Geological Survey of Canada
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SEDIMENTOLOGY AND GEOCHEMISTRY OF THE PURPLE WOODS BOREHOLE, SOUTHERN ONTARIO

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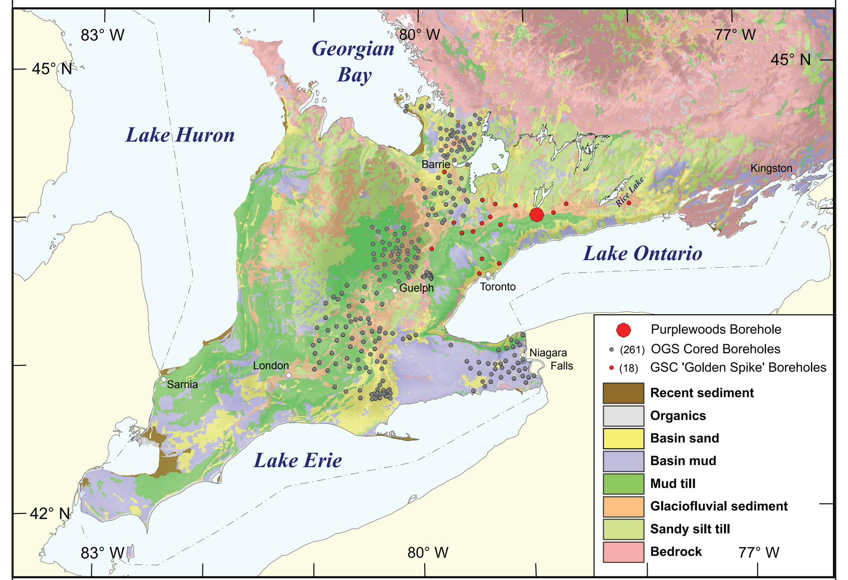


Figure 1: Simplified surficial geology of the southern Ontario area. Modified from Barnett et al., 1991.

Introduction

The development of predictive hydrogeological models is essential to support effective regional ground water management strategies. To better identify and assess aquifer resources, an understanding of local hydrogeology is imperative. In areas of limited hydrogeological data, aquifer potential of a sedimentary basin may be developed from sedimentological and stratigraphic data. Cored boreholes provide stratigraphic control that permits integration of related monitoring and hydraulic test data in a stratigraphic and/or hydrostratigraphic framework for hydrogeological characterization and analysis. Used in conjunction, lithological descriptions and stratigraphic analysis can assist in borehole correlations and provide fundamental information on basin architecture, sedimentology, and genesis. The collection of continuous core is a critical step in developing a sound 3-D geological framework and defendable predictive models (Sharpe et al., 2002). Data collected from continuously cored boreholes assists in both 2- and 3-D geological model development by:

i) providing a framework to interpret lower quality archival data (e.g. water well records)

ii) verifying geophysical data, and

iii) constructing and testing regional conceptual geological models.

The objective of this study is to document litho-stratigraphic and sedimentological data obtained from a 151.8 m deep borehole drilled near Rice Lake, Ontario (Figure 1). The sediment log was produced from bed by bed description of lithofacies, sedimentary structures, and from drill site inspection and drilling rate for unrecovered core.

Regional Setting

Regional mapping, terrain analysis and subsurface studies in the Greater Toronto Area indicate a sedimentary succession of up to 200 m. Figure 2 illustrates the generalized stratigraphy consisting of six major packages: Paleozoic bedrock, lower sediment (e.g. Scarborough, Thorncliffe formations), Newmarket Till, channel sediment, Oak Ridge Moraine sediment, and overlying Halton Till. An element of the stratigraphy is a number of regional unconformities, the most noteworthy of which is eroded into Newmarket Till and also forms the base of a series of large northeast to southwest trending tunnel valleys beneath the Oak Ridges Moraine.

Purple Woods Stratigraphy

Four stratigraphic units are present in the borehole core; from the base up 1) Blue Mountain Formation bedrock, 2) Thorncliffe Formation, 3) Newmarket Till, and 4) Oak Ridges Moraine sediments. The petroliferous shale bedrock is interpreted to be part of the Blue Mountain Formation. The Thorncliffe formation is ~45 m thick and consists of a 5 m thick upward fining succession of gravel-sand capped by 40 metres of mud. The overlying Newmarket Till is ~69 m thick and consists of a sandy-silt diamicton with cobbles, pebbles and granules. The top 33 m of the borehole consists of medium to fine massive sand with traction structures and is interpreted to be Oak Ridges Moraine sediment.

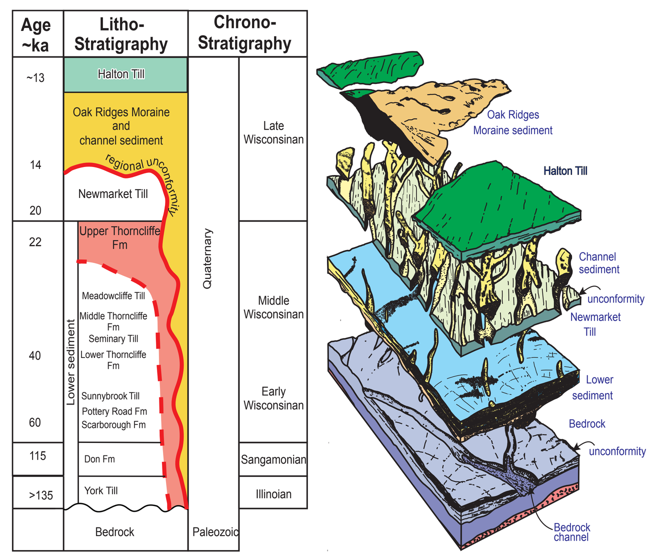


Figure 2: The regional stratigraphic framework of the study area. a) Lithostratigraphy and chronostratigraphy (modified from Karrow, 1974, ages from Barnett, 1992). b) Conceptual stratigraphic architecture (modified from Sharpe et al., 1997; 2011)

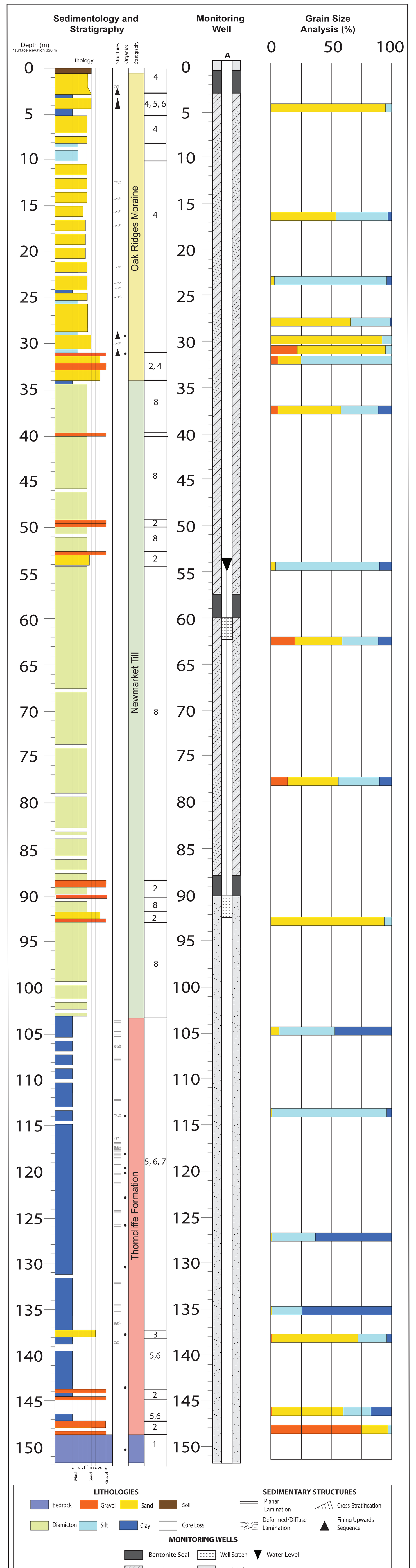
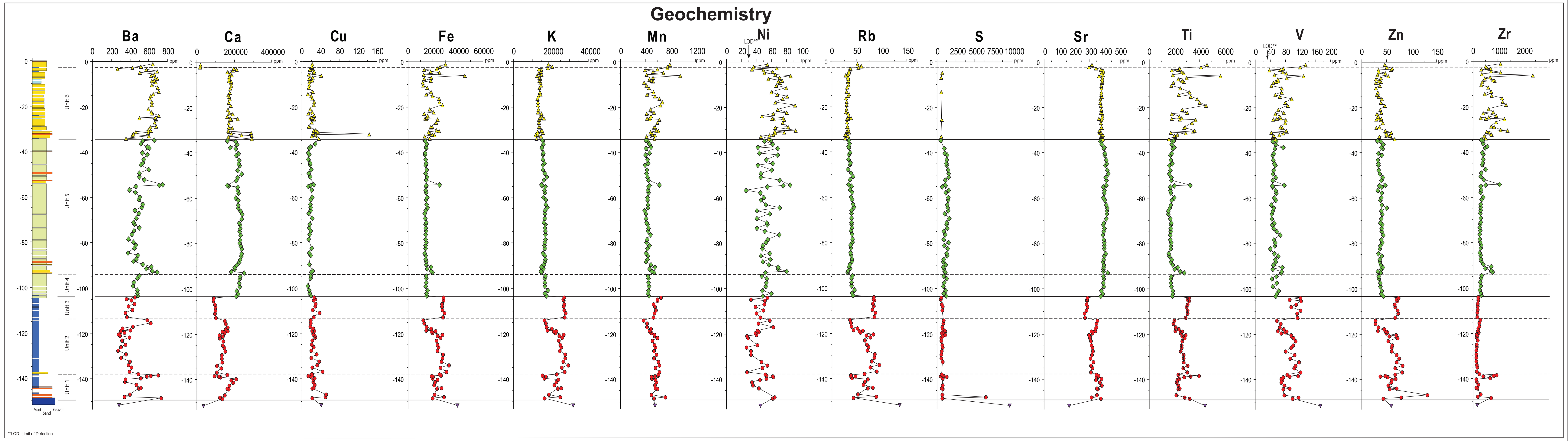


Figure 3: Sedimentological, lithological, stratigraphic logs and piezometer installation for the Purple Woods borehole.



Sediment Descriptions

Facies 1: Bedrock - Blue Mountain Formation

This facies occurs at the base of the hole and consists of black, fissile, petroliferous shale (Figure 4). It is commonly correlated with the Blue Mountain Formation (Armstrong and Dodge, 2007).

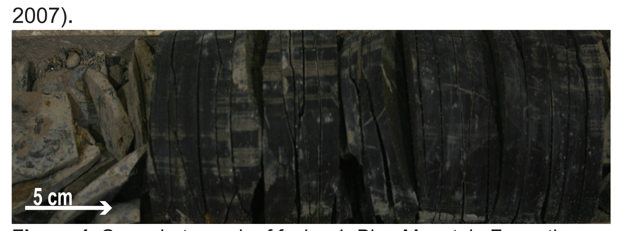


Figure 4. Core photograph of facies 1: Blue Mountain Formation

Facies 2: Sandy Gravel

The sandy gravel facies occurs throught the core as 40 to 50 cm thick beds that have sharp, basal contacts. Gravel is framework supported with a coarse sand matrix that fines upwards to medium sand (Figure 5). Clast size is approximately 20% granules and 80% pebbles and consists of 80% shale, 20% shield in the lower unit, and 50% carbonate, 50% shield in the upper unit.

Figure 5. Core photograph of facies 2: Gravel fining up to coarse sand with pebbles and granules.

Facies 3: Medium sand with organics

The medium sand with organics consists of a 1 m thick bed of fining upwards medium sand with large globules of dark, low density organic matter at the base and as an irregular 2 cm thick band near the middle of the bed (Figure 6). The basal contact is irregular. Colour changes from gray in the pure sand portion to rust coloured at the contact with organics.

Figure 6. Core photograph of facies 3: Sand with irregularly shaped organic globules with pronounced oxidation at the edges

Facies 4: Sand

Sand occurs at multiple locations in the stratigraphy as either a single 1 m thick bed within planar laminated silt clay (Facies 5), as two 1 m thick beds within diamicton (Facies 8), and as a 32 m succession of fining upwards, planar and cross-stratified beds that range in thickness from 0.5 – 4 m. Individual beds commonly grade from lower medium sand to silt, with sparse, sub-rounded to rounded pebbles (50% shield clast, 50% carbonate clast) concentrated at the base of the upper 32m succession and decreasing in abundance upwards (Figure 7).

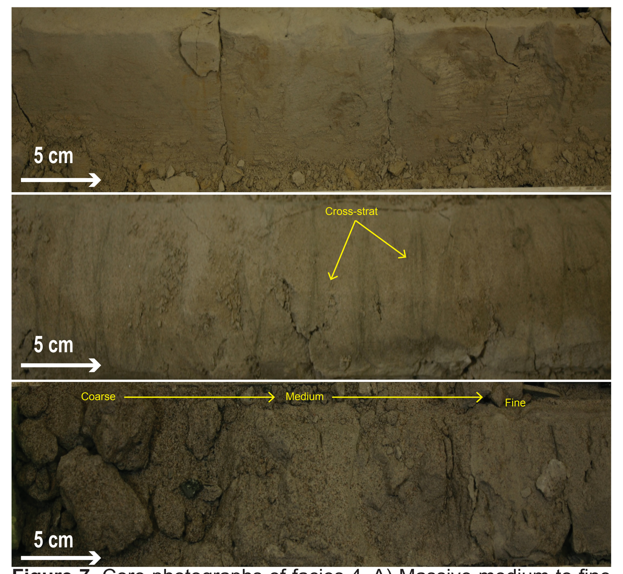


Figure 7. Core photographs of facies 4. A) Massive medium to fine sand. B) Planar to ripple-scale cross-stratified sand (see arrows). C) Fining-upwards sequence from very-coarse sand with sporadic dark pebbles/grains to fine sand over 50cm.

Facies 5: Cross-Stratified to Planar Laminated Mud

The cross-stratified to planar laminated mud facies consists of 1 – 5 cm thick, light grey beds of silt-clay with discontinuous, dark grey, mm-scale laminations that vary from ripple-scale cross-stratified to planar. The basal contact with gravel is abrupt. Where facies 5 overlies facies 6 basal contacts can be either abrupt or gradational. Occasionally, loaded beds with ball and pillow structures are observed at bed contacts with underlying massive mud. Localized, small-scale faulting (micro-faulting) is also observed throughout the mud facies (Figure 8).

Facies 6: Massive Mud

The massive mud facies is composed of 1 to 4 cm thick dark brown/grey massive mud layers that gradationally or abruptly overlie planar laminated mud (Facies 5). Within these massive mud layers, there are common mm- to cm-sized silty blebs (Figure 8).

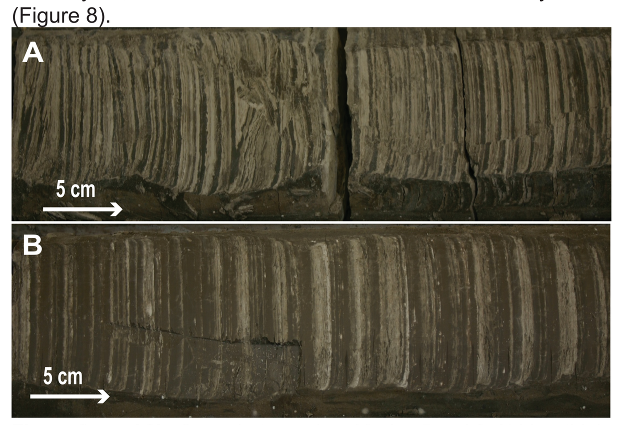


Figure 8a and 8b. Core photographs of facies 5 and 6. A) Very thinly (<1 cm) interstratified massive mud and cross-stratified to planar laminated mud (rhythmites) with microfaulting throughout. B) Thinly (1-2 cm) interstratified massive mud and cross-stratified to planar laminated mud (rhythmites).

Facies 7: Massive mud with granules

The massive silt-clay facies is a 12 m thick bed with sparse granule-sized subangular to sub-rounded carbonate clasts distributed irregularly throughout. Very weakly defined mm-scale diffuse laminations are sporadically present throughout the unit (Figure 9).

Figure 9. Core photograph of facies 7: Massive silt-clay.

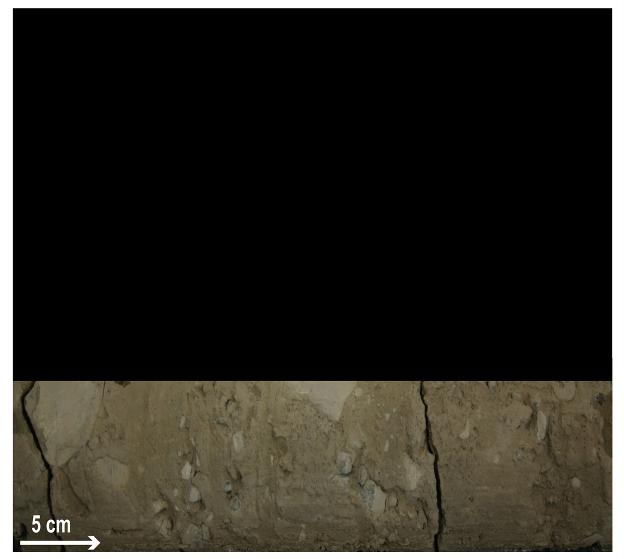


Figure 10. Core photograph of facies 8: sandy-silt diamicton.

Mud Facies Association

The cross-stratified to planar laminated mud (Facies 5) and massive mud facies (Facies 6) form a 41 m thick unit from 103 to 144 m. The individual couplets vary in thickness from 0.5 to 25 cm. Couplets are formed due to differential settling velocities of silt and clay which results in grain-size stratification. Traction structures are interpreted to have formed due to the reworking of the bed by an undercurrent (Figure 11). Variations in couplet thickness, bed spacing, grading and sedimentary structures produce a number of different rhythmite deposits (see Popovic et al., 2016 for descriptions of various types).

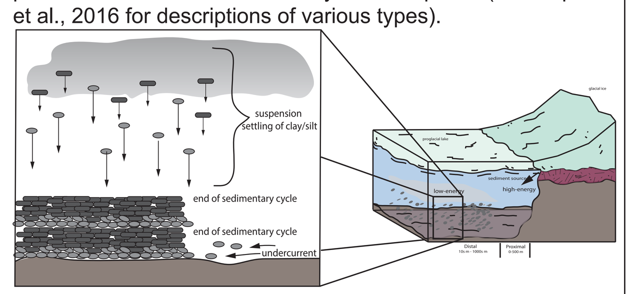


Figure 11. Depositional setting of rhythmites (facies 5 and 6)

Depositional Interpretations

Thorncliffe Formation

The lower 46 m of sediments in the Purple Woods core are interpreted to be part of the Thorncliffe Formation. The lower 1m thick sandy-gravel succession (from 149 to 148 m depth) is composed of angular shale and subrounded Precambrian shield pebble-sized clasts, in a coarse sand matrix, which is overlain by a 41 m thick succession of rhythmites from 144 m to 103 m depth. The sand horizon at 136 m depth contains detrital organic matter. On the basis of stratigraphic position, topographic location, bed thickness, grain size and stratigraphic upward fining to muds these two facies are interpreted to be part of the Thorncliffe Formation forming two elements within a deposited at an ice-marginal grounding line in a subglacial conduit to proximal subaqueous fan setting and an overlying glaciolacustrine basinal mud succession.

The fine-grained composition of the rhythmites suggests that there was very little influx of sediment, coarse silt laminae were likely deposited by density underflows and suspension deposition in a quiescent environment, of either a subglacial or proglacial lake (Figure 11). In glacial lacustrine settings, such bimodal cyclic deposits are commonly interpreted to be varves representing diurnal and seasonal meltwater production reflecting a melt season and winter season. During the summer, underflows deposit multiple laminae of silt, followed by the deposition of more clay-rich massive beds in the winter months when water column turbulence is low or weak due to ice cover (Antevs, 1925).

Newmarket Till

Regionally extensive Newmarket Till is interpreted to be incrementally deposited through active and passive subglacial deposition (Boyce and Eyles, 2000; Sharpe et al., 2002). The angularity and large grain size distribution within this unit indicates glacial abrasion and crushing. Two fining upwards sand beds (Facies 4) interbedded within the till could indicate localized subglacial meltwater flow (e.g. drainage event) in a distributed cavity / conduit system (e.g., Fountain and Walder, 1998).

Oak Ridge Moraine

The uppermost unit consists of a 35 m thick succession of fining upwards sand to silt (Facies 4 and 8) and is interpreted to be Oak Ridges Moraine sediment. Small-scale fining upwards sequences are observed locally within individual beds throughout the 35 m sequence; possibly indicating short term episodic events relating to changes in flow velocity, sediment supply and accommodation space. The large amount of sand within the Oak Ridges Moraine succession indicates that either the grain size is supply limited, that the transport capacity of the flow was only transporting sand, or that you are distal to gravel deposits. In this case, the sand deposition is interpreted to be a result of the latter based on the observed fining upwards successions within the sequence and known gravel deposits to the east within the moraine ridge.

Geochemistry

Borehole	Purple Woods	Easting	666973	Size Fraction:	<0.063 mm	Date Drilled:	May 2008
Location	Purple Woods Conservation Area	Northing	4878158	Original Material:	Disaggregated, seived	Date Logged	February 2015
Project	Groundwater Assessment	UTM Zone	17	Vial Window Material:	4 micron SpectroCertified Mylar polypropylene	Depth Drilled:	151.80m
Study Area	Oak Ridge Morraine	Datum	NAD83	pXRF:	Niton XL3t GOLDD, 50-kV Cygnet X-ray tube	Borehole Diameter:	4 inches
				Dwell Time:	60 seconds per High, Main, and Low filter		
				Mode Type:	Soil Mode, Compton normalization		

Portable X-ray fluorescence spectrometry has proven to be a successful tool to characterize the chemostratigraphy of glacial derived sediments (Knight et al., 2015) and to augment the interpretation of downhole geophysics, micropaleontology results, and pore water geochemistry (Mediloi et al., 2012). This method is best suited to the <0.063 mm size fraction (Plourde et al., 2012, Knight et al., 2012) of unconsolidated sediment that represents crushed bedrock detritus and reworked surficial sediments. The analysis from these studies demonstrate the utility of pXRF analysis for characterization of chemical and mineralogical variations within aquifers and aquitards.

The pXRF derived data was interpreted using single element trends from the base to the top of the borehole. Fourteen elements (Ba, Ca, Cu, Fe, K, Mn, Ni, Rb, S, Sr, Ti, V, Zn, and Zr) were detected in sufficient quantities to produce meaningful results using the pXRF spectrometer. Complete results as well as precision and accuracy using standard reference materials are compiled in Knight et al. (2016).

Chemostratigraphy of the Purple Woods borehole can be divided into 6 units: Units 1-3 are in the Thorncliffe Formation; Units 4-5 are in the Newmarket Till and; Unit 6 is the Oak Ridges Moraine sediments.

Unit 1 (148-138 m; Thorncliffe Formation): Sediments are dominated by angular shale clasts and sub-rounded Precambrian shield pebbles in a coarse sand matrix overlain by grey, closely spaced, clay rhythmites. Unit 1 is defined by a constant increase in Ca and a decrease in Ti, V and Zr over the same interval as the lithological change.

Unit 2 (140-113 m; Thorncliffe Formation): The Ca content of unit 2 displays a marked decrease in concentration compared to the underlying sediment but is still greater than the content of the overlying unit 3 sediments. In the top 5 meters of the unit Fe, K, Mn, R, Ti, V, and Zn all display a decrease in concentration with Sr and Zr displaying a slight increase in concentration.

Unit 3 (113-103 m; Thorncliffe Formation): In this unit sands and silts are overlain by dark grey coloured clay. The sediments that comprise unit 3 display a sharp decrease in the concentration of Ca, Sr, and Zr and an increase in the concentration of Fe, K, Mn, Rb, Ti, V, and Zn. This indicates a change in provenance from carbonate rocks to dominantly shield terrain. Variability in Ni is most likely due to concentrations being near the detection limit.

Unit 4 (103- 94 m; Newmarket Till): Generally, element concentrations in unit 4 return to values similar to those of the uppermost 4 samples of unit 2. However Ca concentrations are considerably higher than the underlying units but are comparable to the highest concentrations obtained from the top of unit 1.

Unit 5 (94-34 m; Newmarket Till): This unit contains sand horizons (located at the base of the unit and at 54 m depth) that display an increase in Ba, Fe, Mn, Ni, Ti, and Zr. Elemental concentrations for K, Rb, and Sr are very consistent in unit 5. Furthermore, Cu and S display no change in concentration between unit 4 and unit 5. Seven samples above the lowermost spike in concentration for the sand unit display a consistent increase in Ca, K and Rb. Ti displays a decrease in concentration over this same interval. This trend could be the result of a steady adjustment to a change in provenance or to element mobility due to fluid migration within the diamicton above the sand horizon contact.

Unit 6 (34-0 m; Oak Ridges Moraine sediment): The interbedding of fine to course sand and gravel in the basal 5 m of the unit is reflected in the high degree of variability in the chemistry of many elements. Some elements such as K, Rb, and Sr display little to no variability throughout the unit and with the underlying unit 5 chemistry, until the uppermost 3 samples where surficial soil forming processes are reflected in a shift in elemental concentrations for many elements (eg.Ca, K, Rb, Sr, Ti, and V). Fe, Mn, Ti, V, and Zr display a high degree of variability throughout unit 6 compared to the underlying unit 5 sediments, likely a reflection of the variability in the provenance of the silt and clay size fraction.

Geochemical trends suggest that the provenance of the Purple Woods borehole sediment is relatively consistent and depositional processes did not partition sediment adequately to impart a strong signal for most of the borehole, however unit 3 and 4 do display marked shifts in provenance from carbonate rocks to shield terrain.

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Acknowledgements

The Purple Woods core was collected under the auspices of the Eastern Central Ontario Conservation Authority and the Conservation Associations Moraine Coalition (CAMC). Transfer of the core was facilitated by Gayle Soo Chan (ECCA), Rick Gerber and Steve Holysh (CAMC) and David Sharpe (GSC). A critical review by David Sharpe is much appreciated. This work was carried out at GSC–Ottawa under the Aquifer assessments and support to mapping Groundwater Inventory Project of the Groundwater Geoscience Program. This work is a contribution of the GSC-OGS Southern Ontario project on groundwater 2014-2019.

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GEOLOGICAL SURVEY OF CANADA
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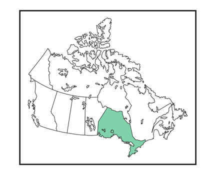

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doi:10.4095/299433

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Recommended citation
Coffin, L.M., Knight, R.D., Popović, N., Prowse, N.D., and Russell, H.A.J. 2017. Sedimentology and geochemistry of the Purple Woods borehole, Southern Ontario; Geological Survey of Canada, Open File 7899, 1 poster. doi:10.4095/299433

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