≥ 5.5’ 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 ^{14}C 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 surface as only a narrow (1-8 miles 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 (again, assuming correct reassignment of misordered samples to depth). Clear indications of pedogenesis, including leaching, oxidation, root infiltration, fines translocation and ped development through the 0-1.5 ft. interval, and the presence of a platy, illuviated, argillic horizon from 3.5-5.5 ft. suggest extensive modification by soil-forming processes, and hence, that a representative sample of Alborn Member till was not obtained. Consequently, these samples are not isolated for comparison in Fig.3. It is important to note that the assignment of this uppermost diamicton in CW02 to the Alborn Member is somewhat tenuous, given the misassignment of textures to depth intervals, 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.). Hobbs and Knaeble (2009) depict the surface unit at site CW02 as Cromwell Formation till (*Qat*), 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. 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 Hobbs and Knaeble (2009) and exists at surface as close as 3 miles east of CW02.

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Appendices: Logging and analysis of core materials and borehole geophysical logs

Appendix A – Logging and analysis of core materials

Appendix A.1 Textural analysis

Q#	Sample	Top (f)	Bot. (f)	Sand Separate	Silt Separate	Clay Separate	Gravel Fraction	Deposit Type	Leached	Dry Color	Wet Color	Formation
00Q0045274	CW02/01	1	1.5	0.52	0.37	0.12	0.13	Soil Modified Till	Y	7.5YR 4/4	10YR 4/4	QAIA
	CW02/10*	4	4.5	0.15	0.62	0.22	0.01	Soil Modified Till	Y	5YR 4/4	5Y 4/4	QAIA
	CW02/11*	8.5	10.5	0.97	0.01	0.02	0.01	Outwash	Y	10YR 4/4	10YR 5/8	QCMU
	CW02/12*	15	15.5	0.96	0.02	0.02	0.08	Outwash	Y	10YR 4/4	10YR 6/6	QCMU
	CW02/13*	19	19.5	0.97	0.01	0.03	0.26	Outwash	Y	10YR 3/4	2.5Y 7/6	QCMU
	CW02/14*	22	22.5	0.98	0	0.02	0	Outwash	Y	10YR 5/3	2.5Y 7/6	QCMU
	CW02/15*	27	27.5	0.99	0	0.01	0.11	Outwash	Y	7.5YR 3/2	2.5Y 8/2	QCMU
	CW02/08	44	44.5	0.54	0.33	0.13	0.09	Till	N	5Y 4/2	5Y 4/4	QCMU
	CW02/09	48.5	50	0.53	0.31	0.16	0.13	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/02*	54	54.5	0.63	0.27	0.1	0.19	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/03*	63	63.5	0.61	0.3	0.09	0.34	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/04*	66.5	67	0.58	0.29	0.13	0.1	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/05*	81.5	82	0.56	0.3	0.14	0.16	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/06*	94	94.5	0.56	0.3	0.14	0.16	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/07*	106	106.5	0.54	0.32	0.14	0.14	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/16	108.5	109	0.56	0.33	0.11	0.08	Till	N	7.5YR 3/2	5Y 4/4	QCMU
	CW02/17	119.5	120	0.56	0.33	0.11	0.1	Till	N	7.5YR 3/2	5Y 4/4	QCMU
00Q0045272	LF01/01	6	6.25	0.97	0.03	0	0	Deltaic	Y	2.5Y 7/2	2.5Y 7/8	QNVT
	LF01/02	10	10.25	0.97	0.03	0	0.01	Deltaic	N	2.5Y 5/4	2.5Y 7/8	QNVT
	LF01/03	13	13.25	0.76	0.24	0	0	Deltaic	N	2.5Y 5/2	2.5Y 6/8	QNVT
	LF01/04	16	16.25	0.03	0.9	0.07	0	Glaciolacustrine	N	2.5Y 5/3	2.5Y 4/4	QNVT
	LF01/05	16.5	16.75	0.02	0.93	0.05	0	Glaciolacustrine	N	2.5Y 5/3	10YR 3/4	QNVT
	LF01/06	19.5	20	0.01	0.87	0.12	0	Glaciolacustrine	N	2.5Y 4/1	2.5Y 5/2	QNVT
	LF01/07	39.5	40	0.3	0.42	0.27	0.02	Till	N	2.5Y 4/1	2.5Y 5/2	QNVT
	LF01/08	43.5	43.75	0.09	0.56	0.35	0.03	Ice Contact	N	2.5Y 6/2	2.5Y 5/2	QNVT
	LF01/09	46	46.25	0.52	0.35	0.13	0.05	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/10	52	52.25	0.58	0.29	0.13	0.22	Till	N	2.5Y 5/2	2.5Y 5/2	QNVT
	LF01/11	53	53.25	0.48	0.34	0.18	0.06	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/12	55	55.25	0.46	0.34	0.2	0.09	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/13	58	58.25	0.46	0.36	0.18	0.03	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/14	62	62.25	0.45	0.36	0.19	0.06	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/15	65	65.25	0.47	0.36	0.18	0.1	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/16	72	72.25	0.47	0.32	0.21	0.07	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/17	75	75.25	0.45	0.33	0.23	0.08	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/18	78	78.25	0.65	0.27	0.08	0.02	Lensoidal	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/19	80.5	81	0.85	0.09	0.06	0.07	Glaciofluvial	N	2.5Y 4/2	2.5Y 5/2	QNVT

	LF01/20	81.5	81.75	0.88	0.08	0.04	0.28	Glaciofluvial	N	2.5Y 4/2	2.5Y 5/4	QNVT
	LF01/21	81.75	82	0.67	0.15	0.18	0.05	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
	LF01/22	84	84.25	0.95	0.03	0.02	0	Glaciofluvial	N	2.5Y 5/2	10YR 6/4	QNVT
	LF01/23	84.25	85	0.56	0.29	0.15	0.03	Till	N	2.5Y 4/1	2.5Y 5/2	QNVT
	LF01/24	90	90.5	0.53	0.33	0.14	0.05	Till	N	2.5Y 3/1	2.5Y 5/2	QNVT
00Q0045273	LF02/01	3	3.5	0.5	0.34	0.16	0.05	Till	N	2.5Y 5/4	10YR 6/6	QNVT
	LF02/02	6.5	7	0.47	0.33	0.2	0.05	Till	N	2.5Y 4/4	10YR 6/6	QNVT
	LF02/03	12.5	13	0.47	0.35	0.18	0.05	Till	N	2.5Y 4/4	10YR 6/6	QNVT
	LF02/04	16.5	17	0.44	0.35	0.2	0.07	Till	N	2.5Y 4/2	2.5Y 4/4	QNVT
	LF02/05	18.5	18.75	0.52	0.35	0.13	0	Lensoidal	N	2.5Y 6/4	2.5Y 5/6	QNVT
	LF02/06	21	21.5	0.45	0.34	0.21	0.1	Till	N	2.5Y 3/1	2.5Y 4/4	QNVT
	LF02/07	24.5	25	0.97	0.02	0.01	0.01	Glaciofluvial	N	2.5Y 5/3	2.5Y 7/6	QNVT
	LF02/08	27	27.5	0.91	0.08	0.01	0.05	Glaciofluvial	N	2.5Y 4/1	2.5Y 5/4	QNVT
	LF02/09	30.5	31	0.53	0.31	0.16	0.06	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/10	33.5	34	0.49	0.32	0.19	0.05	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/11	38	38.5	0.5	0.31	0.18	0.07	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/12	42	42.5	0.49	0.33	0.17	0.07	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/13	46.5	47	0.46	0.32	0.21	0.06	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/14	50	50.5	0.46	0.34	0.2	0.28	Till	N	5Y 3/1	2.5Y 4/2	QNVT
	LF02/15	54	54.5	0.46	0.36	0.18	0.05	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/16	58	58.5	0.46	0.34	0.2	0.04	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/17	61	61.5	0.47	0.31	0.22	0.08	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/18	65	65.5	0.5	0.32	0.18	0.11	Till	N	2.5Y 3/2	2.5Y 4/2	QNVT
	LF02/19	68	68.5	0.47	0.33	0.2	0.06	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/20	73	73.25	0.64	0.27	0.09	0.08	Till	N	2.5Y 4/2	2.5Y 4/2	QNVT
	LF02/21	75.5	76	0.53	0.32	0.15	0.07	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/22	80.5	81	0.48	0.34	0.18	0.11	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/23	84.5	85	0.47	0.32	0.21	0.05	Till	N	2.5Y 3/2	2.5Y 4/2	QNVT
	LF02/24	88	88.5	0.47	0.36	0.17	0.04	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/25	93	93.5	0.47	0.35	0.19	0.03	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/26	97.5	98	0.48	0.31	0.21	0.04	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/27	102	102.5	0.44	0.35	0.21	0.04	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/28	106	106.5	0.47	0.34	0.19	0.07	Till	N	2.5Y 3/1	2.5Y 4/2	QNVT
	LF02/29	107.25	107.5	0.87	0.09	0.05	0.58	Glaciofluvial	N	2.5Y 5/2	2.5Y 6/2	QNVT
	LF02/30	112	112.5	0.58	0.29	0.13	0.06	Till	N	5Y 3/1	2.5Y 4/2	QNVT

Appendix A.2 Description and correlation of log units

Description of Log Units

QUATERNARY

Wisconsinan Episode

New Ulm Formation
Villard Member

nd	DELTAIC - Interbedded very fine grained to very coarse grained sand and very fine to medium gravels
ns	GLACIOLACUSTRINE - Very fine to fine grained sand interbedded with very fine grained silt to sandy silt.
nvt	LOAMY TILL - Loam textured, unsorted sediment (diamicton).
nva	SANDY LOAM TILL - Loam to sandy loam textured, unsorted sediment (diamicton).
ng	OUTWASH - Massive to planar parallel to cross stratified fine to very coarse sand and very fine to coarse gravel.

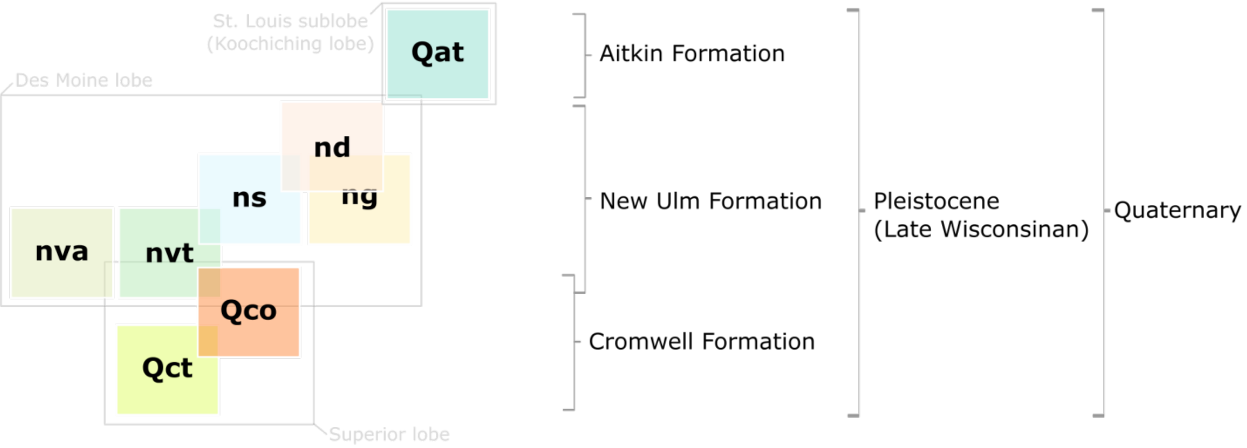
Aitkin Formation
Alborn Member

Qat	SILT LOAM TILL - Predominantly silt loam to clay loam textured, unsorted sediment (diamicton).

Cromwell Formation
Automba and/or St. Croix Phase

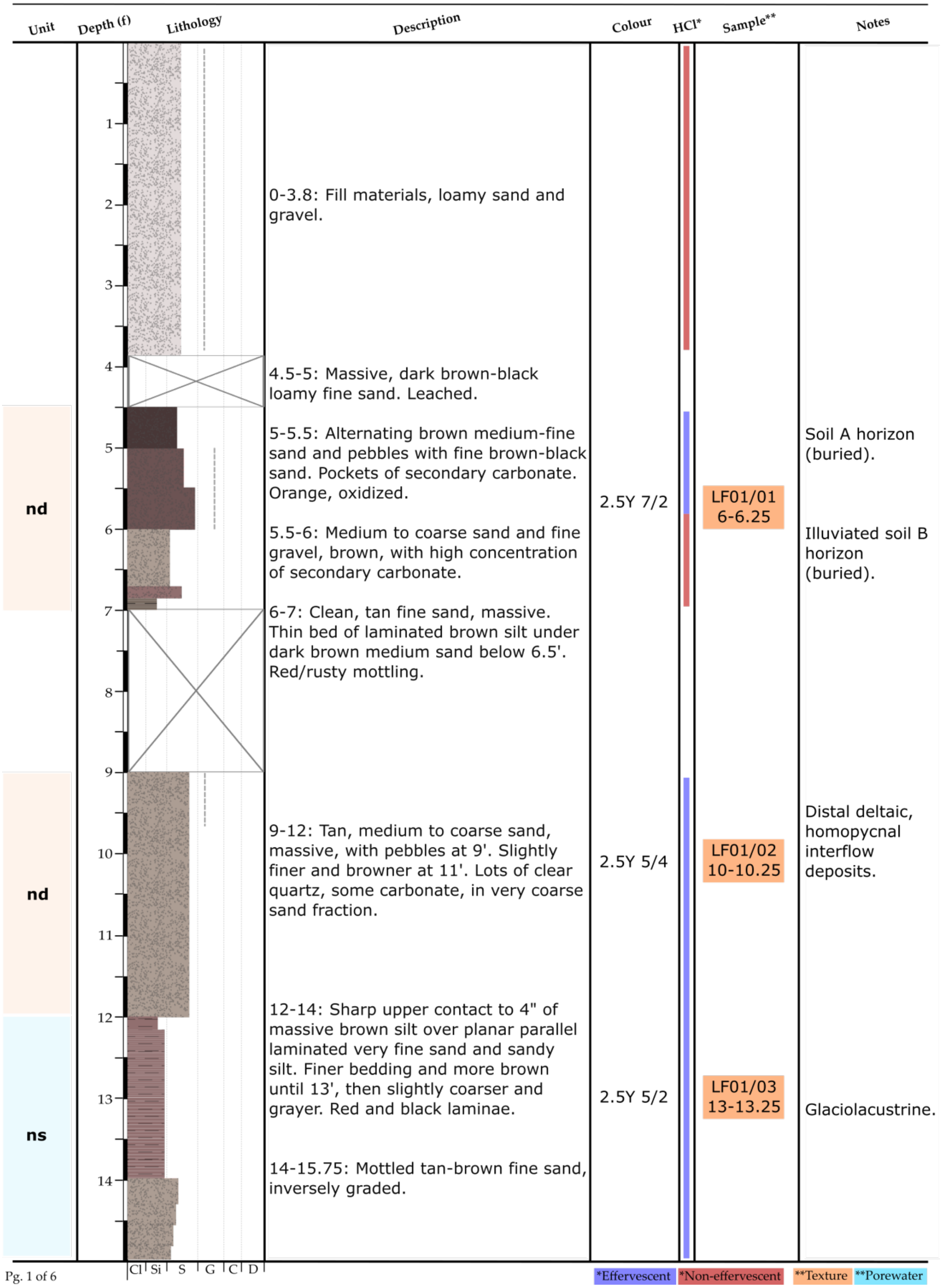
Qco	OUTWASH - Massive to planar parallel to cross stratified fine to very coarse sand and very fine to coarse gravel.
Qct	SANDY LOAM TILL - Sandy loam to loam textured, unsorted sediment (diamicton).

Correlation of Log Units



Appendix A.3 Core descriptions
LF01 – Graphical log

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015
CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



0-3.8: Fill materials, loamy sand and gravel.

4.5-5: Massive, dark brown-black loamy fine sand. Leached.

5-5.5: Alternating brown medium-fine sand and pebbles with fine brown-black sand. Pockets of secondary carbonate. Orange, oxidized.

5.5-6: Medium to coarse sand and fine gravel, brown, with high concentration of secondary carbonate.

6-7: Clean, tan fine sand, massive. Thin bed of laminated brown silt under dark brown medium sand below 6.5'. Red/rusty mottling.

9-12: Tan, medium to coarse sand, massive, with pebbles at 9'. Slightly finer and browner at 11'. Lots of clear quartz, some carbonate, in very coarse sand fraction.

12-14: Sharp upper contact to 4" of massive brown silt over planar parallel laminated very fine sand and sandy silt. Finer bedding and more brown until 13', then slightly coarser and grayer. Red and black laminae.

14-15.75: Mottled tan-brown fine sand, inversely graded.

2.5Y 7/2

2.5Y 5/4

2.5Y 5/2

LF01/01
6-6.25

LF01/02
10-10.25

LF01/03
13-13.25

Soil A horizon (buried).

Illuviated soil B horizon (buried).

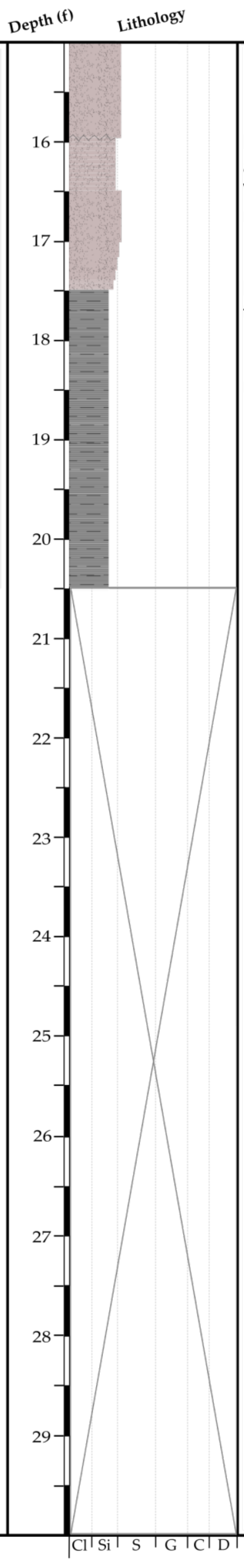
Distal deltaic, homopycnal interflow deposits.

Glaciolacustrine.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

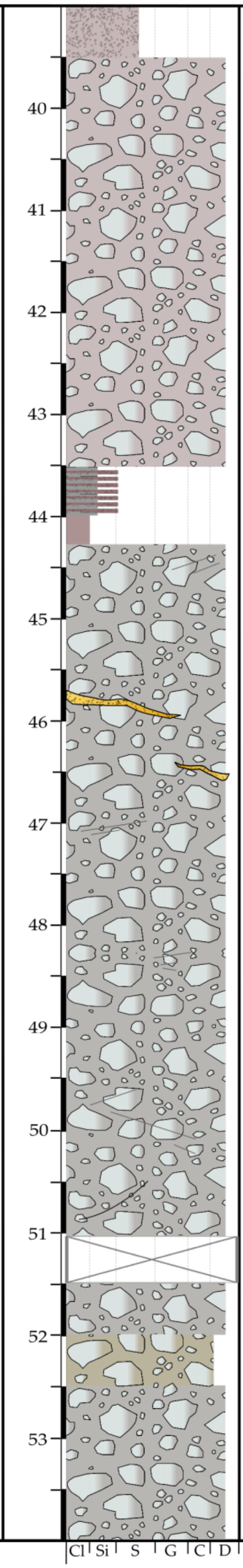


Unit	Description	Colour	HCl*	Sample**	Notes
ns	15.75-16.5: Planar parallel to ripple laminated tan-brown very fine sand and silt. Black laminae of silt @ 16'. Vaguely scoured contact to overlying massive brown fine sand.	2.5Y 5/3	🟦	LF01/04 16-16.25	Glaciolacustrine.
	16.5-17.5: Brown silt with very fine black laminae at depth. Inverse grading towards gradational lower contact.	2.5Y 5/3	🟦	LF01/05 16.5-16.75	
	17.5-20.5: Grey microlaminated clay-rich silt, relatively dense.	2.5Y 4/1	🟦	LF01/06 19.5-20	

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

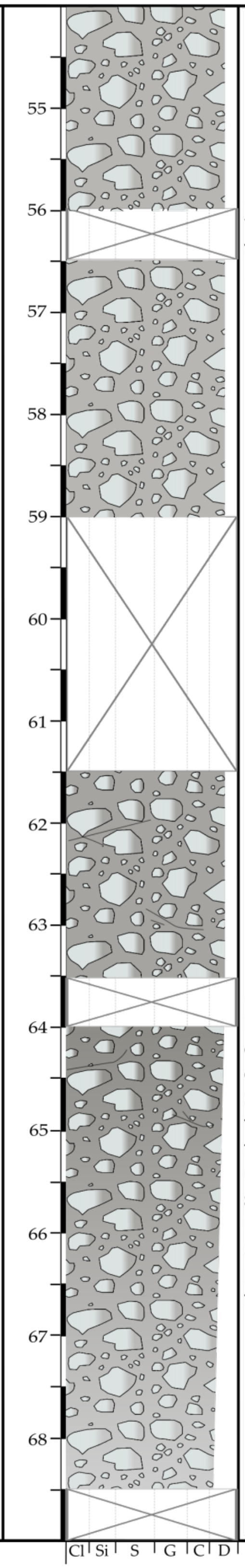


Unit	Description	Colour	HCl*	Sample**	Notes
nvt	39-39.5: Deformed brown, medium sand.		🟦		No core recovered from 30-39'.
	39.5-43.5: Massive, matrix-supported diamicton. Moderately clast-rich. Clasts mostly subrounded, mostly carbonates, very fine to medium gravel-size. Gray-brown loam matrix. Granular structure. Deformed light grey banding @ 39.5'. More compact below 40'. Stringers of grey very fine sand @ 41'. Mixing of brown and dark brown matrices below 41.5'.	2.5Y 4/1	🟦	LF01/07 39.5-40	Ablation till, Riding Mountain-Winnipeg Provenance.
	43.5-44: Alternating dry gray silt and dark brown fine sand.	2.5Y 6/2 (silt)	🟦	LF01/08 43.5-43.75	Depression hollow ponding.
	44-44.25: Massive brown clay.		🟦		
nva	44.25-52: Relatively dense, grey, massive, matrix-supported diamicton. Sandy loam matrix. Frequent fractures, some with light brown or rust coloured fine sandy skins/infills. Some fracturing, probably an artefact of coring and exhumation/expansion. Very fine to medium gravel-sized clasts, mostly subrounded but vary to subangular. Felsics, mafics, carbonate, shale present; perceived increase in shale content with depth. Higher proportion of medium gravel-sized clasts below 50'.	2.5Y 3/1	🟦	LF01/09 46-46.25 51-51.5	Subglacial till, Riding Mountain-Winnipeg provenance.
	52-52.25: Carbonate-cemented, light brown, compact, fine sandy loam diamicton.	2.5Y 5/2	🟦	LF01/10 52-52.25	
	52.25-54: Similar diamicton to 44.25'+, less fractured.	2.5Y 3/1	🟦	LF01/11 53-53.25	

🟦 *Effervescent 🟥 *Non-effervescent 🟧 **Texture 🟦 **Porewater

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

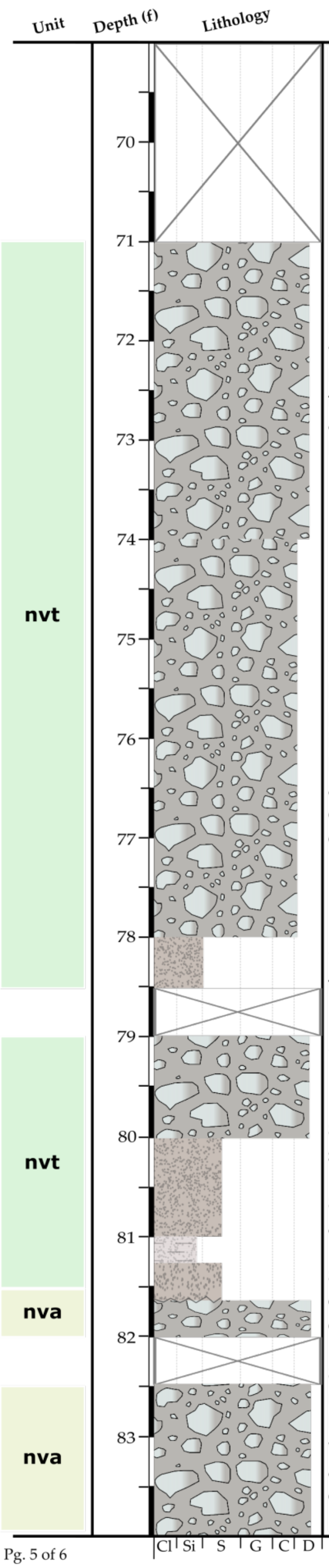
CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Unit	Description	Colour	HCl*	Sample**	Notes
nvt	54-59: Similar diamicton as above, but with apparent higher proportion of felsic lithologies. Several clasts around 55' are partially disintegrated and have highly weathered rinds.	2.5Y 3/1 2.5Y 3/1		LF01/12 55-55.25 56-56.5 LF01/13 58-58.25	Subglacial till, Riding Mountain-Winnipeg Provenance.
nvt nvt	61.5-69: Very dense brown to grey-brown, massive, matrix-supported diamicton. Loam matrix; fines with depth, grading to siltier loam texture. Subtle colour change from grey-brown to grey with depth. Subhorizontal fractures (exhumation related?) from 61.5-65'. Very fine to coarse gravel-sized subangular to subrounded clasts. High proportion of carbonate clasts. Some shale, though visibly lower proportion than above, or perhaps just fewer large shale clasts. Chert @ 62'.	2.5Y 3/1 2.5Y 3/1		LF01/14 62-62.25 63.5-64 LF01/15 65-65.25 68.5-69	Subglacial till, Riding Mountain-Winnipeg provenance.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015
CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



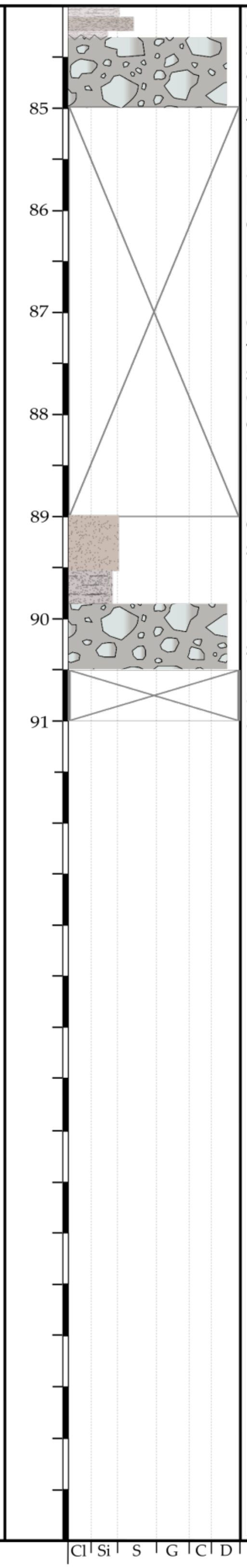
Description	Colour	HCl*	Sample**	Notes
71.5-74: Overconsolidated grey, massive, matrix-supported diamicton with loam matrix. Extremely dense. Many potassium feldspars. Increase in felsic igneous lithologies overall. Pink argillyte @72' - potentially Superior basin sourced.	2.5Y 3/1	🟦	LF01/16 72-72.25	Subglacial till and basal sorted sediment deposits, Riding Mountain-Winnipeg provenance; local incorporation of Rainy provenance materials.
74-78.25: Similar diamicton as above, but with siltier loam matrix. High proportion of carbonate and pink felsic igneous (possibly a few reds) lithologies, visible shale. Large (7 cm a-axis) chert clast at 76.5'. Very fine gravel-sized clasts of cherty lithologies common in this interval.	2.5Y 3/1	🟦	LF01/17 75-75.25	
78.25-78.5: Light brown, well-sorted fine sand, probably lensoidal.	2.5Y 3/1	🟦	LF01/18 78-78.25 78.5-79	
79-80: Similar diamicton as 71.5'+.		🟦		
80-81: Well-sorted light brown medium sand.	2.5Y 4/2 (m. sand)	🟦	LF01/19 80.5-81	
81-81.25: Bedded grey very fine sand and silt.		🟦	LF01/20 81.5-81.75	
81.25-81.5: Poorly-sorted fine to very coarse sand and very fine to fine gravel. Carbonate-rich.	2.5Y 3/1	🟦	LF01/21 81.75-82	
81.5-84: Overconsolidated grey, massive, matrix-supported diamicton. Extremely dense. Sandy loam matrix with obvious textural change from above diamicton. Scoured upper contact.		🟦		

🟦 *Effervescent 🟥 *Non-effervescent 🟧 **Texture 🟦 **Porewater

Core ID: LF01 **Location:** Litchfield, MN **Elevation (f):** 1114.5 **Drilling Method:** Hollow-stem **Logging Date:** 10/13/2015

CWI Unique No.: 773058 **Co./T/R/S/SS:** 47/119N/31W/11/ABACBB **Coring Date:** 06/09/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Description	Colour	Sample**	Notes
nva	84-84.25: Massive, grey silty very fine sand over brown medium sand. No apparent structure. Drilling issues encountered at this depth, possible that this could be slough from uphole (?).	2.5Y 5/2	LF01/22 84-84.25	
	84.25: Water saturated grey sandy silt, mixed with underlying diamict; either drilling slough or an erosive contact.	2.5Y 4/1	LF01/23 84.25-85	Subglacial till and basal sorted sediment deposits, Riding Mountain-Winnipeg provenance; local incorporation of Rainy provenance materials.
	84.25-85: Grey, overconsolidated, massive, matrix-supported diamicton. Coarse-grained sandy loam matrix texture. Very fine to medium gravel-sized subangular to subrounded clasts. Carbonate and shale present but clearly in lower proportions than uphole. Proportionally more felsic igneous lithologies. Purplish-red rhyolite and vesicular basalt indicative of local incorporation of northeastern-sourced/Northshore lithologies.			
nva	89-89.75: Massive grey to light brown medium sand grading at depth to grey sandy silt.	2.5Y 3/1	LF01/24 90-90.5	
	89.75-90.5: Similar diamicton as 84.25'+.		90.5-91	

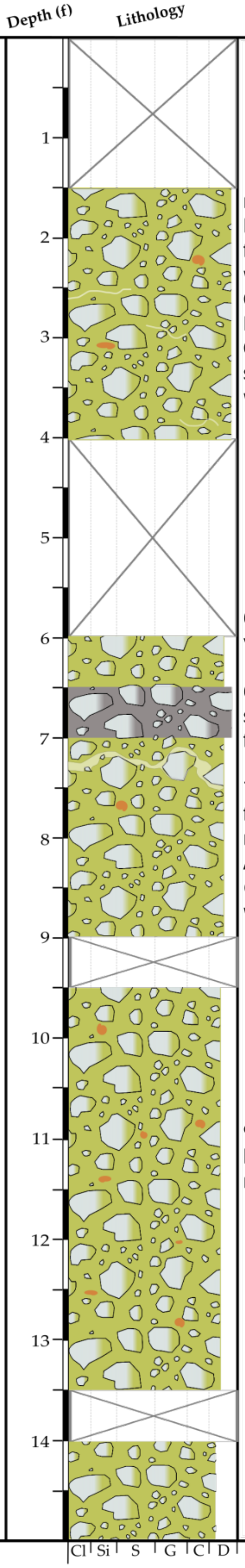


*Effervescent *Non-effervescent **Texture **Porewater

LF02 – Graphical log

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

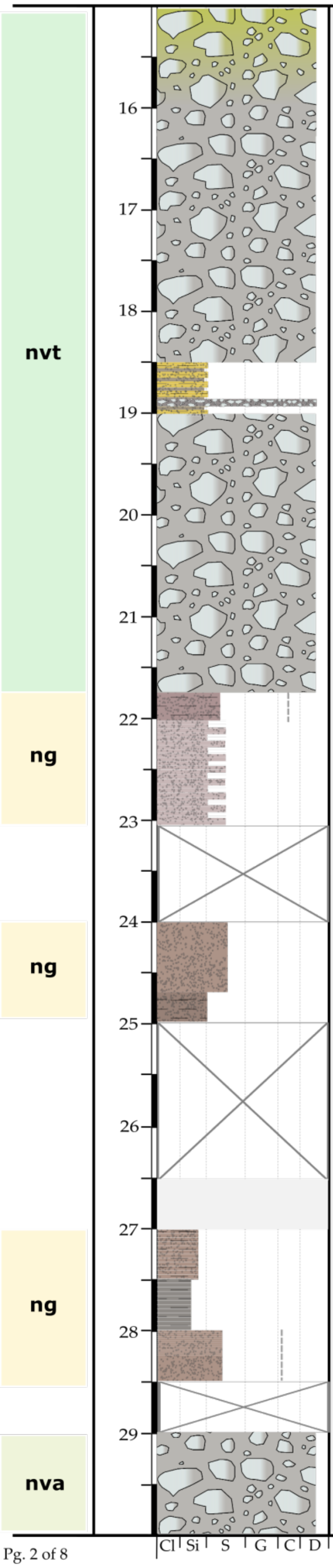


Unit	Description	Colour	HCl*	Sample**	Notes
nva	1.5-4: Oxidized olive to yellow-brown, massive, matrix-supported diamicton. Loam matrix. Moderately clast-rich; felsics and mafic igneous/carbonate/ weathered shale. Granular structure. Clear stringers of secondary carbonate. Red ochre spots present throughout. Clasts mostly subrounded but vary to subangular. Several broken-up, weathered micaceous granites.	2.5Y 4/4	🟦	LF02/01 3-3.5	Soil-modified ablation (?) till, Riding Mountain-Winnipeg provenance.
nva	6-6.5: Similar diamicton as 1.5'+ but very dessicated. Poor recovery.		🟦		
nvt	6.5-7: Dark gray, massive, matrix-supported diamicton. Coarse grained, friable. Possibly mixed with slough (?).	2.5Y 4/4	🟦	LF02/02 6.5-7	
nvt	7-9: Similar diamicton as 1.5'+, but finer matrix, and more clast-rich, with more visible shale present. Accumulation of secondary carbonate @ 7.25'. Frequent broken-up, weathered micaceous granites.		🟦		
nvt	9.5-13.5: Similar diamicton as 7'+, but lacks secondary carbonate. Frequent red ochre spots.	2.5Y 4/4	🟦	LF02/03 12.5-13	Ablation (?) till, Riding Mountain-Winnipeg provenance.
				13.5-14	
nvt			🟦		

🟦 *Effervescent 🟥 *Non-effervescent 🟧 **Texture 🟦 **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



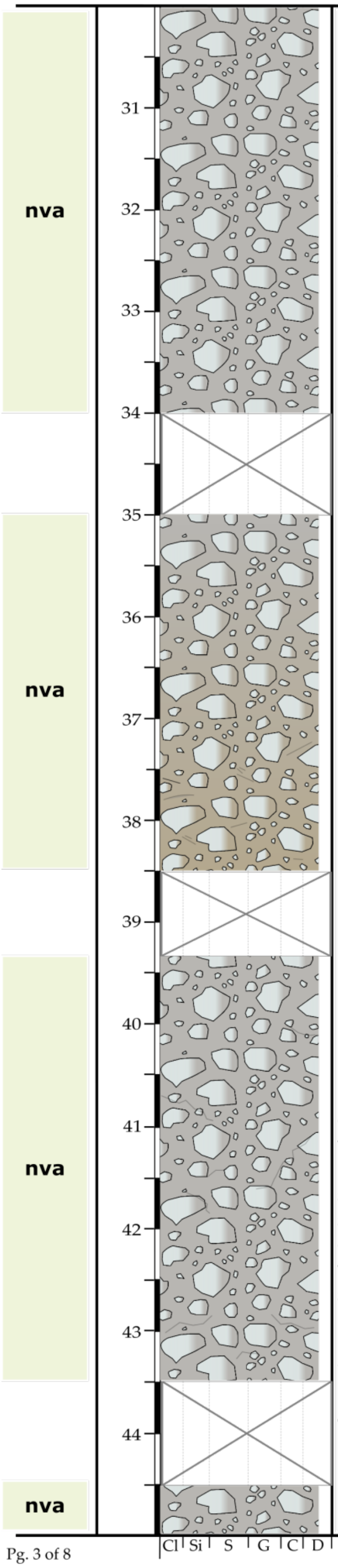
Description	Colour	HCl*	Sample**	Notes
14-16.3: Yellow-brown oxidized massive, matrix-supported diamicton. Sandy loam matrix with granular structure. Grades to unoxidized grey-brown colour at base.		🟦		Ablation (?) till, Riding Mountain-Winnipeg provenance.
16.3-18.5: Same as above, but unoxidized and grey. Red rusty precipitate along cracks. Rich in shale. Fining matrix with depth, grading to sandy clay loam at base.	2.5Y 4/2	🟦	LF02/04 16.5-17	
18.5-19: Alternating planar parallel laminated yellow-brown very fine sand and grey-brown silty very fine sand. Capped by rusty bedding @ 18.5'. 1.5" thick dark grey massive, matrix-supported diamict inclusion with sandy clay loam matrix at 18.75'.	2.5Y 6/4	🟦	LF02/05 18.5-18.75	
19-21.75: Dark grey, overconsolidated, massive, matrix-supported diamicton. Sandy clay loam matrix. High fissility with a platy breakage structure. Subangular to subrounded carbonates, felsic and mafic igneous. Some visible shale, but proportionally less than above. Purple basalt @ 20'.	2.5Y 3/1	🟦	LF02/06 21-21.5	
21.75-23.1: Brown silty sand and gravel over light brown oxidized planar parallel bedded sand, alternating between fine and medium grain size. Several thin beds of black medium sand.		🟦		Proglacial outwash.
24-25: Moderately well-sorted, massive, brown medium sand over 3" of dark brown silty sand at base. Quartz and carbonate-rich.	2.5Y 5/3	🟦	LF02/07 24.5-25	
26.5-27: Drilling slough.				
27-28.5: Brown very fine bedded sandy silt over bedded grey silt over poorly sorted fine to coarse brown sand with occasional fine subrounded gravels. Sand is bedded in upper 3", massive below.	2.5Y 4/1	🟦	LF02/08 27-27.5	
			28.5-29	
		🟦		

🟦 *Effervescent 🟥 *Non-effervescent 🟧 **Texture 🟦 **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit **Depth (f)** **Lithology** **Description** **Colour** **HCl*** **Sample**** **Notes**



29-38.5: Overconsolidated, grey, massive, matrix-supported diamicton. Loam to sandy loam matrix, siltier pockets in places. Clast-rich in upper 1', less so at depth. Primarily subrounded clasts, includes carbonate and relatively low amounts of visible shale. Red volcanic at 33'. Fractured in places. Platy structure and browner matrix below 36.5'.

39.3-48.5: Compact, dark grey, massive, matrix-supported diamicton. Loam to sandy loam matrix with granular structure. Fractured throughout, especially 41.4-43.5'; may be due to exhumation and/or core splitting, except 46' where fine brown sand infills voids. Many very fine to fine gravel-sized carbonate clasts throughout. Most larger clasts are subrounded felsic igneous lithologies (e.g., pink granite @ 45'). Shale present but appears less frequently with depth. Several red lithologies pulled from core (e.g., purple basalt @ 40').

Colour:

2.5Y 3/1

2.5Y 3/1

2.5Y 4/2

2.5Y 3/1

Sample:

LF02/09 30.5-31

LF02/10 33.5-34

LF02/11 38-38.5

38.5-39

LF02/12 42-42.5

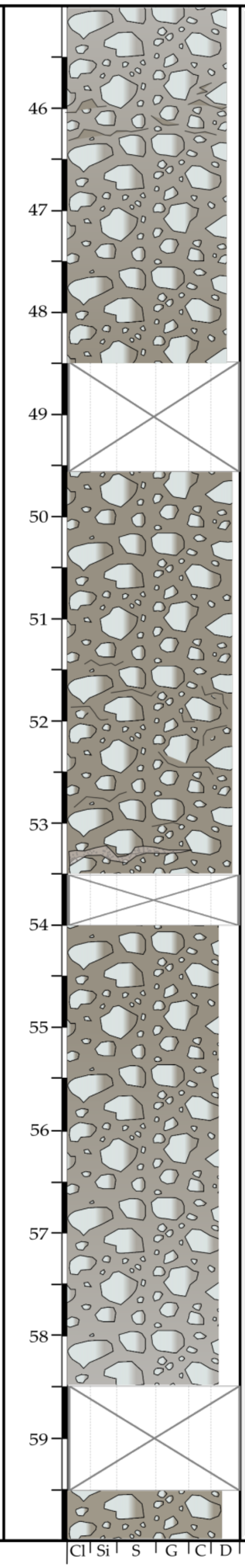
43.5-44

Notes:

Subglacial till, Riding Mountain-Winnipeg provenance; variable mixing with Rainy provenance materials.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015
CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

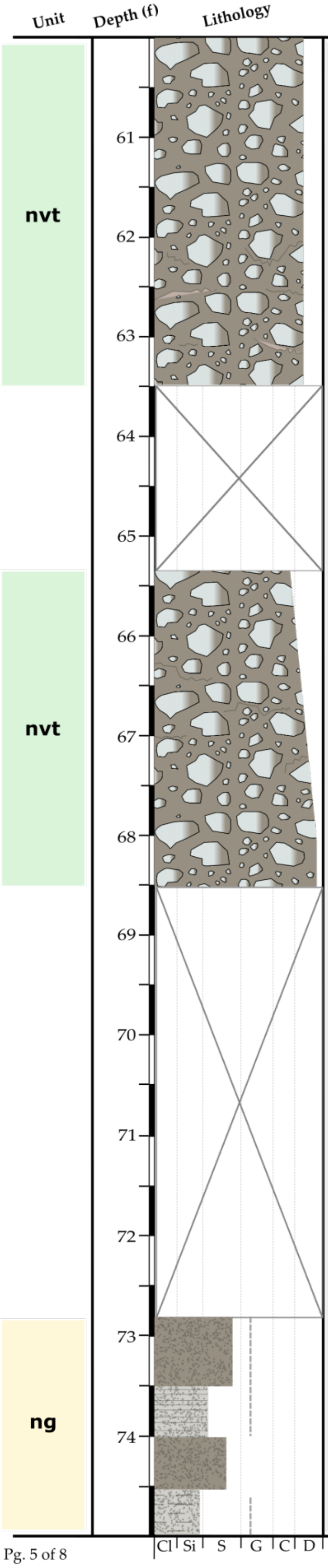


Unit	Description	Colour	HCl*	Sample**	Notes
nvt		2.5Y 3/1	🟦	LF02/13 46.5-47	
				48.5-49	
nvt	49.6-53.5: Similar diamicton as 39.3'+, but slightly browner and finer-grained loam matrix texture. More dense than above. High fracture density from 51.5-53.5'. Large greywacke clast (3" a-axis) @ 52'. Sub-horizontal stringer of light brown-grey very fine sand @ 53.5'.	5Y 3/1	🟦	LF02/14 50-50.5	Subglacial till, Riding Mountain-Winnipeg provenance.
				53.5-54	
nvt	54-61.5: Similar diamicton as 49.6'+. Less fractured. Dominance of felsic igneous and carbonate lithologies, some shale. Lignite @ 55.5'. Becomes browner and matrix is siltier @ 59.5'.	2.5Y 3/1 2.5Y 3/1	🟦	LF02/15 54-54.5 LF02/16 58-58.5	
				58.5-59	
nvt			🟦		

🟦 *Effervescent 🟥 *Non-effervescent 🟧 **Texture 🟦 **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

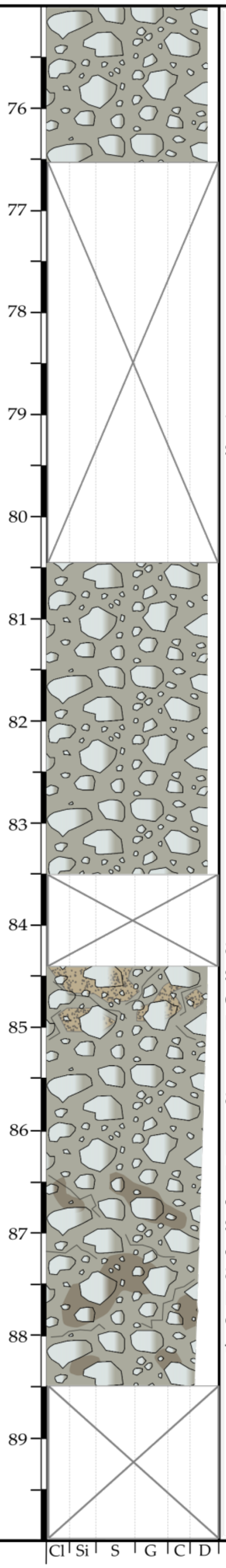


Description	Colour	HCl*	Sample**	Notes
	2.5Y 3/1	🟦	LF02/17 61-61.5	
61.5-65.3: Grey-brown, overconsolidated, massive, matrix-supported diamicton. Loam matrix. Many carbonates, felsic and mafic igneous lithologies, some shale. Most clasts subangular to subrounded. Fractured throughout, some with rusy skins.		🟦	63.5-64	
65.3-65.5: Lag of coarse sand, mixed with diamicton. Possibly drilling-induced.	2.5Y 3/2	🟦	LF02/18 65-65.5	Subglacial till, Riding Mountain-Winnipeg provenance.
65.5-73: Similar diamicton as 61.5'+. Matrix coarsens with depth to sandy loam and becomes more compact. No obvious change in lithological assemblage, but becomes slightly greyer/less brown. Fewer fractures towards base.	2.5Y 3/1	🟦	LF02/19 68-68.5 68.5-69	
73-75: Inversely graded sequence; very poorly sorted brown loamy coarse sand and very fine to fine gravel, grading to faintly stratified grey fine sand with occasional very fine to fine gravel, over sharp transition to brown, well sorted medium sand, over scoured contact to grey very fine sand and silt with occasional very fine to fine gravel.	2.5Y 4/2 (v.f. sand)	🟦	LF02/20 73-73.25	

🟦 *Effervescent 🟥 *Non-effervescent 🟧 **Texture 🟦 **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

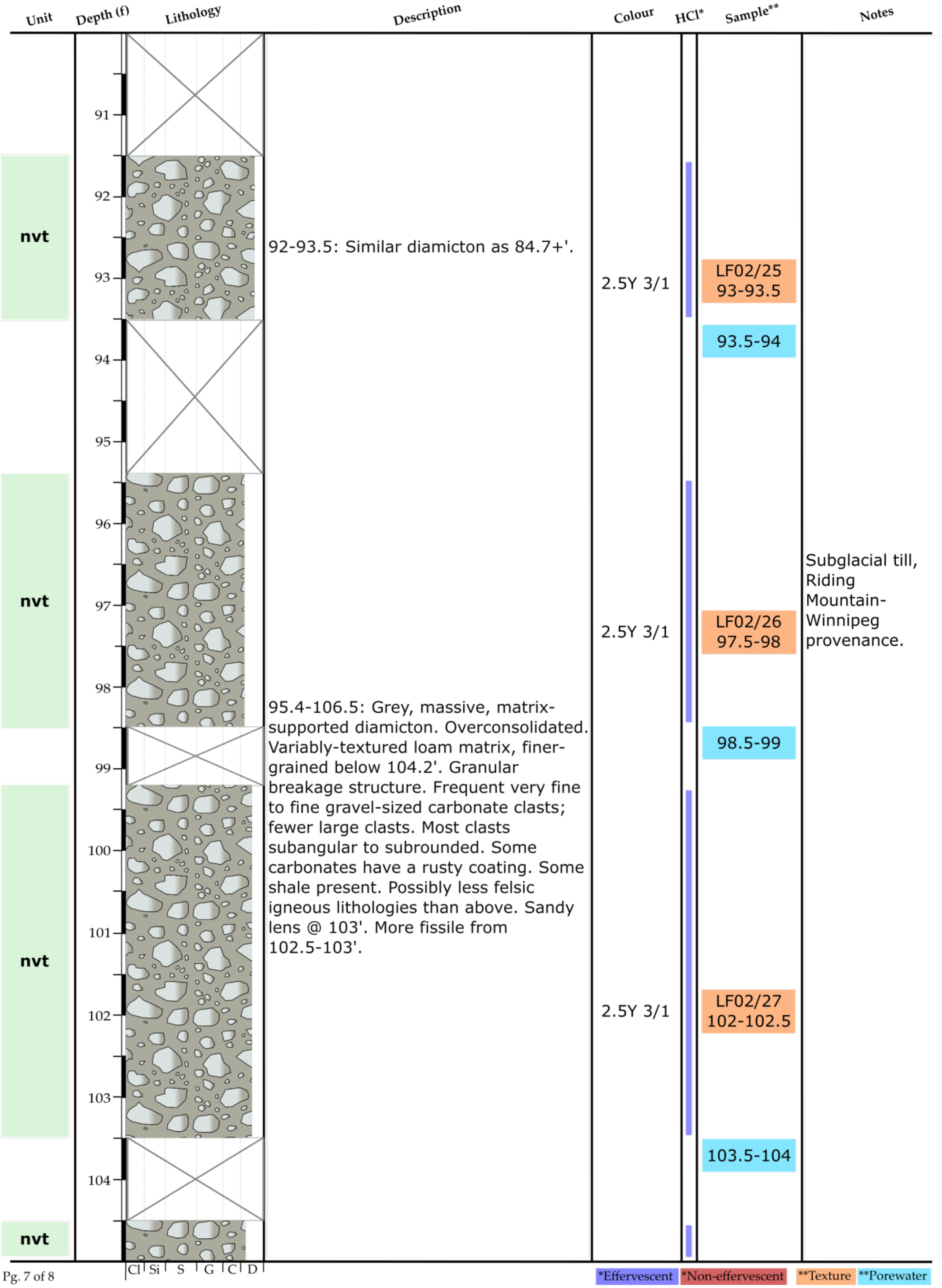


Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
nva			75-83.5: Massive, grey-brown matrix-supported diamicton. Very compact. Loam matrix. Very similar to 49.6'+.	2.5Y 3/1		LF02/21 75.5-76	Subglacial till, Riding Mountain-Winnipeg provenance.
nva				2.5Y 3/1		LF02/22 80.5-81.5	
						83.5-84	
nvt			84.4-84.7: Light brown fine to medium sand coating fragments of diamict; could be related to drilling issues and barrel removal at this depth.	2.5Y 3/2		LF02/23 84.5-85	
			84.7-88.5: Similar diamicton as 75'+. Matrix fines downwards and becomes browner in places. Fissile, platy breakage structure around 85'. Several angular clasts, though these are mostly shale. Otherwise lithologically similar to above. Higher fracture density from 86.5-88.5'. Lignite @ 87'. Mixed with light brown very fine sand from 91.5-92' - possibly dried slurry from top of barrel.	2.5Y 3/1		LF02/24 88-88.5	
						88.5-89	

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015

CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



92-93.5: Similar diamicton as 84.7+'.

2.5Y 3/1

LF02/25
93-93.5

93.5-94

2.5Y 3/1

LF02/26
97.5-98

98.5-99

Subglacial till, Riding Mountain-Winnipeg provenance.

95.4-106.5: Grey, massive, matrix-supported diamicton. Overconsolidated. Variably-textured loam matrix, finer-grained below 104.2'. Granular breakage structure. Frequent very fine to fine gravel-sized carbonate clasts; fewer large clasts. Most clasts subangular to subrounded. Some carbonates have a rusty coating. Some shale present. Possibly less felsic igneous lithologies than above. Sandy lens @ 103'. More fissile from 102.5-103'.

2.5Y 3/1

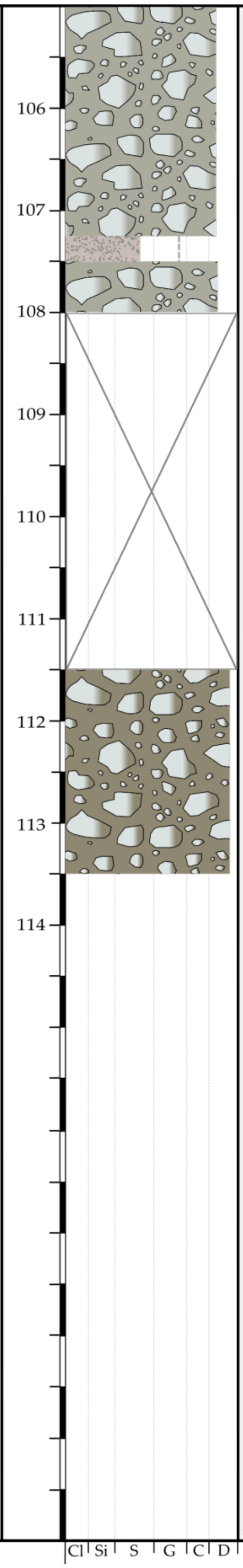
LF02/27
102-102.5

103.5-104

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: LF02 **Location:** Litchfield, MN **Elevation (f):** 1139.3 **Drilling Method:** Hollow-stem **Logging Date:** 10/16/2015
CWI Unique No.: 773052 **Co./T/R/S/SS:** 47/119N/31W/02/CACDBD **Coring Date:** 06/19/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
nvt			106.5-107.5: Similar diamicton as 95.4'+, with loam matrix. Large disintegrated grey shale clast @ 107'. Very poorly sorted, light brown, carbonate-rich fine to coarse sand and very fine to medium subangular gravels from 107.25-107.5'. Some red volcanics present. 107.5-113.5: Similar diamicton as 95.4'+, but with noticeably coarser and browner matrix. A couple of large (2"+) clasts present. Predominantly carbonate lithologies. Shale present.	2.5Y 3/1 2.5Y 5/2		LF02/28 106-106.5 LF02/29 107.25-107.5 108.5-109	Subglacial till, Riding Mountain-Winnipeg provenance.
nva				5Y 3/1		LF02/30 112-112.5	

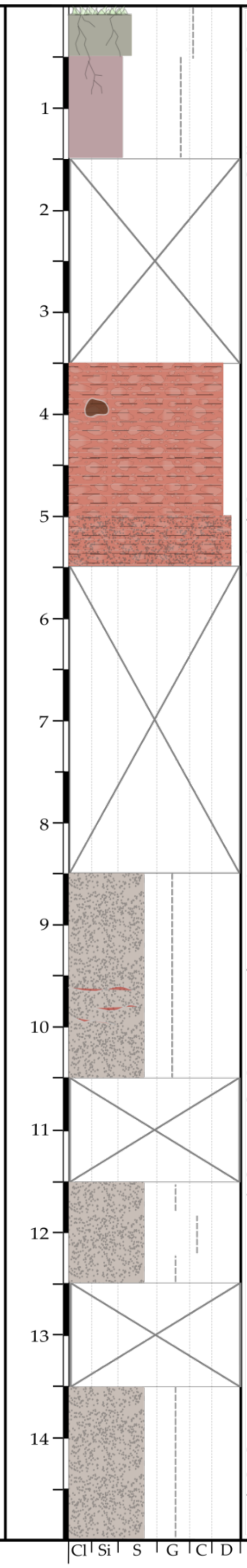


*Effervescent *Non-effervescent **Texture **Porewater

CW02 – Graphical log

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

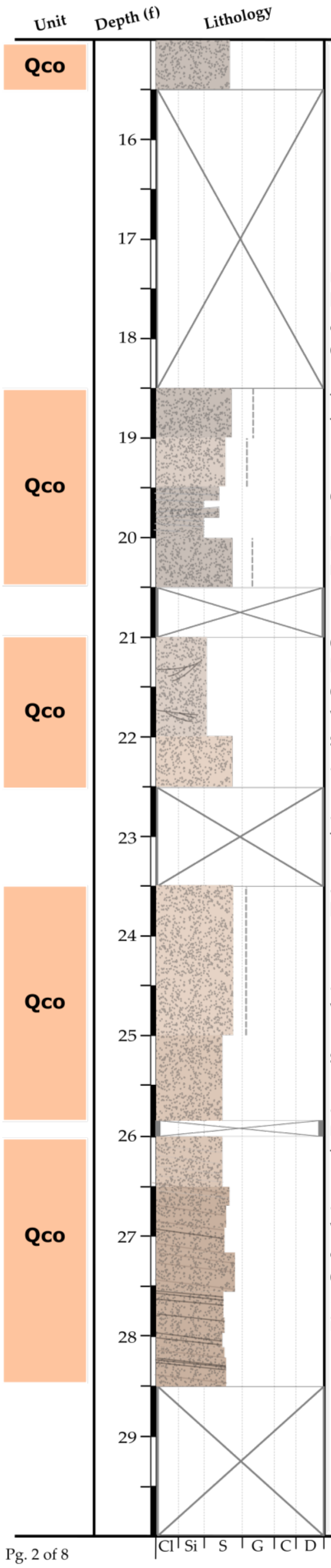


Unit	Description	Colour	HCl*	Sample**	Notes
Qat	0-0.5: Topsoil; brown loam with occasional angular gravels. Roots penetrate to ~0.7'. 0.5-1.5: Reddish-brown soil modified silt loam with fine gravels and occasional up to medium gravels.	7.5 YR 4/4	🟥	CW02/01 1-1.5	Soil A horizon.
Qat	3.5-5.5: Vaguely-stratified oxidized reddish-brown to orange-brown silt loam diamicton, becomes sandier below 5 ft. 1" diameter dark brown clay ball inclusion @ 4'. Occasional very coarse sand to fine gravels strewn throughout. Several cobble-sized angular clasts @ 4.5'. Colour change to olive brown @ 5.25'.	5 YR 4/4	🟥	CW02/02 4-4.5	Subglacial till, Mixed Superior-Winnipeg provenance.
Qco	8.5-12.5: Poorly sorted, tan to light brown massive sand and gravel. Predominantly medium sand, but ranging from fine to very coarse. Fine to medium subrounded gravels; felsic, mafic and red volcanics, and metasedimentary lithologies. Some rusted cemented layering below 9.5'. Occasional very coarse gravels to fine cobbles, some rounded to well-rounded. Becomes cobbly/gravelly @ 12', then better sorted medium to very coarse sand below, though sands are very loose and likely experienced mixing and/or settling in core liner.	10 YR 4/4	🟥	CW02/03 8.5-10.5	Proglacial outwash, Superior provenance.
Qco			🟥		
Qco	13.5-15.5: Fine tan to brown sand with lesser medium to very coarse sand and occasional subrounded to rounded gravels. Varied lithologies, some iron fm., vesicular basalt. Sand becomes mostly coarse to very coarse @ 15'.		🟥		

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Description

18.5-19: Vaguely stratified dark brown medium sand. Moderately well-sorted, but with coarse to very coarse sand and occasional fine gravel. 1 or 2 coarse subrounded gravels. Predominantly clear quartz, other felsics igneous, some reds in sand fraction.

19-19.5: Poorly-sorted fine to very coarse sand and fine to medium gravel. Lighter in overall colour than above, but more visible mafic component. Low recovery.

19.5-20.5: Brown medium sand with occasional subhorizontal bedding with brown, well-sorted very fine sand, grading into very poorly-sorted fine to very coarse sand and fine to medium subangular to subrounded gravel below 20'. Rich in darks, reds.

21-22: Very well-sorted light brown fine sand with occasional black ripples.

22-22.5: Sharp upper contact; lighter brown to tan medium to coarse sand. Moderately well-sorted. Massive.

23.5-25: Very poorly-sorted fine to very coarse sand and gravel. Dominated by coarse to very coarse sand and fine gravel. Poor recovery.

25-26.5: Well sorted, massive, brown medium sand. Increase in clear quartz from above.

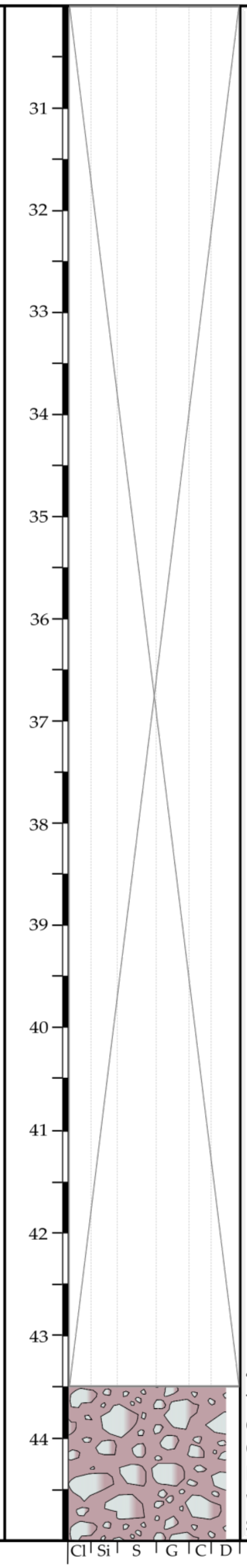
26.5-28.5: Stratified brown sand. Beds vary from medium to very coarse sand, and 3" to <0.5" in thickness. Frequent dark black layers of fine sand. Apparent ~10 degree dip but could be drilling induced.

Colour	HCl*	Sample**	Notes
10 YR 4/4	🟥	CW02/04 15-15.5	
10 YR 3/4 (c. sand)	🟥	CW02/05 19-19.5	
	🟥		Proglacial outwash, Superior provenance.
10 YR 5/3		CW02/06 22-22.5	
	🟥		
	🟥	CW02/07 27-27.5	

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

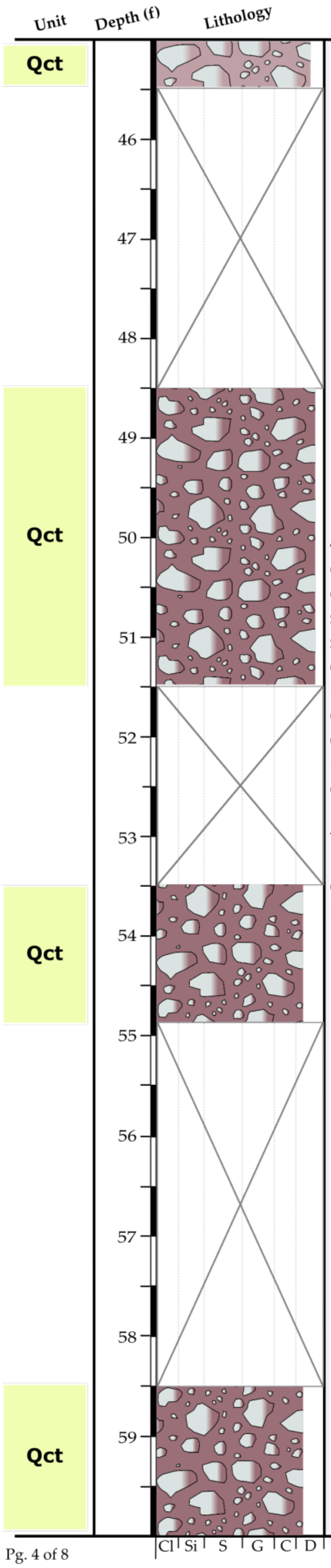
CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
Qct			43.5-44.5: Massive, purplish-red, faintly stratified, matrix-supported diamicton. Sandy loam matrix. Granular breakage structure. Stratified black residue present beneath weathered mafics. Several large (2"-3") subangular and subrounded mafics.	5 YR 4/2	🟦	CW02/08 44-44.5	Subglacial till, Superior provenance.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015
CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Description

44.5-60.5: Reddish-brown, relatively compact, massive, matrix-supported diamicton. Sandy loam matrix, granular structure. Moderately clast-rich; subangular to subrounded fine to very coarse gravels. Many metasedimentary lithologies including slate and greywacke. Lesser red volcanic component. Rare to absent light felsic igneous component. Apparent well-developed clast macrofabrics in places. Matrix texture is slightly finer grained from 44.5-45.5'. Silt siltier from 53.5-54' and 58.5-60.5'. Fewer large clasts, more felsic igneous and more rounded clasts below 58.5'.

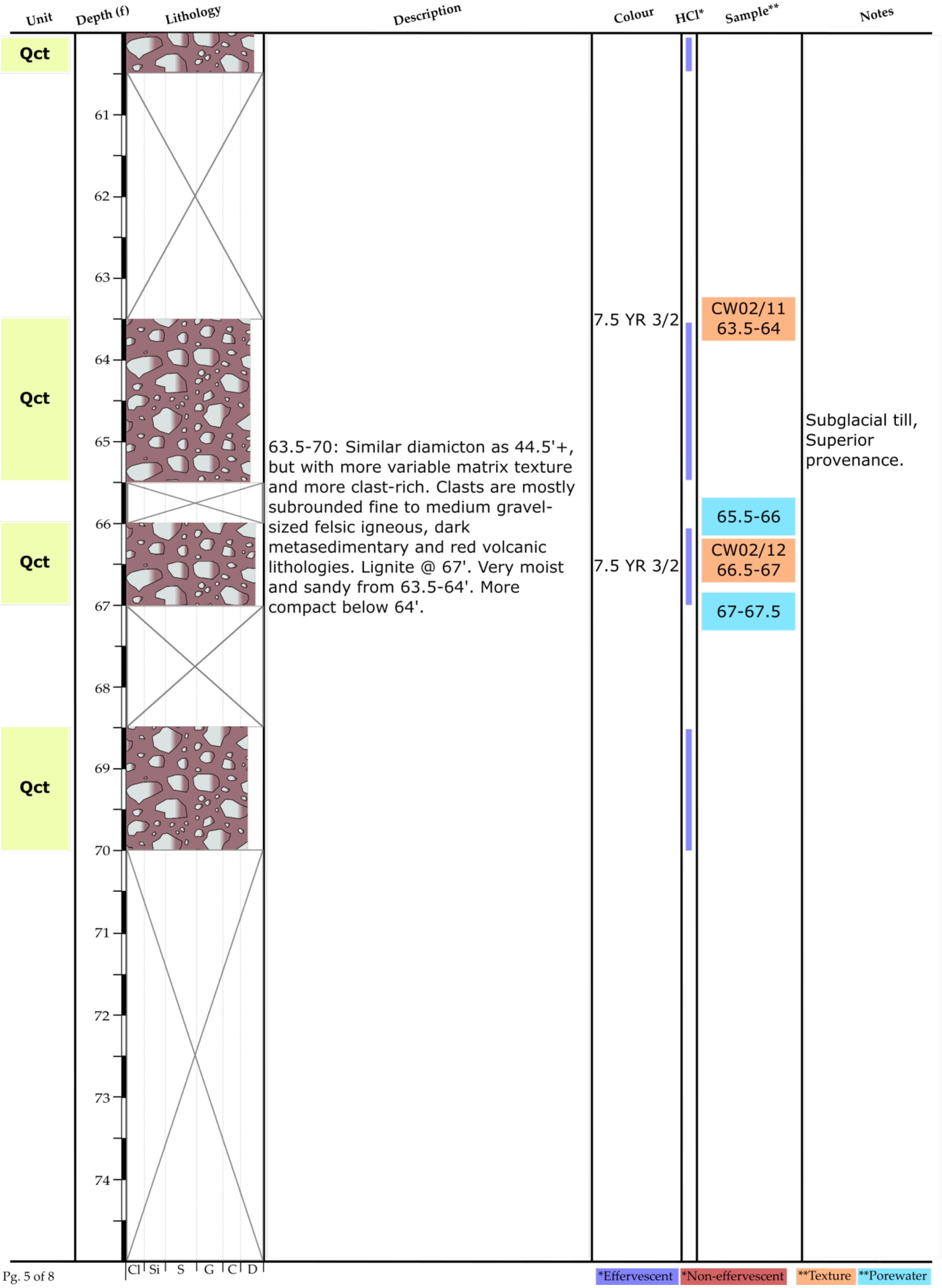
Colour	HCl*	Sample**
7.5 YR 3/2		CW02/09 48.5-50
7.5 YR 3/2		CW02/10 54-54.5

Notes

Subglacial till, Superior provenance.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015
CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



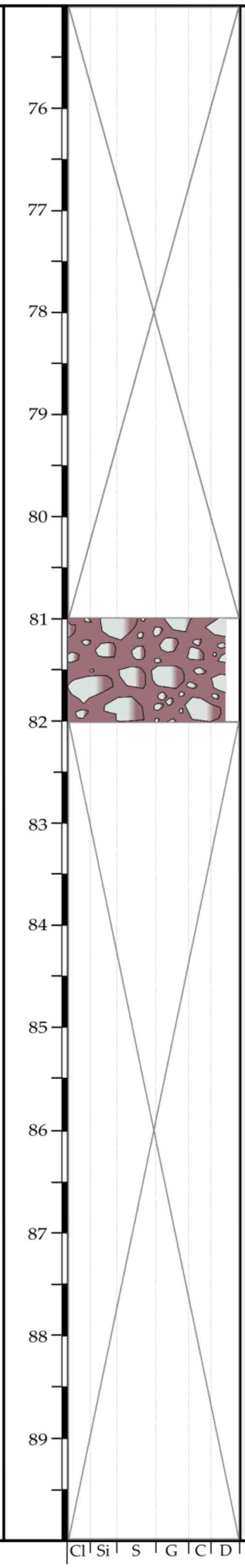
63.5-70: Similar diamicton as 44.5'+, but with more variable matrix texture and more clast-rich. Clasts are mostly subrounded fine to medium gravel-sized felsic igneous, dark metasedimentary and red volcanic lithologies. Lignite @ 67'. Very moist and sandy from 63.5-64'. More compact below 64'.

Subglacial till, Superior provenance.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS

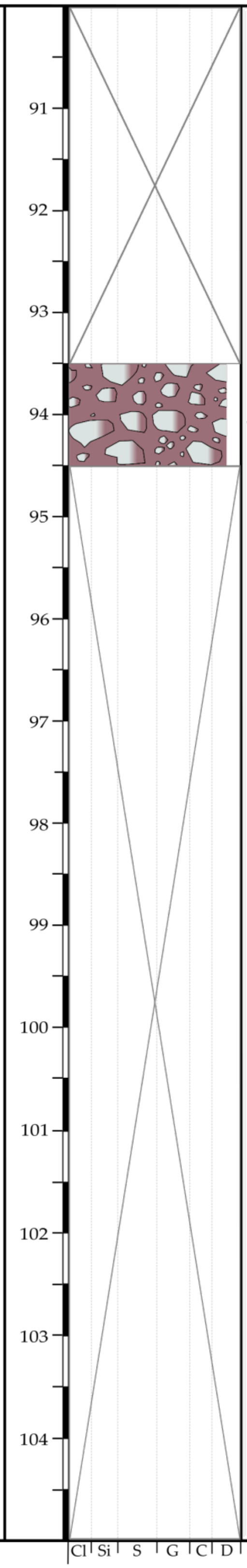


Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
Qct	81-82		81-82: Similar to 63.5+. Reddish-brown to reddish-grey, massive, matrix-supported diamicton. Sandy loam matrix. Relatively clast-poor in this interval. Similar lithological assemblage as above.	7.5 YR 3/2	▮	CW02/13 81.5-82	Subglacial till, Superior provenance.

🟦 *Effervescent 🟥 *Non-effervescent 🟧 **Texture 🟦 **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015

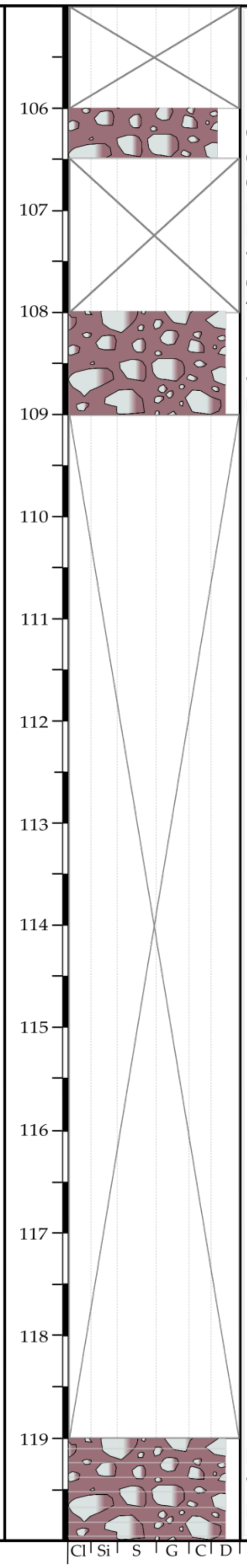
CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Unit	Depth (f)	Lithology	Description	Colour	HCl*	Sample**	Notes
Qct	94		93.5-94.5: Similar to 81'+. Matrix has slightly redder hue and siltier texture. Very coarse gravel-sized broken-up slate clast @ 94.5'.	7.5 YR 3/2	🟦	CW02/14 94-94.5	Subglacial till, Superior provenance.

*Effervescent *Non-effervescent **Texture **Porewater

Core ID: CW02 **Location:** Cromwell, MN **Elevation (f):** 1331.9 **Drilling Method:** Hollow-stem **Logging Date:** 10/21/2015
CWI Unique No.: 773064 **Co./T/R/S/SS:** 09/49N/20W/33/CABABA **Coring Date:** 06/26/2015 **Logging Geologist:** Kaleb Wagner **Location Described:** MGS



Unit	Description	Colour	HCl*	Sample**	Notes
Qct	106-106.5: Reddish-brown to reddish-grey, massive, matrix-supported diamicton. Sandy loam matrix. Coarse gravel-sized (3" a-axis) well-rounded metasedimentary clasts @ 106'. Same lithological assemblage as above (red volcanics and metasedimentary rocks dominant). Slightly redder matrix hue than above.	7.5 YR 3/2	🟦	CW02/15 106-106.5 106.5-107	Subglacial till, Superior provenance.
Qct	108-109: Similar diamicton as 106'+ with slightly sandier matrix. Retains red hue.	7.5 YR 3/2	🟦	CW02/16 108.5-109	
Qct	119-120: Similar diamicton as 108'+, but very faintly stratified. Apparent well-developed clast macrofabrics ~ parallel to sense of stratification.	7.5 YR 3/2	🟦	CW02/17 119.5-120 120-120.5	Subglacial till, Superior provenance.

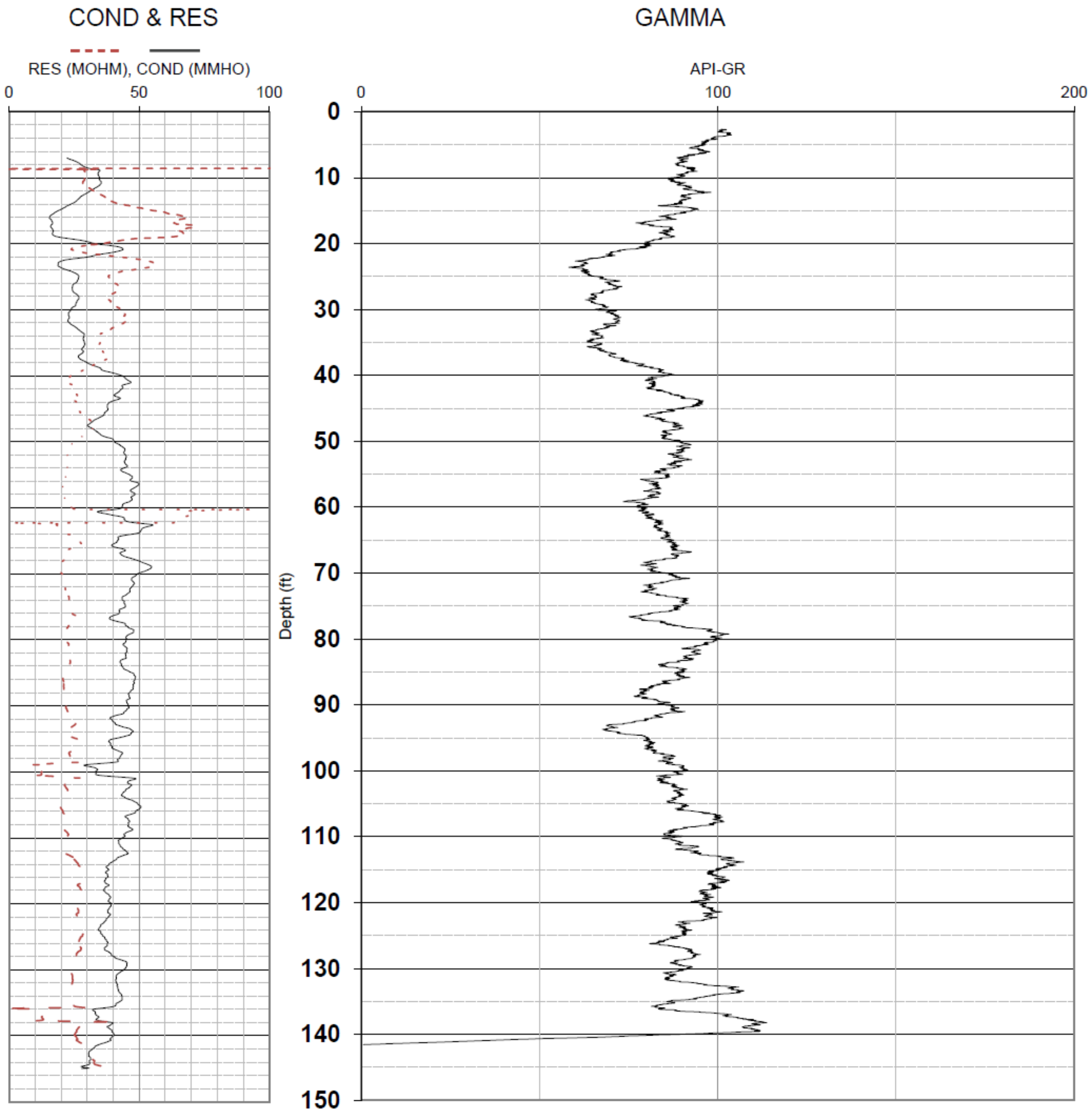
🟦 *Effervescent 🟥 *Non-effervescent 🟧 **Texture 🟦 **Porewater

Appendix B – Borehole geophysical logs

EM Induction Log – CWO1A

Unique Number: **CW01A_em_induction.xlsx**

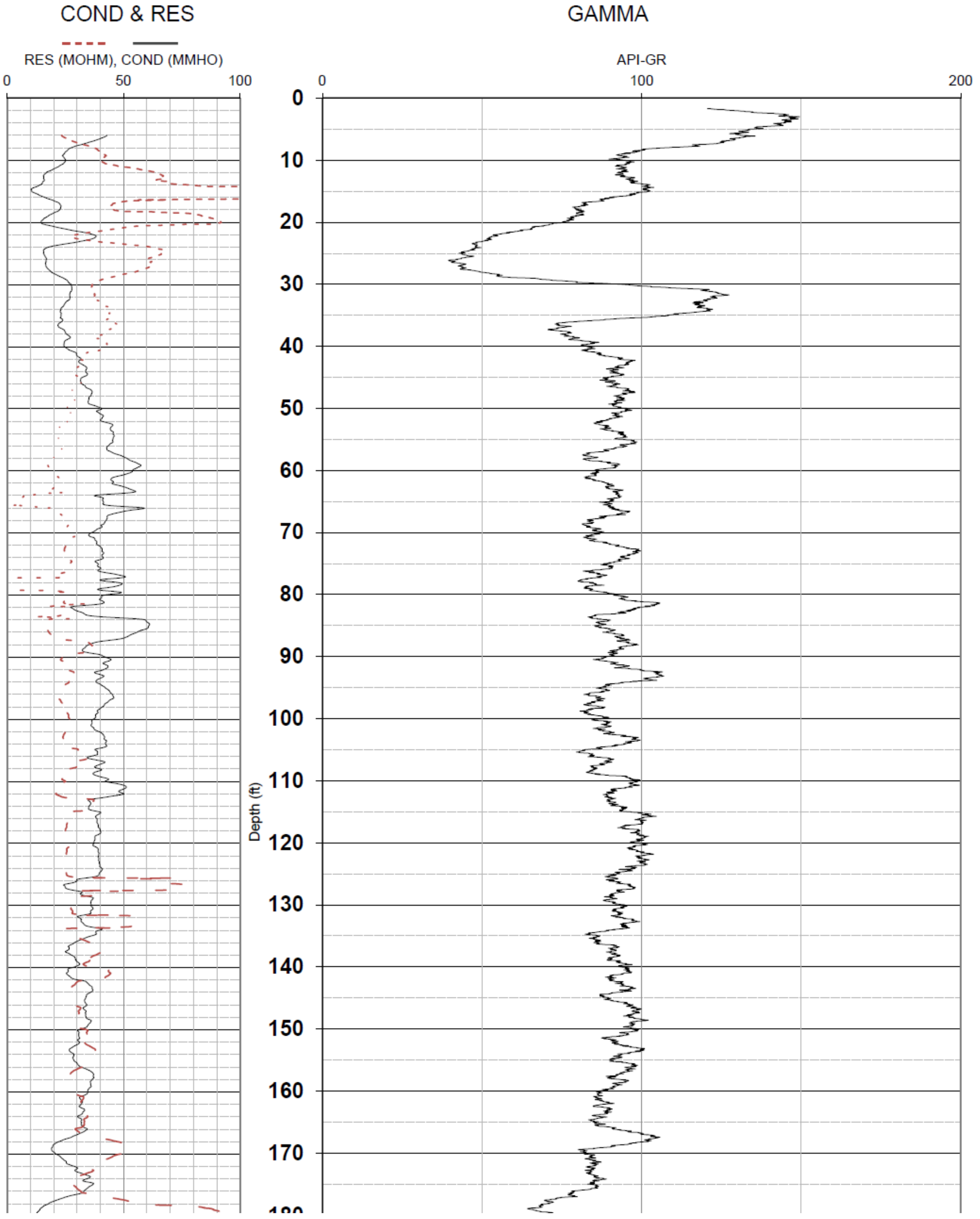
Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969

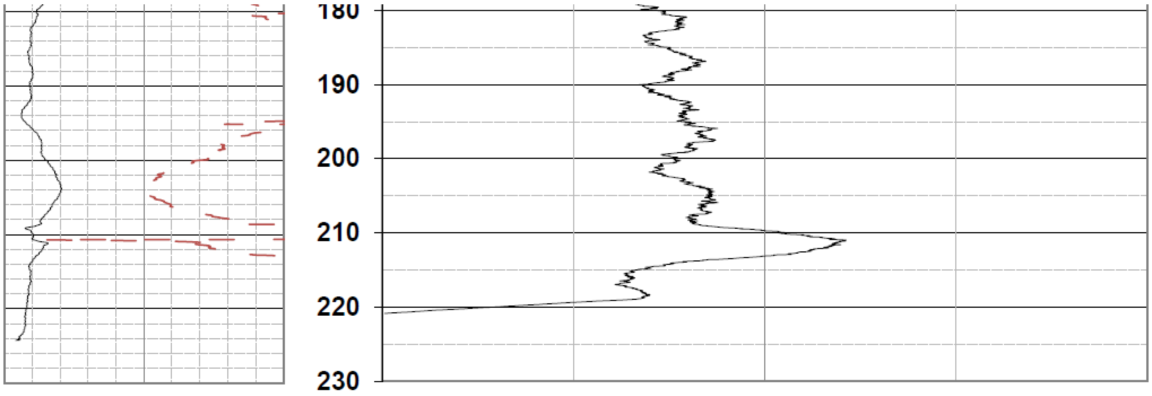


EM Induction Log – CWO1B

Unique Number: **CW01B_em_induction.xlsx**

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

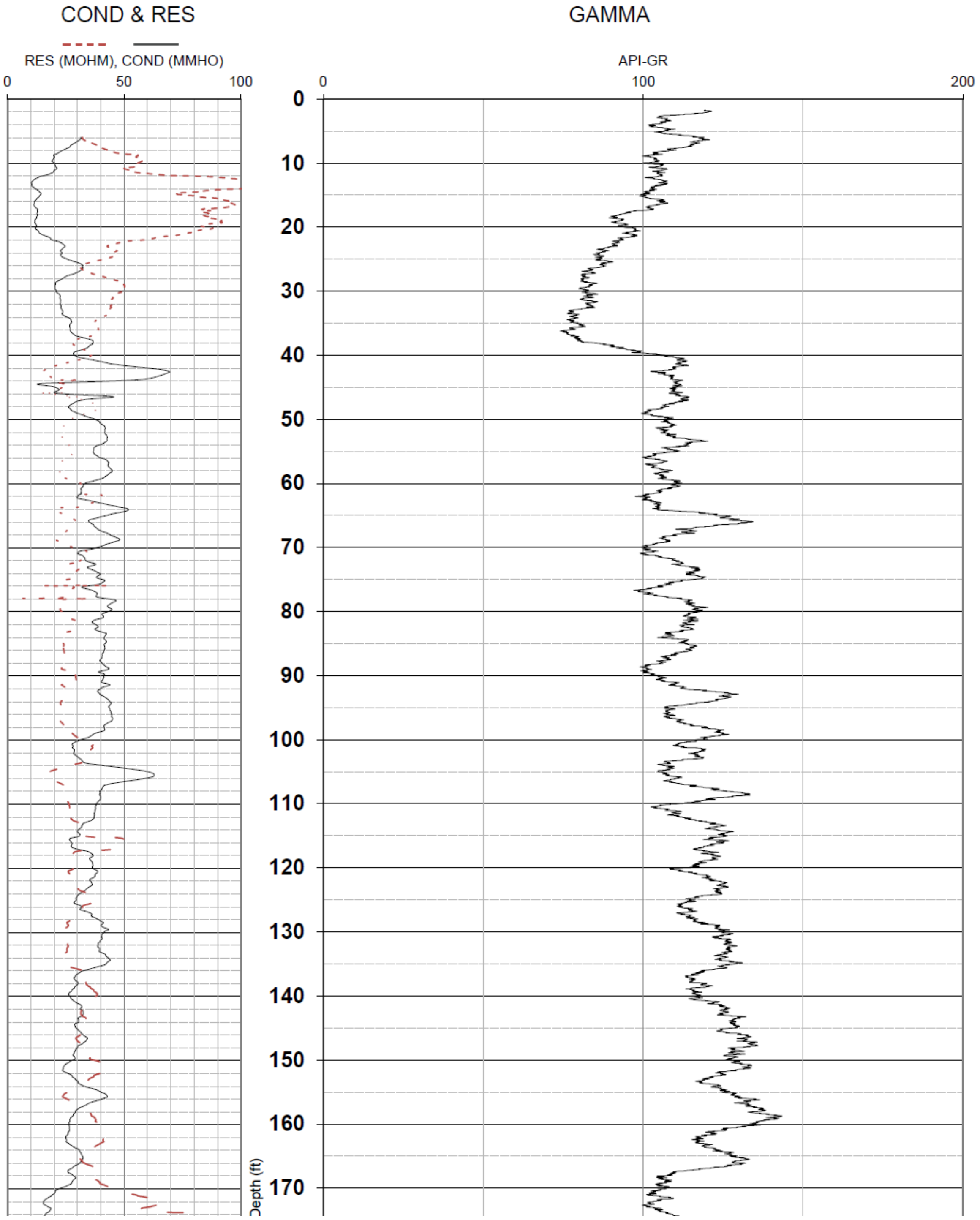


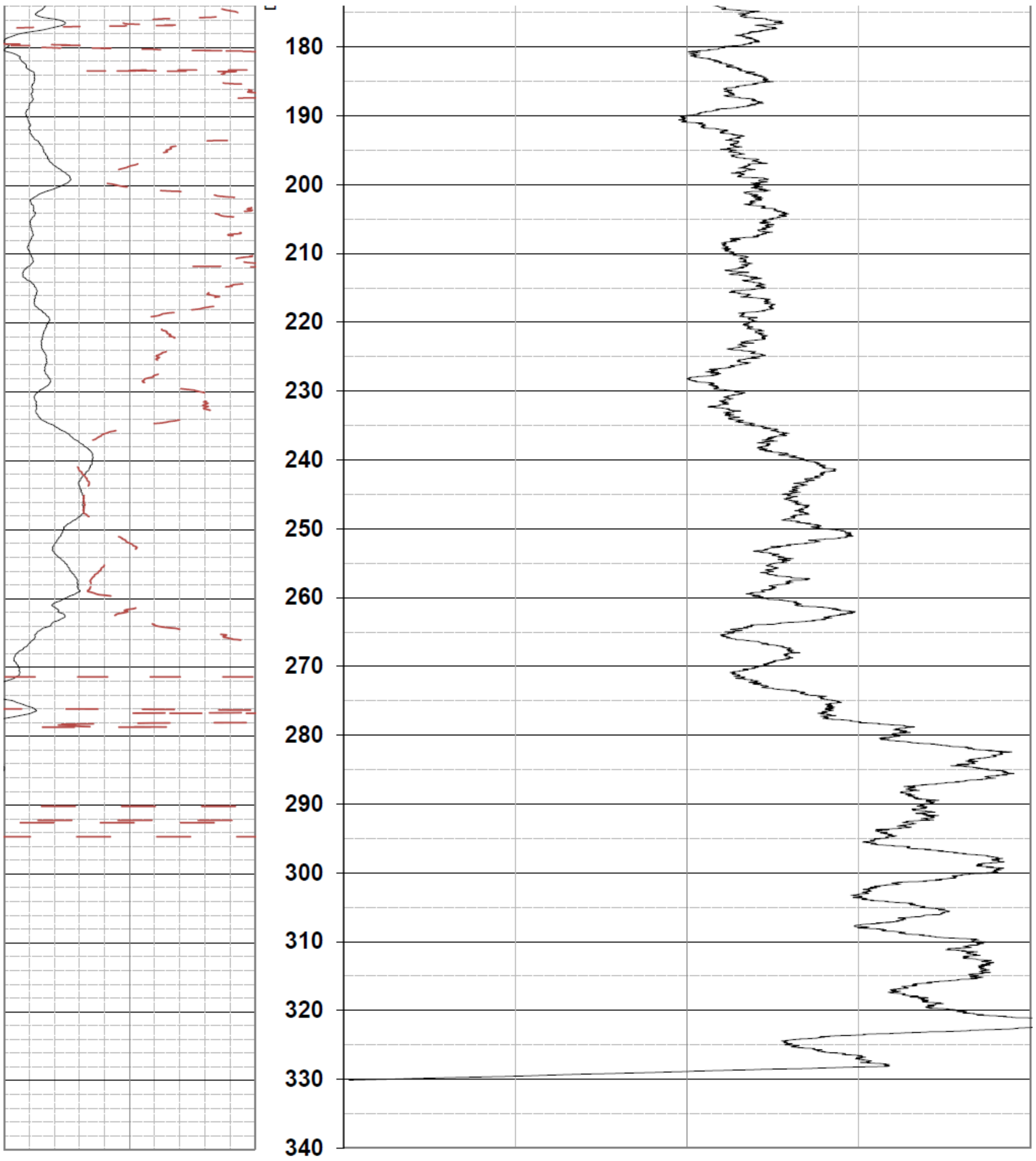

180
190
200
210
220
230

EM Induction Log – CWO1C

Unique Number: **CW01C_em_induction.xlsx**

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

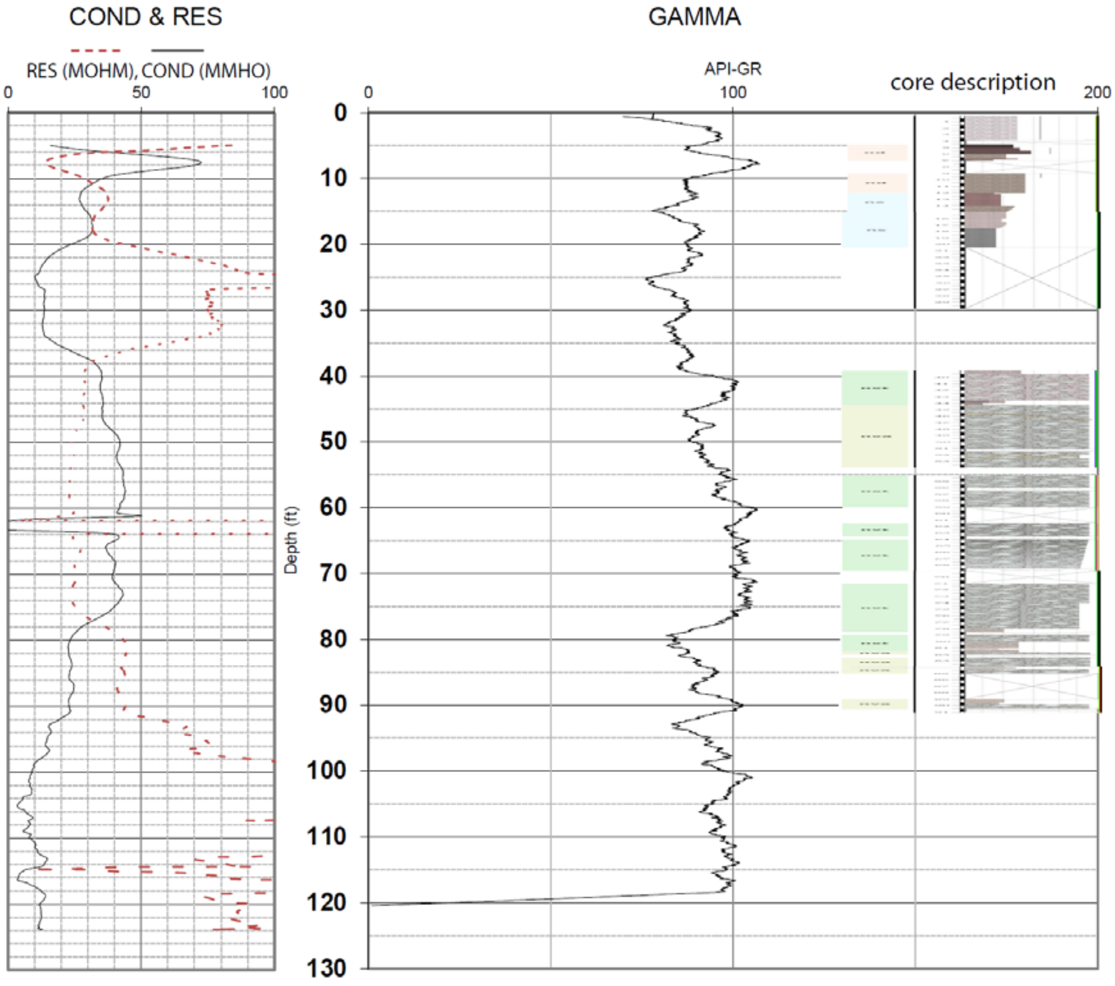



180
190
200
210
220
230
240
250
260
270
280
290
300
310
320
330
340

EM Induction Log with core description (see Appendix A) – LFO1F

Unique Number: **LFO1F_em_induction.xlsx**

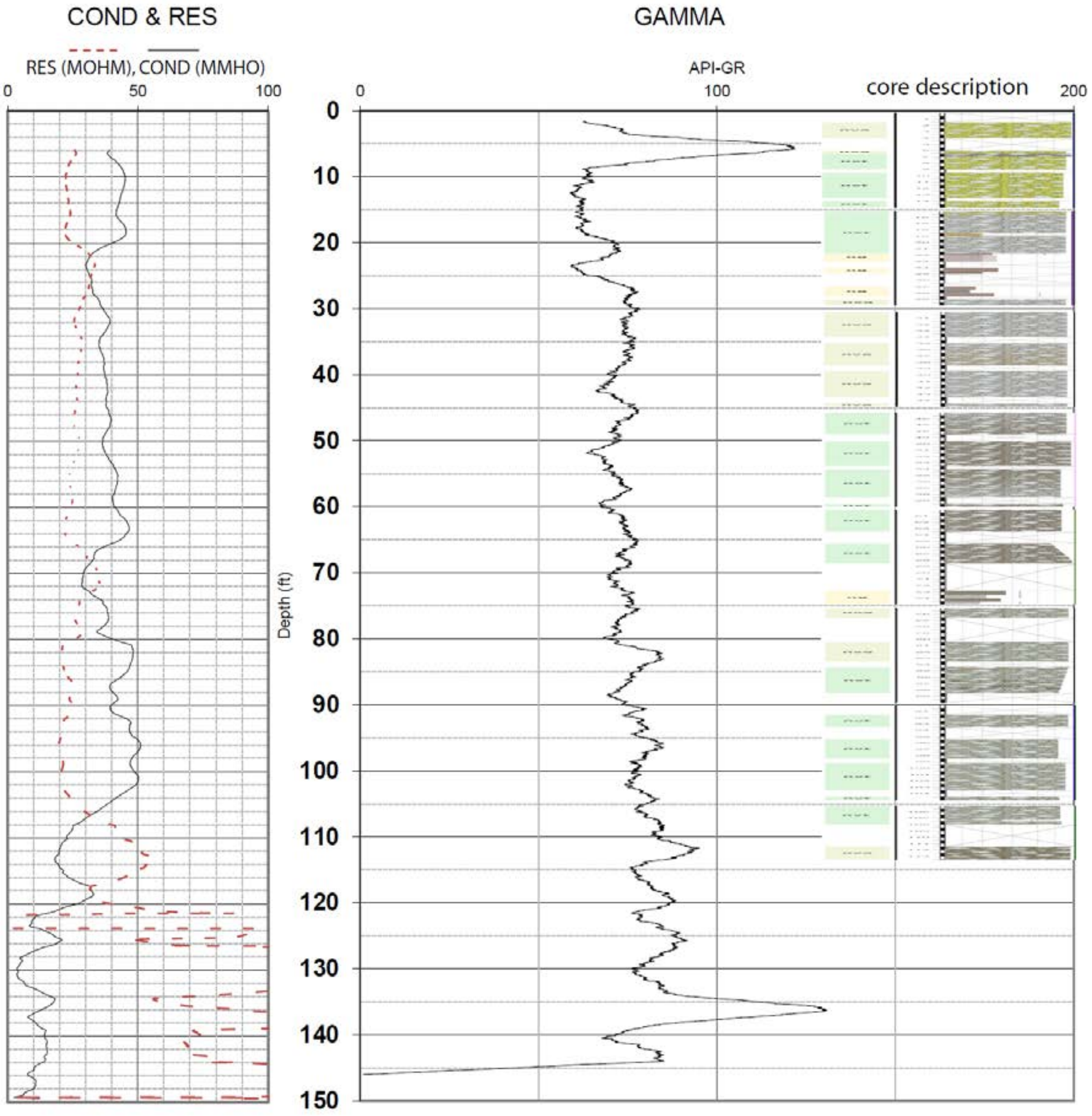
Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969



EM Induction Log with core description (see Appendix A) – LFO2F, first run

Unique Number: **LFO2F_em_induction.xlsx**

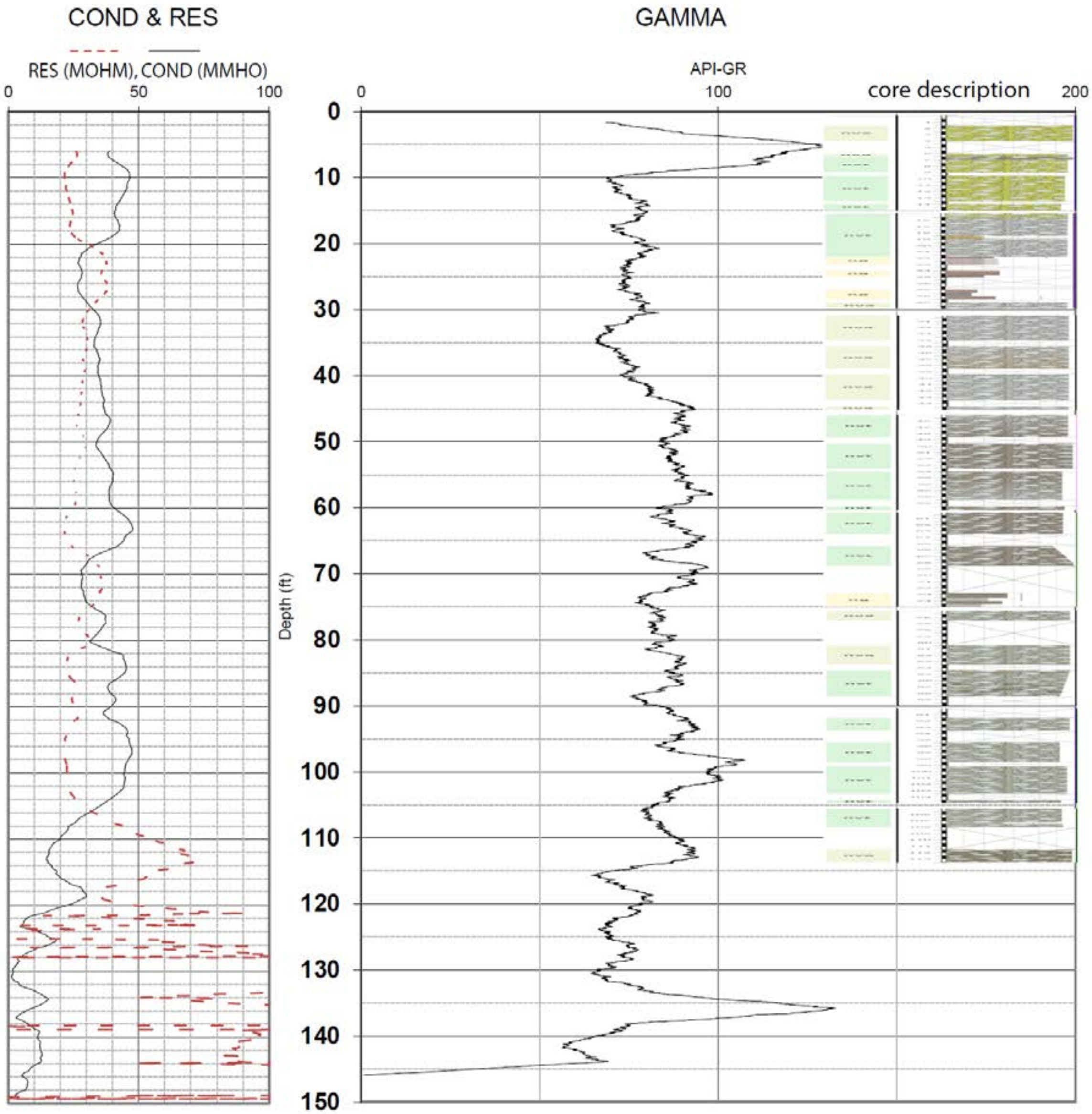
Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969



EM Induction Log with core description (see Appendix A) – LFO2F, second run

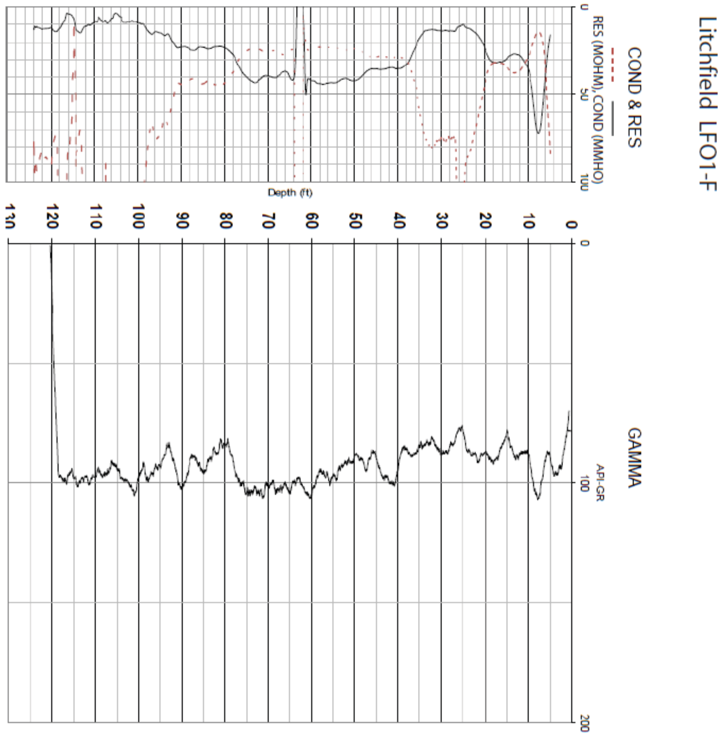
Unique Number: **LFO2F_em2_induction.xlsx**

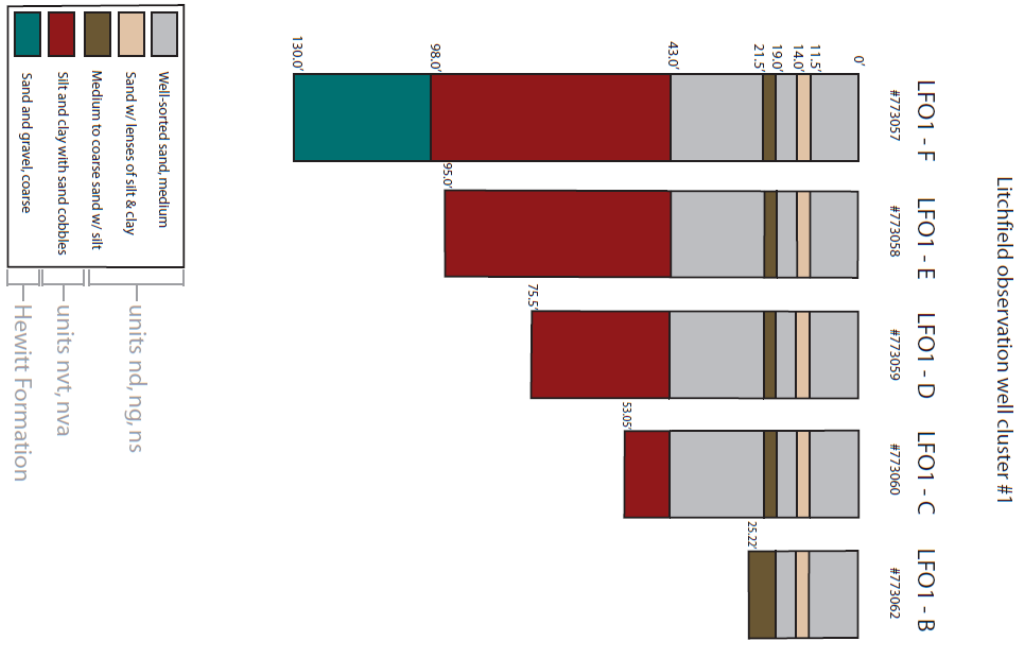
Minnesota Geological Survey
University of Minnesota
2609 Territorial Rd.
St. Paul, MN 55114
(612) 626-2969



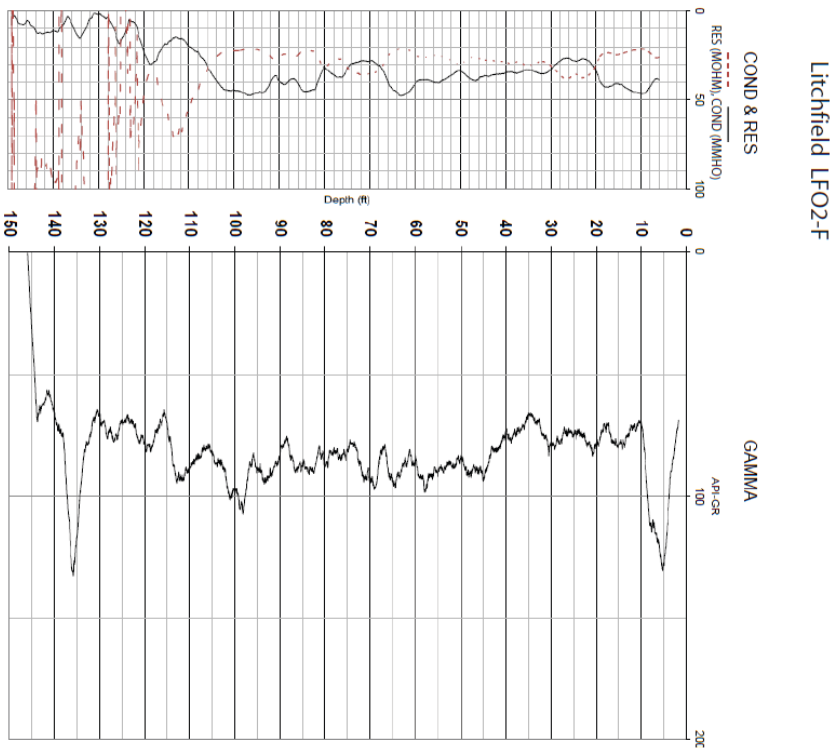
Appendix C – Generalized borehole lithostratigraphy and borehole geophysical logs

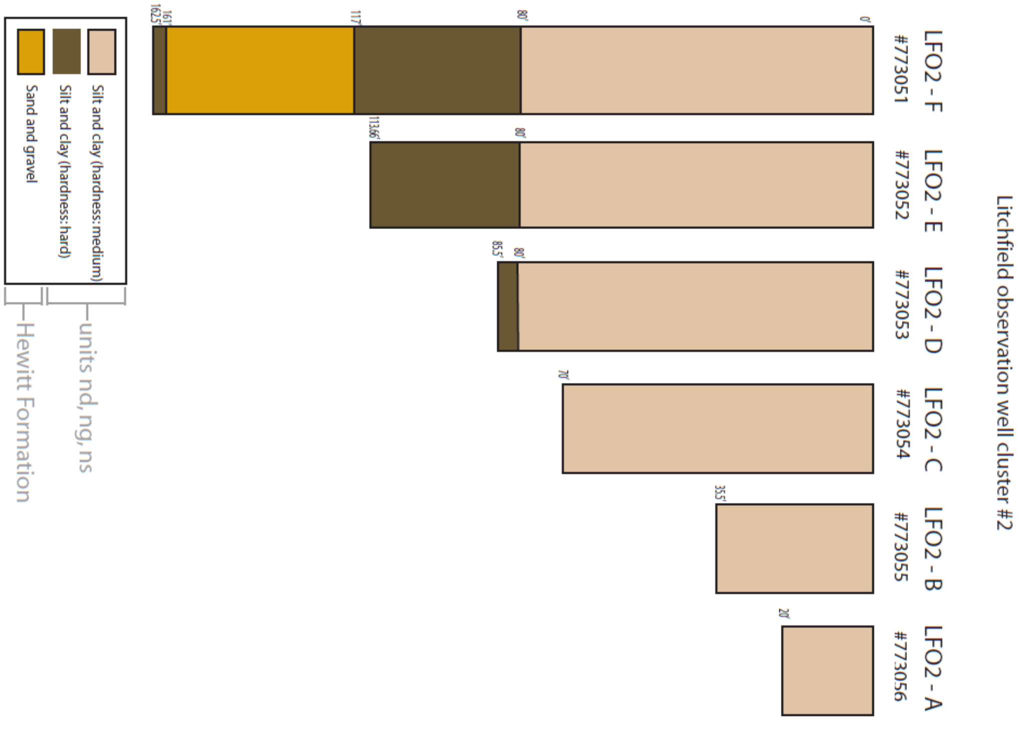
Litchfield observation well cluster 1



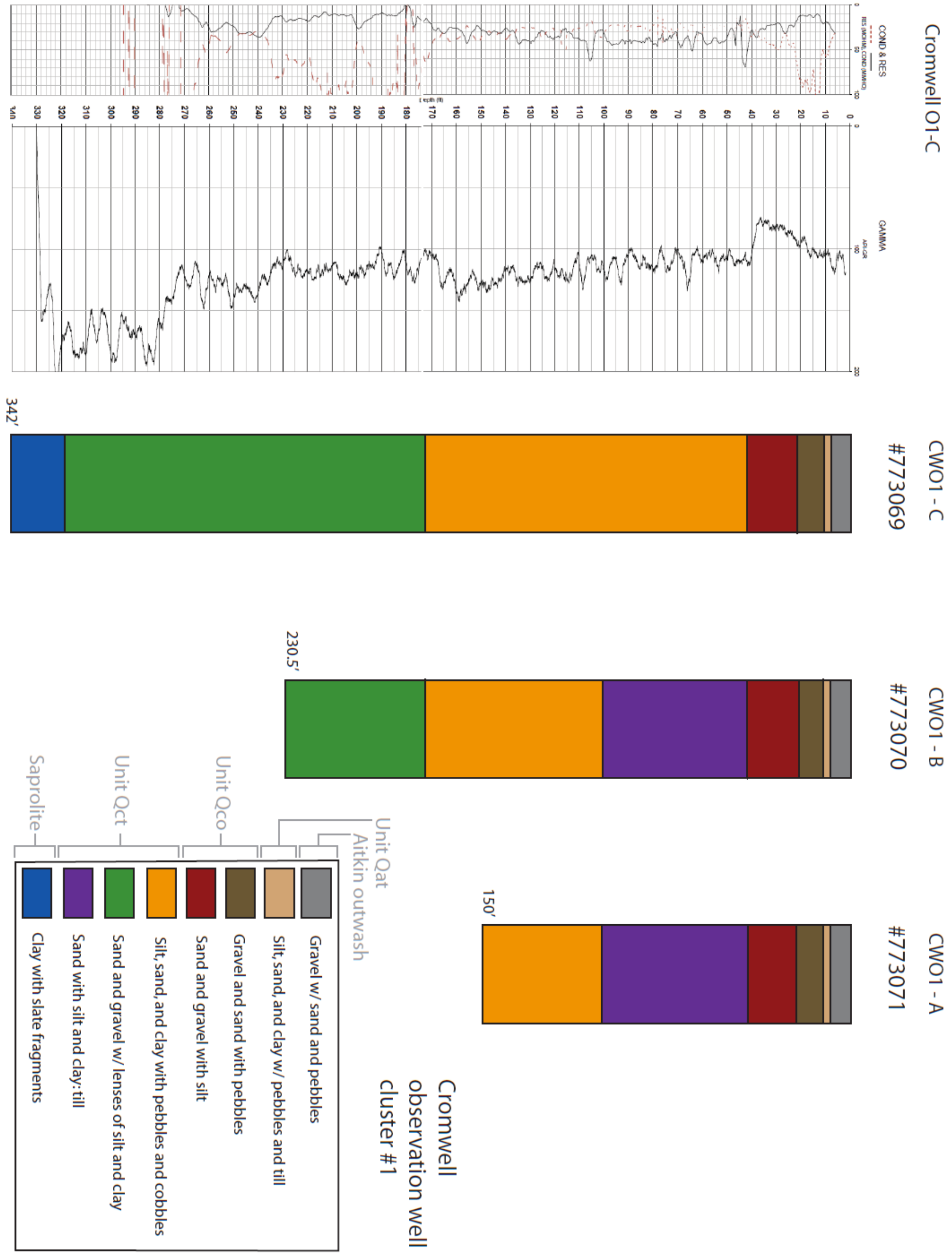


Litchfield observation well cluster 2





Cromwell observation well cluster 1



Cromwell observation well cluster 2 (EM-induction log from cluster 1, CWO1-A)