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Strathroy and Westminster sediment cores,
London area, southern Ontario**

R.D. Knight, L. Nicks, and H.A.J. Russell

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Lithofacies and chemostratigraphy of the Strathroy and Westminster sediment cores, London area, southern Ontario

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2023

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1.0 Introduction

The Groundwater Geoscience Program of the Geological Survey of Canada (GSC) has concentrated efforts on constructing and compiling a 3-D map of the subsurface beneath southern Ontario (Carter et al., 2021; Clark et al., 2020). Part of the program focused on establishing a regional-scale geochemical framework of unconsolidated glacial derived sediments that overlie the bedrock. The geochemical characterization of sediments is crucial to the understanding of previously glaciated terranes of southern Ontario. Although much work has been carried out on sequence stratigraphy and basin analyses of glacial derived sediments within this region, there remains a lack of associated geochemical data. Geochemical studies, in the form of chemostratigraphy, are crucial for advancing knowledge of chemical and mineralogical variations within sediments and supplement sediment description, grain size data, downhole geophysical and stratigraphic correlations (e.g., Crow et al., 2012). They also provide a geochemical baseline for assessing the interaction between host sediments and ambient groundwater chemistry. Geochemical data collected from borehole cores provide an opportunity to establish a chemostratigraphic framework that complements other stratigraphic correlation tools, such as lithostratigraphy, event-stratigraphy, and bio-stratigraphy.

To acquire a comprehensive geochemical dataset, the GSC in collaboration with the Ontario Geological Survey (OGS), Conservation Authorities, and non-government organizations, has spearheaded the application of portable X-ray fluorescence (pXRF) spectrometry as an alternative to expensive traditional laboratory based methods (Knight et al., 2021). With the use of pXRF spectrometry large sample sets can be analyzed in a cost-effective and time-efficient manner. This has allowed the GSC Groundwater Geoscience Program to establish geochemical assays of tills and sedimentary sequences within boreholes as a routine part of sediment studies. Contemporary research on pXRF spectrometry has shown that resulting analysis provide accurate geochemical data comparable to more traditional analytical techniques (Rouillon and Taylor, 2016).

The objective of this open file is to publish the analysis of 226 sediment samples collected in collaboration with the Upper Thames River Conservation Authority (UTRCA) from two cored boreholes located in Strathroy and Westminster, Ontario. Sediment samples were collected by the UTRCA and sent to the GSC in Ottawa where they were analyzed using a pXRF spectrometer. Resulting geochemical data and associated sediment lithologies should be considered as a baseline assay of the subsurface of this region of Southern Ontario. These boreholes represent the westward extent of the current Groundwater Geoscience Program project's study area. This report documents the contribution of these reference data to an emerging subsurface chemostratigraphic database for southern Ontario as illustrated in Figure 1 and summarized in Table 1.

Table 1. Summary of southern Ontario boreholes with geochemical analysis completed as part of a regional geochemical framework. Geochemical data from boreholes by pXRF methods are referenced in the right hand column. The following short form names under Source agency refer to GSC- Geological Survey of Canada, OGS – Ontario Geological Survey, CAMC- Conservation Authorities Moraine Coalition, UTRCA – Upper Thames River Conservation Authority, CLOCA – Central Lake Ontario Conservation Authority, U of Guelph – University of Guelph, U of Ottawa – University of Ottawa.

Borehole Name	Borehole ID	Easting	Northing	Depth (m)	Source Agency	Number of	pXRF	Laboratory Chemistry	Reference
Aurora	GSC-BH-AUR-01	626120	4871860	141	GSC	120	120	32	Knight et al., 2015a
Brantford-Woodstock	BW-07-05	504440	4784065	67.2	OGS	44	44		
	BW-07-06	516750	4766800	79.7	OGS	53	53		
	BW-07-07	527089	4764908	61.6	OGS	42	42	42	
	BW-07-09	510649	4761686	55.1	OGS	40	40		
	BW-07-15	542576	4773875	38.4	OGS	35	35		Knight et al., 2018c
	BW-07-17	537484	4783222	61.2	OGS	43	43		
	BW-07-20	559256	4789517	65.8	OGS	34	34		
	BW-08-06	500814	4762673	36.2	OGS	29	29		
Clarington	GSC-BH-CLA	672905	4872453	127	U of Guelph	96	96		Knight et al., 2016e
Dundas Valley	DV-05	541105	4800483	103.1	OGS	60	60		
	DV-06	518276	4814982	78.2	OGS	94	94	94	Stepner et al. 2018
	DV-08	520975	4812880	75.7	OGS	81	80		
Gads Hill	GH-10-01	509313	4812153	56.9	OGS	40	40		Knight et al., 2018b
GTA - Grasshopper	GSC-BH-GHP-01	679505	4879974	139.8	CAMC / GSC	185	185		
GTA - Kleinburg	GSC-BH-KLN-01	608497	4859678	104.9	CAMC / GSC	162	162		
GTA – Mount Albert	GSC-BH-MTA-01	635892	4886251	98.9	CAMC / GSC	92	92		Knight et al., 2018a
GTA - Pontypool	GSC-BH-PON-01	689068	4886446	171.1	CAMC / GSC	150	150		
GTA - Rice Lake	GSC-BH-RLK-01	735964	4887130	181.6	CAMC / GSC	170	170		
High Park	GSC-BH-HPK-01	624104	4834313	43.8	CAMC / GSC	58	58		Knight et al., 2016c
Strathroy	GSC-BH-SRY	448621	4751759	68.7	UTRCA / GSC	118	118		

London, Westminster	GSC-BH-WMR	484324	4754562	70.5	UTRCA / GSC	108	108		
Niagara Peninsula	BH13-NP-2014	628215	4749786	45.7	OGS	47		47	
	BH14-NP-2014	640187	4756676	42.1	OGS	38		38	
	BH27-NP-2014	633076	4758904	51.1	OGS	52		52	
	BH32-NP-2014	619599	4746591	46.4	OGS	41		41	
	BH33-NP-2014	638538	4777117	53.1	OGS	48	48		
	BH59-NP-2015	591658	4776011	42.2	OGS	39	39	22	
	BH77-NP-2015	562792	4762132	33.25	OGS	27	27		
Orangeville	BH09-OF-2008	553171	4852413	52.8	OGS	46		46	
	BH20-OF-2009	561002	4863630	22.5	OGS	25		25	
	BH23-OF-2009	568074	4864148	74.4	OGS	66		66	
	BH25-OF-2009	553103	4832245	31.7	OGS	29		29	
	BH27-OF-2009	561045	4834791	46.7	OGS	38		38	
	BH43-OF-2010	549394	4829200	36.7	OGS	43		43	
Oro	BH-30-AKB-2006	612147	4943667	54.9	OGS	66		66	
	BH-32-AKB-2006	609032	4928931	70.5	OGS	61		61	
	BH-37-AKB-2006	610966	4927024	102.1	OGS	94		94	
Pickering	GSC-BH-PIK1	657068	4867918	71.6	GSC/CAMC/ U of Ottawa	97	97	97	
	GSC-BH-PIK2	657061	4867916	11.4	GSC/CAMC/ U of Ottawa	14	14	14	
Purple Woods	GSC-BH-PWD	666973	4878158	151.8	CLOCA / GSC	135	135		Knight et al., 2016a
Queensville	GSC-BH-QUE	626499	4889266	96.2	CAMC / GSC	87	87	32	Knight et al., 2016b
South Simcoe	SS-12-02	602163	4902748	161.2	OGS	98	98	98	
	SS-11-04	586055	4878237	124.4	OGS	86	86		
	SS-11-08	590082	4894188	145.6	OGS	91	91		
	SS-12-03	593299	4906003	91.1	OGS	48	48		
	SS-12-04	610758	4905514	153.9	OGS	85	85		
	SS-12-07	612194	4877514	95.2	OGS	60	60	60	

	SS-12-08	604560	4890531	68.7	OGS	40	40	
	SS-13-06	612674	4896493	174.4	OGS	138	138	
Warden	2010-WAR	638868	4840084	80.5	CAMC / GSC	119	119	37
Waterloo	OGS-03-04	526733	4809858	292	OGS	57		57
	OGS-03-05	515170	4816991	244	OGS	46		46

2.0 Borehole sample collection

The boreholes are located outside the city of London in southwestern Ontario. (Fig. 1 and 2). Borehole information including elevation (m.asl), easting and northing coordinates (UTM NAD 83 - Zone 17), and depths are shown in Table 2.

Drilling of the boreholes was completed by All Terrain Drilling Limited in 2004 (Strathroy) and 2005 (Westminster) using a mud-rotary drill. Sediment was recovered in 1.5 m long PVC tubes that were sealed with duct tape. Core was originally logged by L. Nicks for lithofacies and sedimentary structures at the Upper Thames River Conservation Authority (UTRCA). The core was subsequently stored indoors in a non-heated space. The dried-out core was shipped to Ottawa in January 2016. Due to the unconsolidated nature of the sand-rich sediment there was some sediment loss during the transport and movement of the core, which is reflected by the low recovery rates in many sand units. The core was re-logged at the GSC in February and March of 2016 to capture information about borehole ID, run number, top and bottom run depths, recovery, date of logging and identification of the geologist that logged the sediment core. A metric tape measure was aligned with the base of the sediment in the core tube, which was then logged from the base upwards with observations and measurement for: thickness; lower and upper contacts; lithology (principal and secondary material); grain size; colour (using a Munsell colour chart); grading; sorting; bedding spacing and dip; sedimentary structures; tectonic structures (faults, joints, etc.); fossils; and weathering. Grain size was described based on the classification of Wentworth (1922); upper (U) and lower (L) are used as additional grain size descriptors for each subdivision. Bed thickness terminology followed McKee and Weir (1953) and Ingram (1954): lamina (<1cm); very thinly-bedded (1-3cm); thin bedded (3-10cm); medium bedded (10-30cm) and thick bedded (>30cm). A modified version of Eyles et al., (1983) classification scheme was used to organize facies. For completeness and consistency this information was always collected in the same order. Once logging was completed for each drill run, it was photographed and sampled for pXRF analyses at regular intervals (approximately every 75 cm) or whenever there was a change in lithology.

Sample numbers and midpoint depth for each sample was recorded on a sample sheet. Sample numbers begin at 001 and are preceded by the three-letter acronym for the borehole identifier. At each sample location, approximately 300 grams of sediment (~ 8 cm long) was collected from half the width of the core while leaving the remaining half the core intact for future analysis. Gravel sized pebbles (>2mm) were removed from samples before being homogenized and subdivided for total organic carbon (TOC), grain size (GS) and pXRF analysis.

3.0 Geological Setting

Both boreholes terminate in middle Devonian bedrock. The base of the Westminster borehole consists of 3.69 m of pale grey-fossiliferous limestone of the Dundee Formation. The base of the Starthroy borehole consists of 3.2 meters of fissile massive mudstone/soft shale that may correspond to Facies 3 of the Dundee Formation (Birchard, 1990), or part of the overlying Hamilton Group.

Quaternary sediments intersected in the boreholes consist of diamictons associated with the Port Stanley Drift (Fig. 3). Exposures of Port Stanley Drift along the north central shore of Lake Erie show 5 separate sediment horizons whereas inland (this study area) a single sediment horizon was documented (Barnett 1982; 1987; 1992).

Two main facies of the Port Stanley till (drift) have been documented by Barnett, (1992) and comprise a fine-grained facies to the south and a coarse-grained facies to the north. Regional stratigraphic context of the Port Stanley till are in Figure 3.

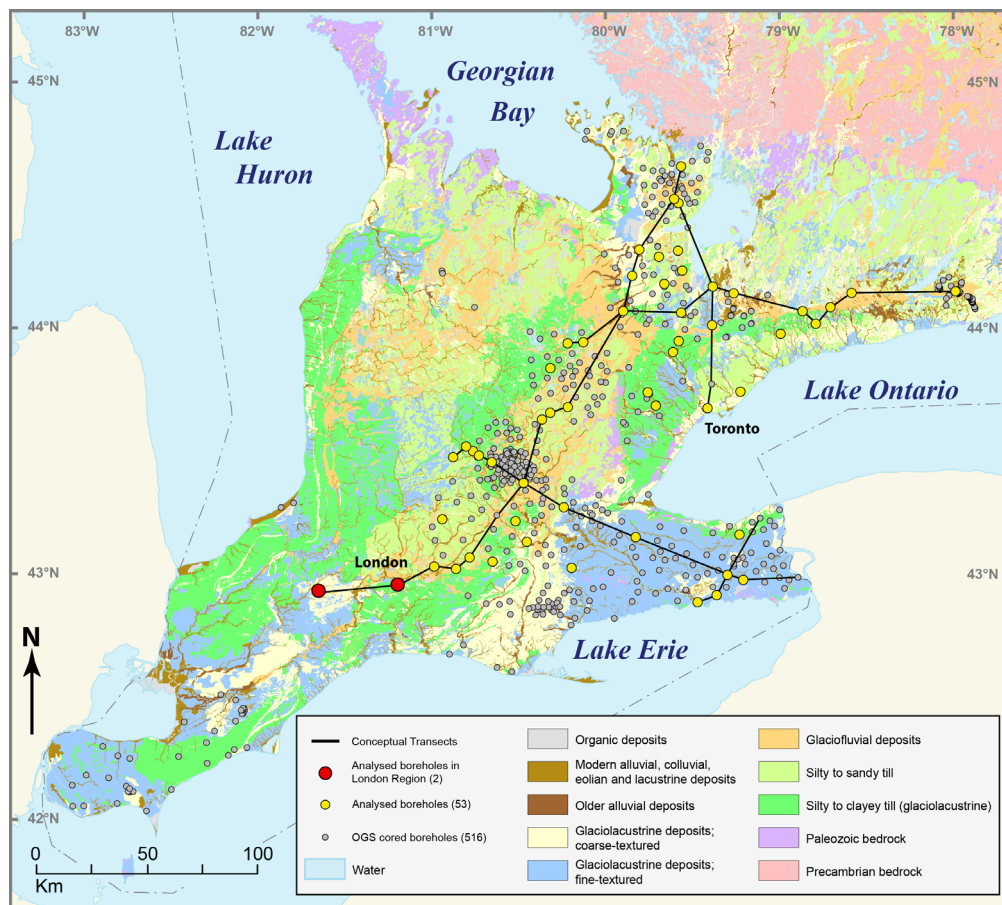


Figure 1. Location of the Strathroy and Westminster boreholes near London Ontario (large red dots) in relation to other OGS and GSC cored borehole sites. Large yellow dots represent past pXRF-analysed boreholes associated with conceptual transects shown as solid black lines. Surficial geology of southern Ontario modified from OGS MRD128-Rev, (2010).



Figure 2: Location of the Strathroy and Westminster boreholes and nearby boreholes in the Brantford-Woodstock area drilled by the Ontario Geological Survey. Image from Google Earth, 2017.

Table 2 – Borehole location and elevation.

Borehole ID	Depth (m)	Number of pXRF analysed samples	Easting	Northing	Elevation (m.asl)
Strathroy	68.7	118	448 621	4 751 759	231
Westminster	70.4	108	484 324	4 754 562	267

Lobe		Erie	Ontario		
			Hamilton	Toronto	
Geologic Time					
WISCONSINAN	Late	Greatlakean Stade			
		Two Creeks Interstade			
		Port Huron Stade		Wildfield Till Complex	
		Mackinaw Interstade	Halton Till		
		Port Bruce Stade	Wentworth Till	sandy till	
			Port Stanley Drift	sandy till	
		Maryhill Till			
	Erie Interstade	Malihide Fm.	lake sediments		
	Nissouri Stade	Catfish Creek Drift			
	Middle	Plum Point Interstade	Wallacettown Fm.	lake sediments	U. Thorncliffe Fm.
		Cherrytree Stade			Meadowcliffe Till
					M. Thorncliffe Fm.
	Port Talbot Interstade	Tyrconnell Fm.		Seminary Till	
	Early	Guildwood Stade		Canning Till (?)	L. Thorncliffe Fm.
St. Pierre Interstade				Sunnybrook Till	
Nicolet Stade				Pottery Road Fm.	
				Scarborough Fm.	
Sangamonian			Don Fm.		
Illinoian	Bradville Drift		York Till		

Figure 3: Stratigraphic correlation of Quaternary stratigraphy for southwestern Ontario (modified from Karrow, 1989, and Barnett, 1992).

4.0 Lithofacies Descriptions

Detailed lithologic descriptions acquired during core logging by the UTRCA are shown below with accompanying illustrated images of the core lithologies. A summary of sediment facies names, description and interpreted depositional environment carried out by the UTRCA are shown in Table 2 and illustrated in stratigraphic context in Figure 4.

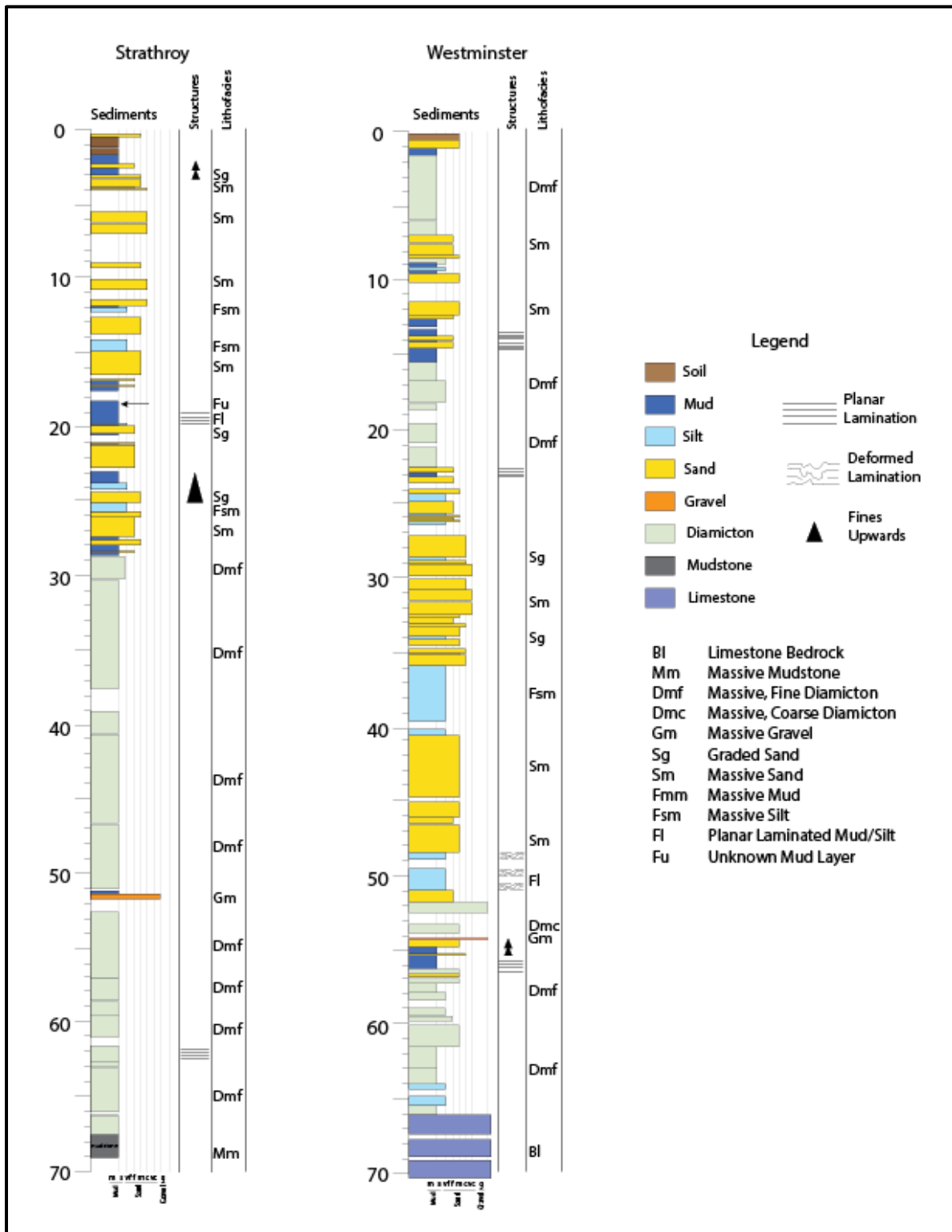


Figure 4. Stratigraphy of the Strathroy and Westminster boreholes as determined during core logging carried out by the UTRCA.

Limestone Bedrock (Bl)

Paleozoic limestone is observed in the Westminster borehole where it accounts for the lowermost 3.69 m of core recovery. The limestone is pale grey, fossiliferous, and is attributed to the Dundee Format (Figure 5).

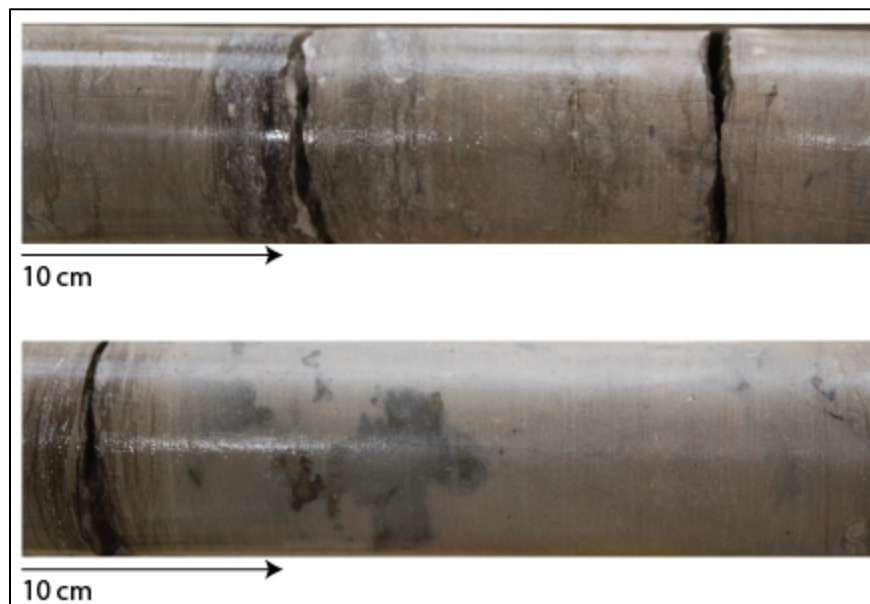


Figure 5: Limestone facies (Bl) at the base of the Westminster borehole. The arrow represents a 10 cm long line with the arrowhead pointing towards the top of the borehole. Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Mudstone (Mm)

This fissile-like, dark, massive mudstone facies (Fig. 6) occur as a 3.2 m thick unit at the base of the Strathroy borehole.

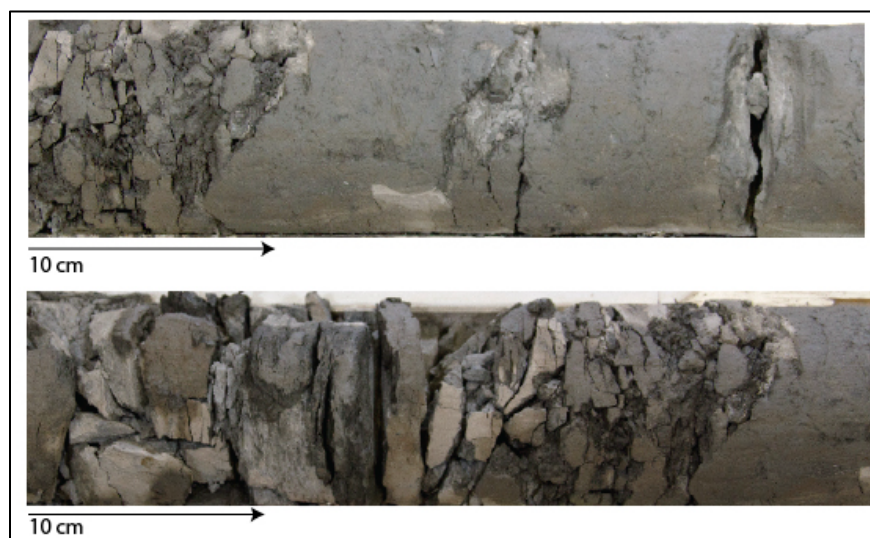


Figure 6: Mudstone facies occurring at the base of the Strathroy borehole. Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Fine-grained Diamicton (Dmf)

This facies occurs in both boreholes and consists of a moderate-to well sorted clay and silt diamicton (Fig. 7) with < 10% gravel clasts (and in most cases < 2%). Sub-angular to angular pebble size (typically < 50 mm), clasts are dispersed throughout the facies. Clasts consist predominantly of limestone (in the Westminster borehole and shale in the Strathroy borehole). Bed contacts are difficult to define, however, bed thickness is generally >20 cm and forms units ranging from 6 – 20 m.

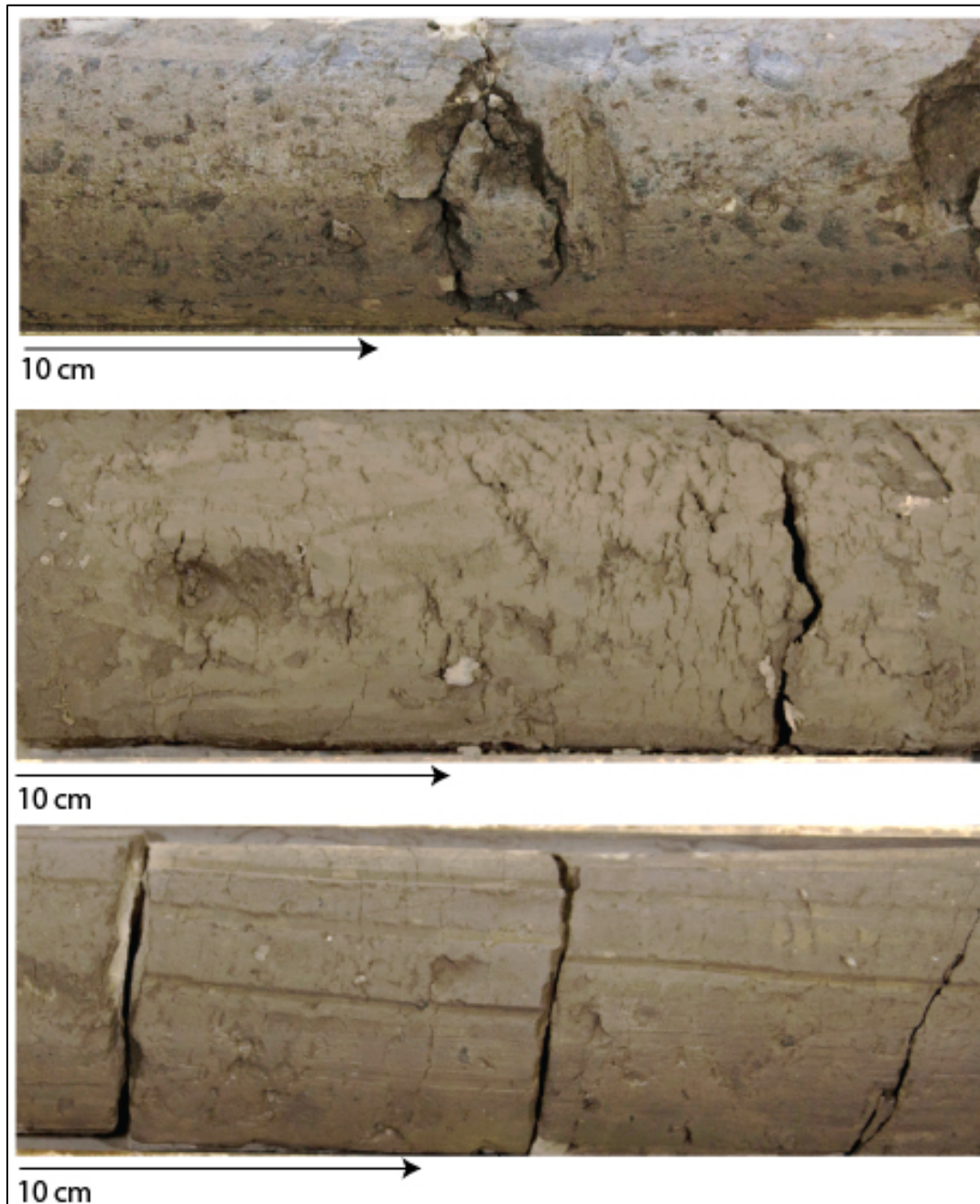


Figure 7: Fine-grained diamicton (Dmf). Note the low percentage of clasts. Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Coarse-grained Diamicton (Dmc)

This facies only occurs in Westminster borehole, is poorly sorted and generally comprised of larger clasts with a less homogenous distribution than clast observed in faces Dmf (Fig. 8). Clast sizes ranges from granule to cobble comprising 80% limestone or shale; 20% Precambrian shield rocks (granites etc). Clasts occupy >10% of the bed volume (typically closer to 25%) with a mixture of sand and clay. Bed thickness ranges from 10 – 50 cm with the thickest unit being 1.27 m thick at ~ 52 m depth. Bed contacts are gradational with other diamicton facies or clay-rich facies.

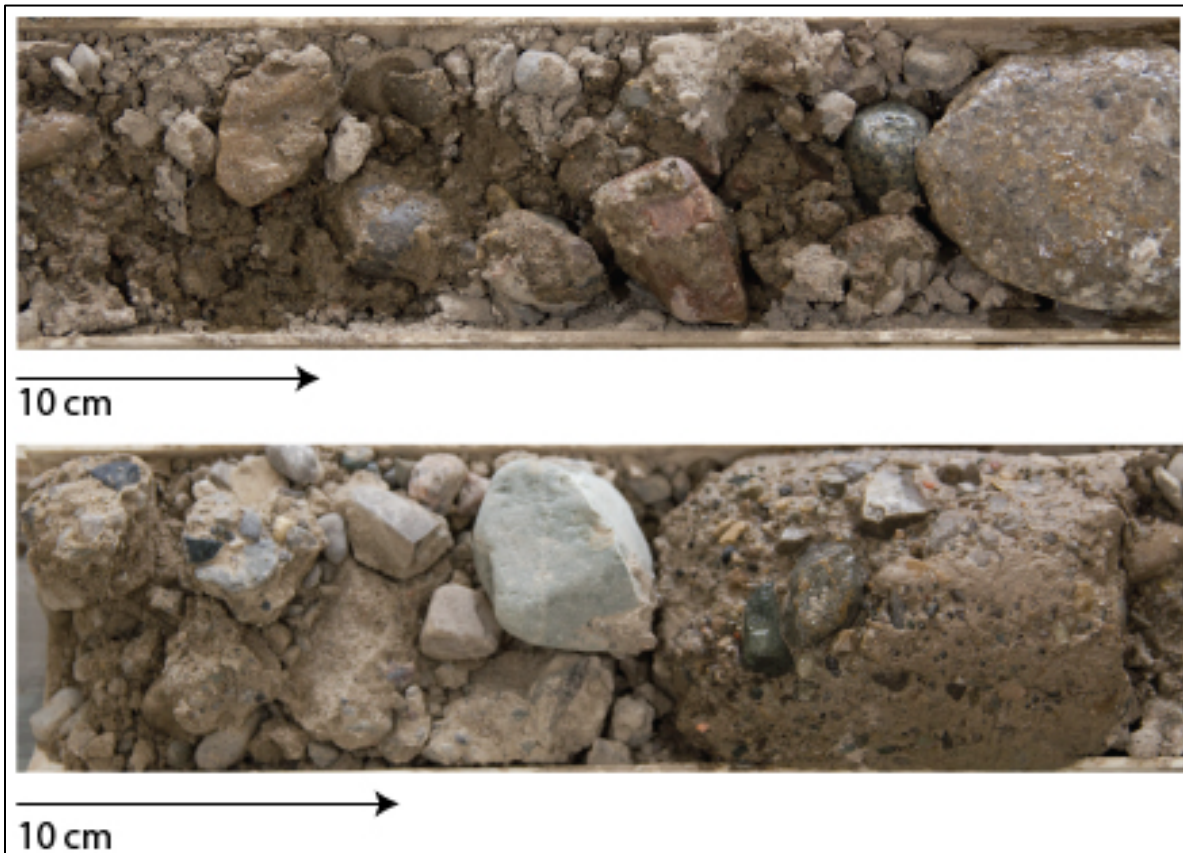


Figure 8: Coarse-grained diamicton (Dmc). Note the abundance of clasts compared to Dmf (Fig. 6).
Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Massive Mud (Fmm)

This facies occurs in both boreholes and consists of brown to dark brown massive mud as shown in Figure 9. Beds range in thickness from 5 – 50 cm with sharp/planar basal contacts. Massive mud facies sediments are often associated with other fine-grained facies such as massive silt (Fsm) and laminated mud (FI).

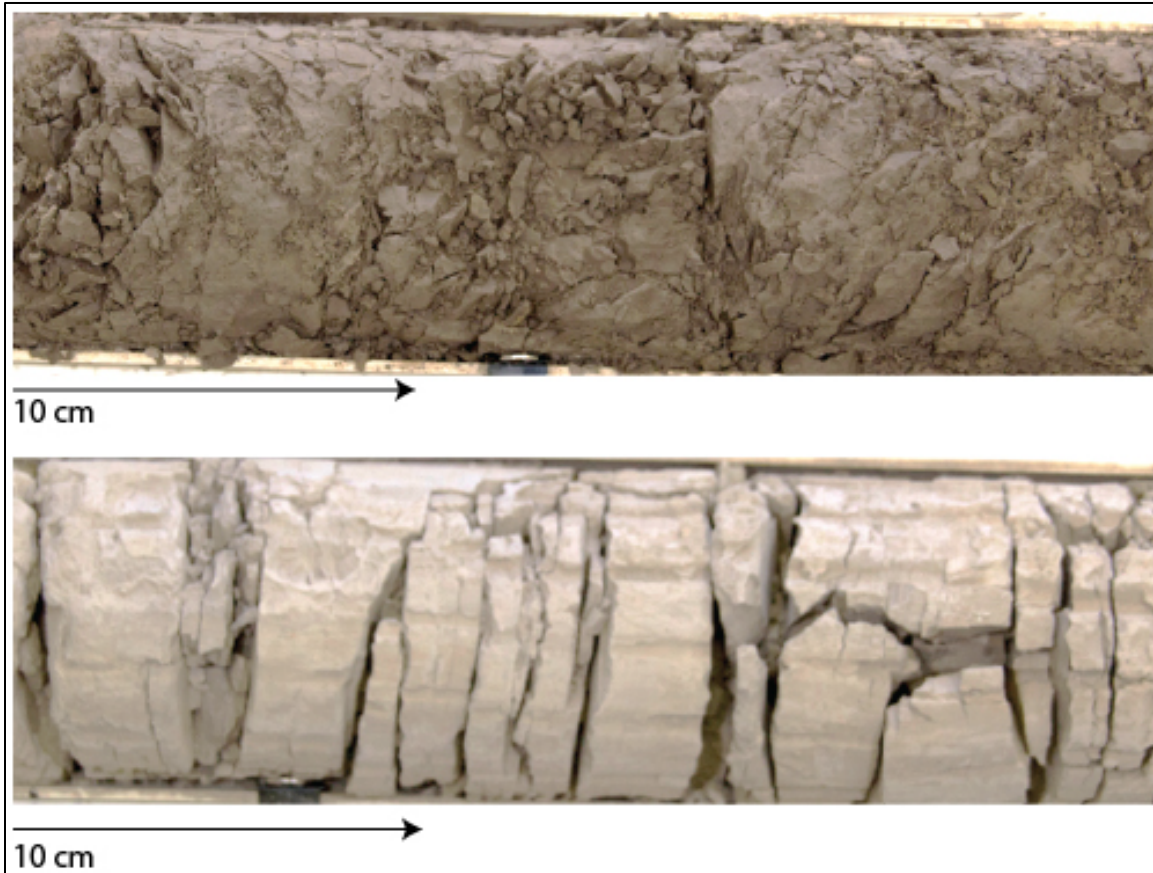


Figure 9: Massive mud facies (Fmm). Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Massive Silt (Fsm)

The massive silt facies occurs in both boreholes but is more extensive in the Westminster borehole where it comprises a 5 m-thick unit. The sediment consists of a grey to light brown, unconsolidated silt with very fine-grained sand dispersed throughout (Fig. 10). Beds are generally 5 – 35 cm thick with gradational basal contacts. The massive mud facies commonly overlie graded sand beds (Sg) forming a fining upward sequence.

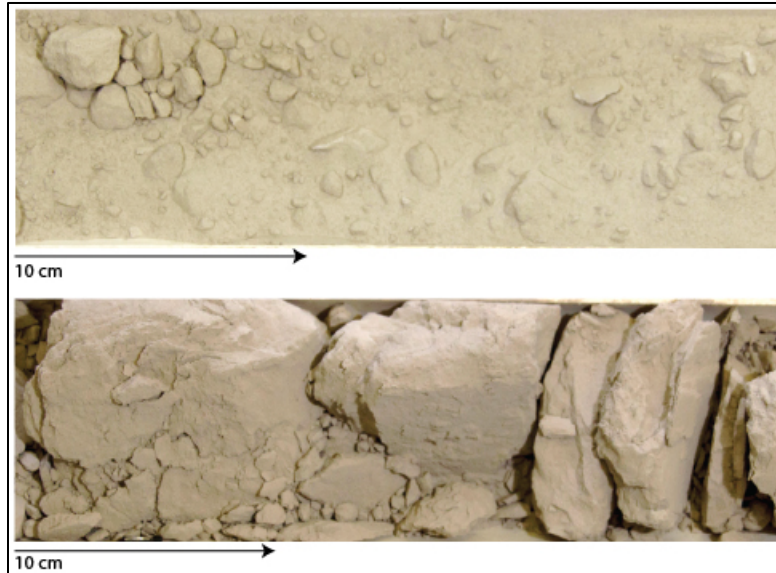


Figure 10: Unconsolidated (top) and consolidated (bottom) massive silt facies (Fsm). Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Laminated Mud (FI)

The laminated mud facies occurs sparsely throughout both boreholes and consists of a dark to light brown mud with mm-scale planar lamination with minor undulations (Fig.11). Although these beds resemble rhythmites, there are no discernable mud caps (representing a change in seasonality). The basal contacts are generally sharp although they may be gradual when overlying other mud-rich facies. Beds range in thickness from 3-20 cm and form units up to 45 cm thick.

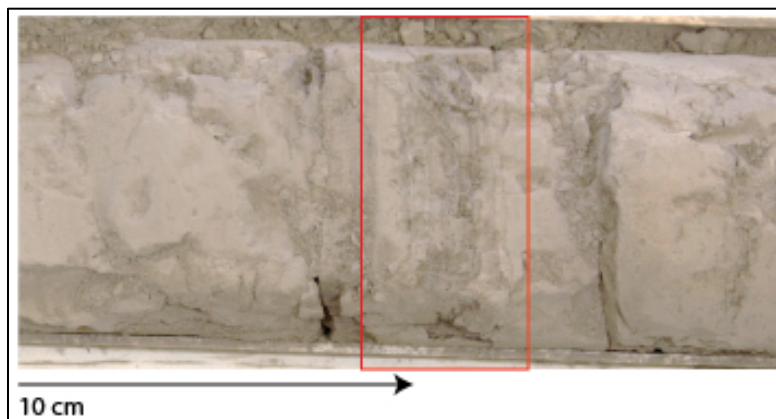


Figure 11: Laminated mud facies (FI) bounded by red lined rectangle. Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Mud unknown (Fu)

This mud facies occurs as an 8 cm thick bed with a sharp basal contact at ~18 m depth in the Strathroy borehole and is texturally and visually distinct from the surrounding strata. The facies consist of a greenish-grey to brown coloured clay with a waxy texture (Fig. 12).



Figure 12: Mud observed within the Strathroy borehole. Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Gravel (Gm)

Well sorted, pebble or cobble sized gravel as shown in Figure 13. In the Westminster borehole pebble shape ranges from sub-angular to sub-rounded and clasts are typically composed of limestone. Matrix content is sparse to non-existent; however, it is likely underrepresented due to poor core recovery. In the Strathroy borehole the facies Gm consists of cobble-sized limestone clasts with no matrix. In both boreholes, the facies occur as a single 15 – 30 cm thick bed between 50 – 55 m depth with sharp but irregular basal contacts.



Figure 13: Pebble-sized, sub-rounded gravel facies (Gm). Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Graded Sand (Sg)

This facies occurs in both boreholes and consists of unconsolidated, brown/grey fine to medium-grained sand that grades upwards into very fine to fine-grained sand with minor silt. Beds range in thickness from 5 – 110 cm. Basal contacts are typically sharp and correspond with an abrupt change in grain size. No photographs were obtained for this lithofacies.

Massive Sand (Sm)

This facies commonly occurs in both boreholes and consists of medium grained sand with fine and/or coarse-grained sand dispersed throughout (Fig. 14). Bed thickness ranges from 3 – 20 cm and may form units up to 7 m thick. Basal contacts are generally sharp and planar when interstratified with mud-rich facies, however contacts are amalgamated and difficult to discern when over or underlain by sandy facies.

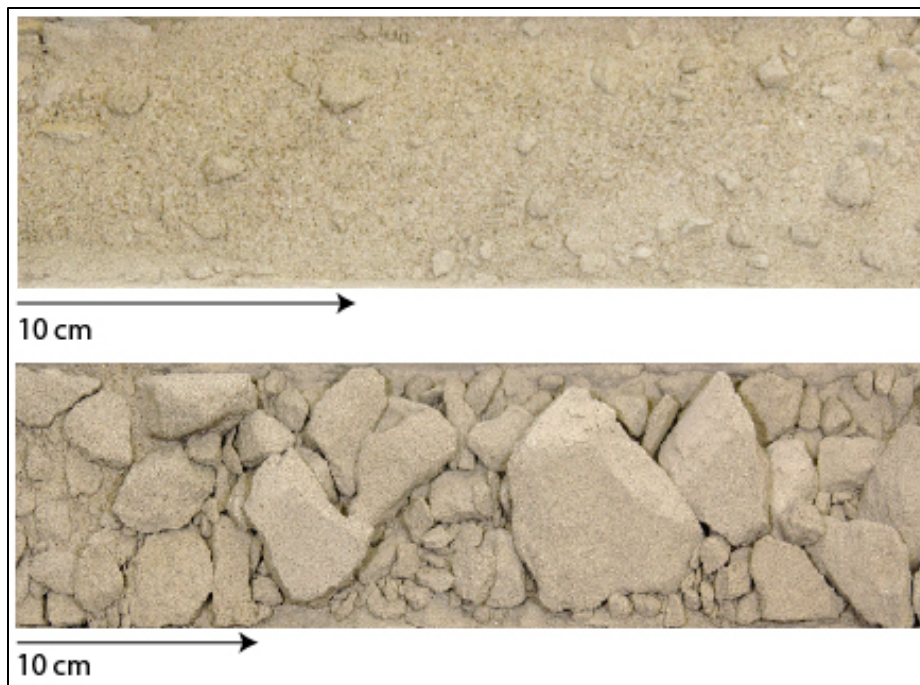


Figure 14: Massive sand facies (Sm) observed in both boreholes. Photograph by L. Nicks, courtesy of Upper Thames River Conservation Authority.

Table 2: Facies descriptions and interpretations for the Strathroy and Westminster borehole.

Code	Facies	Borehole	Description: Thickness, Basal contact Texture, Sedimentary Structures, Deformation	Interpretation	Figure
Bl	Bedrock Limestone	Westminster	-pale grey-fossiliferous -3.69 m thick unit at base of borehole	-Paleozoic Dundee Formation	5
Mm	Bedrock Mudstone, massive	Strathroy	-fissile -massive -3.2 m thick (base of borehole)	-interpreted as the mudstone/soft shale of the Hamilton Group (Mid Devonian); shallow marine deposit.	6
Dmf	Diamicton, massive, fine	Westminster and Strathroy	-clay to silt matrix -moderately to well sorted -angular to sub-angular pebble and granule clasts (rare cobbles) -predominantly limestone (Westminster) or shale (Strathroy) -clasts comprise <10% of the total bed volume (Commonly < 2%) -basal contacts: difficult to discern -bed thickness: ≥ 20 cm -units: 6 – 20 m thick	- glacial reworking of lacustrine mud (Dreimanis, 1960) -Port Stanley Till	7
Dmc	Diamicton, massive, coarse	Westminster	-mixed of sand and clay matrix -poorly sorted -abundant granules, pebbles and cobbles (85% limestone or shale clasts, 15% Precambrian shield). -clasts = >10% bed volume -basal contacts: gradational with other diamicton or clay-rich facies -bed thickness: 10 – 50 cm -unit: 1.27 m thick	-clast size/shape is indicative of glacial abrasion and crushing	8
Fmm	Mud, massive	Westminster and Strathroy	-brown -massive mud -basal contacts: sharp/planar -bed thickness: 5 – 50 cm	-fine particles in suspension flocculate, aggregate and settle during overflow and interflow conditions	9

Fsm	Silt, massive	Westminster	<ul style="list-style-type: none"> -grey/brown -silt with very fine sand -unconsolidated -basal contacts: gradational or amalgamated -beds thickness: 5 – 35 cm -unit: 5 m thick 	-fine particles in suspension flocculate, aggregate and settle during overflow and interflow conditions	10
Fl	Mud, laminated	Westminster and Strathroy	<ul style="list-style-type: none"> -dark to light brown mud -mm-scale planar lamination (local undulation) -no discernable mud caps -basal contacts: gradual to sharp -bed thickness: 3-20 cm -units: ~45 cm thick 	-laminations likely deposited by density underflows and suspension deposition in a quiescent environment	11
Fu	Mud, unknown	Strathroy	<ul style="list-style-type: none"> -green-grey/brown colour -clayey -waxy feel -basal contacts: sharp/planar -bed thickness: 8 cm 		12
Gm	Gravel, massive	Westminster and Strathroy	<ul style="list-style-type: none"> -well-sorted -clasts: limestone -sub-angular to sub-rounded -pebbles (Westminster); cobbles (Strathroy) -matrix content may be under represented due to poor recovery -basal contacts: sharp/irregular -bed thickness: 15-30 cm 	<ul style="list-style-type: none"> -rapid deposition of a traction carpet from an efflux jet or waning flow -coarsest sediment settles out first 	13
Sg	Sand, graded	Westminster and Strathroy	<ul style="list-style-type: none"> -medium to very fine sand (occasional silt) -upwards fining -basal contacts: sharp -bed thickness: 5 – 110 cm thick 	-suspension settling from a waning low energy underflow	
Sm	Sand, massive	Westminster and Strathroy	<ul style="list-style-type: none"> -medium sand with fine and/or coarse grained sand dispersed throughout -basal contacts: sharp when interstratified with mud-rich facies -bed thickness: 3-20 cm -unit: 7 m thick 	-rapid/continuous suspension settling from an underflow/efflux jet	14

5.0 pXRF Analytical Methods

Prior to pXRF analyses the silt and clay size fraction (<0.064 mm) was isolated using the GSC sedimentology laboratory. This size fraction eliminates the nugget effects of sand sized particles common to unconsolidated or crushed bedrock detritus. One hundred and eight samples were isolated from the Westminster core along with an additional 118 samples from the Strathroy borehole. Once sieved and separated, sediment was transferred to 23 mm diameter plastic vials, filling them to an approximate height of 30 mm to obtain a sample of infinite thickness (a pre-requisite of pXRF determinations, Knight et al., 2021). Samples were sealed with 4 µm thick Chemplex Prolene Thin-Film and placed within a shielded test stand above the pXRF measurement window.

Data collection was conducted using a Niton XL3t GOLDD spectrometer manufactured by Thermo Scientific, equipped with a Cygnet 50 kV, 2-watt Ag anode X-ray tube and a XL3 silicon drift detector (SDD) with 180,000 counts per second (cps) throughput. Samples were analyzed using both manufacturer standard soil mode (trace elements), and Mining modes (major elements), relying on pre-set instrument calibrations. Soil mode utilizes Compton normalization of analyses which is recommended for elements expected to occur below <1 wt.% concentrations while Mining mode uses normalization by Fundamental parameters which is best suited for elements occurring >1 wt.%. Samples were analyzed for a total of 180 seconds in each of these settings as part of an established protocol (Knight et al., 2021, Plourde et al., 2012); 60 second dwell times per filter in soil mode (Main, Low, High), and 45 second dwell times per filter in mining mode (Main, Low, High, Light). Prior to pXRF data collection the spectrometer housing was cleaned with compressed air, distilled water and Kimwipes®. A daily internal system check of the spectrometer was completed to ensure proper functioning of the instrument.

Reproducibility and Precision of Standards

The internal GSC protocol analyzes a set of three standards (Till-1, Till-4, and TCA 8010) and two blanks (SiO₂ and Teflon) at the beginning and at the end of each analytical session. Standards were chosen to best replicate matrix effects of similar lithologies to the analyzed sediments and provide the ability to correct both instrument drift and matrix effects on a project-to-project scale. The silica and Teflon blanks are monitored to ensure cleanliness of the pXRF window and sample stand environment. Commonly the Teflon blank returns values in the 10's of ppm Ti and may return trace amounts of Mo the SiO₂ blank occasionally returns values below the recommended limit of detection for Cd, Hg, K, Pd, Sr, and V in soil mode and Al in mining mode. The elements which are not listed as known impurities on the Chemplex® Prolene® thin-film (potentially containing trace amounts of Ca, P, Fe, Zn, Cu, Zr, Ti and Al) most likely represent internal detector noise. Calcium and Fe which returned values above the limits of detection, as well as Al can be associated with the impurities in Chemplex® Prolene® thin-film or represent possible contamination of the thin film. A study into the precision, accuracy, instrument drift, dwell time optimization and calibration of pXRF spectrometry for reference materials including Till-1, Till-4, and TCA 8010 is available from Knight et al. (2013).

For each element detected in each standard, the count, minimum value, maximum value, mean, standard deviation, relative standard deviation (%RSD), error and recommended values as determined by traditional wet chemistry methods (ICP-ES/ICP-MS) are provided for both soil and mining mode for Till-1, Till-4, and TCA 8010 below each dataset in Appendix A. The percent error row contains the difference between the mean and recommended value; a low percent error indicates that the element is measured

accurately, while high absolute values indicate that a calibration curve is required to correct the data or that the data are not reliable.

Although care must be taken when interpreting data with a high error it may be useful to plot these elements to see if their relative changes in chemostratigraphy correlate with those of other more reliable elements. Since chemostratigraphy utilizes the relative changes in element concentration, high precision in returned values is more important than accuracy. It is also important to note that the precision and accuracy are affected by concentration. Lower concentrations, especially those near the limit of detection (LOD) tend to result in lower precision, and thus higher % RSD.

Limit of Detection

Thermo Scientific provides a list of the sensitivity or limits of detection for the pXRF (Thermo Scientific, personal communication, 2008), which have been included with datasets in Appendix A. The pXRF provides an error of each individual measurement taken throughout the 180 second analysis, this is averaged internally by the instrument and for this study was calculated as 2 standard deviations. In a peculiar shortcoming, some elements return concentrations lower than the provided LOD. We've chosen to report these results as data on chemostratigraphic graphs using returned values however we have indicated the recommended LOD. For any results below LOD we have assigned, for graphing purposes, concentrations equal to half the recommended value.

Data Delivery

Data delivery is provided through a series of nested folders and files as detailed in the of_8312_readme.rtf file. Folders consist of Appendix A containing geochemical data acquired using a pXRF spectrometer and Appendix B containing graphical representation of the geochemical data.

Appendix A contains a word file describing the column headings of the geochemical data spreadsheets. The Appendix also contains two subfolders identified as Strathroy and Westminster, each subfolder contains two Microsoft Excel® workbooks and two .csv files. Workbooks are identified by borehole name (e.g., Strathroy – data type.xlsx) with the Strathroy grain size workbook containing four worksheets and the pXRF workbook for both boreholes (e.g., pXRF Data – Complete.xlsx) containing with two worksheets, one for Soil mode data and one for Mining mode data. Each subfolder also contains separate files for Soil and Mining mode data in .csv format.

Appendix B contains .pdf files displaying graphical representation of the borehole stratigraphy, grain size and single element trends for geochemical data in both Soil and Mining modes. On these graphs dashed horizontal lines correspond to the lithological breaks observed during logging of the sediment core.

6.0 Geochemical results

In Soil mode As, Ba, Ca, Cu, Fe, K, Mn, Ni, Rb, S, Sr, Th, Ti, V, Zn, Zr, and some Pb (Strathroy), U (Westminster), were detected in sufficient quantities to produce results. In Mining mode Al, Ba, Ca, Fe, K, Mg, Mn, Pb, Rb, S, Si, Sr, Th, Ti, Zn, Zr, and As (Strathroy), Y (Westminster), were detected in sufficient quantities to produce meaningful results. Many elements are detected in both modes however Soil mode additionally provides Cu, Ni, and V data whereas Mining mode additionally provides Al and Si data. These results, and simplified stratigraphic units, for each borehole are presented graphically in Appendix B. For ease of chemostratigraphic discussion, significant changes in grain size and elemental

concentrations have been designated as Unit numbers from 1 at the base of the borehole upwards to the surface. Unit numbers are assigned for ease of communication within the context of this open file and should not be used as a formal stratigraphic designation.

In glaciated terrain geochemical data often reflect changes in grain size (see Ba in Soil mode and silt content for the Strathroy borehole) that in turn reflects mineral partitioning associated with weathering, erosion, sediment transport, and depositional processes. Although sand, silt, and clay graphs are shown in the Appendix B chemostratigraphy graphs, the geochemical concentrations are based on the silt and clay sized fraction which excludes the coarse sand-size fraction. Some effects of grain size on pXRF-derived geochemical data are discussed in Bertrand et al. (2015), MacLachlan et al. (2015), and Nuchdang et al. (2018). Chemostratigraphic trends are similar in Soil and Mining mode however each mode may display greater variation between stratigraphic units as shown for Ba (Strathroy borehole) where Soil mode shows a great variation either between each analysis and/or stratigraphic unit. Unless specified, elemental concentrations discussed here refer to Mining mode.

Chemostratigraphy - Strathroy

Unit 1 – base of borehole - 62.5m

Changes in the silt size fraction are reflected in the concentrations of Al, K, Pb (Fig. 15), Rb, S, Si and Sr whereas clay content and Ba concentration are closely related. Although Unit 1 and Unit 2 consist of fine-grained diamicton there is a significant change in sand-silt-clay content and elemental concentrations between the two units. Unit 1 variation between samples most likely is the result of small-scale changes in grain size as shown with the close relationship of silt and Al. Note that the upper for samples of this unit show an increased sand content with a corresponding lower silt and clay content also reflected in the concentration of Al, K, and Rb (Appendix B). Note that Zr for unit 1 and overlying unit 2 sediments show consistent concentrations (Fig. 15).

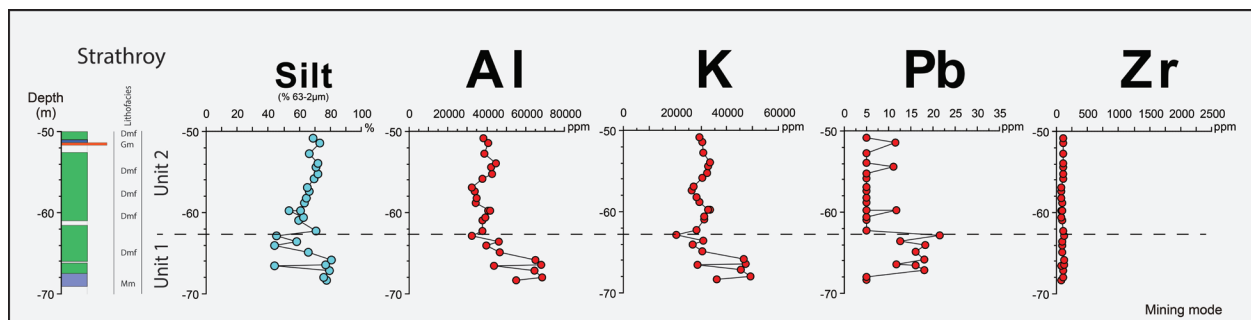


Figure 15: Relationship between silt content and Al, K, and Pb concentration. Note there is no change in Zr concentration.

Unit 2 – 62.5 – 29.0m

The lower contact between unit 1 and 2 is defined by a sharp increase in clay content and Ba concentration with a corresponding decrease in concentrations of Al, Ca, Rb, and Si (Fig. 16). Note that Pb values that are above detection limit in unit 1 fall to mainly below detection limit for unit 2. Although unit 2 shows relatively consistent elemental concentrations throughout (e.g., Fe, S, Zr) there are some relatively small changes in elemental concentrations, notably at a depth of ~ -56m, -52m, (e.g. Ba, Ca, K, Rb, S, Si, Sr, Fig. 16) and a consistent minimal decrease in concentrations from -40m to the top of the unit (e.g. Al, Fe, K).

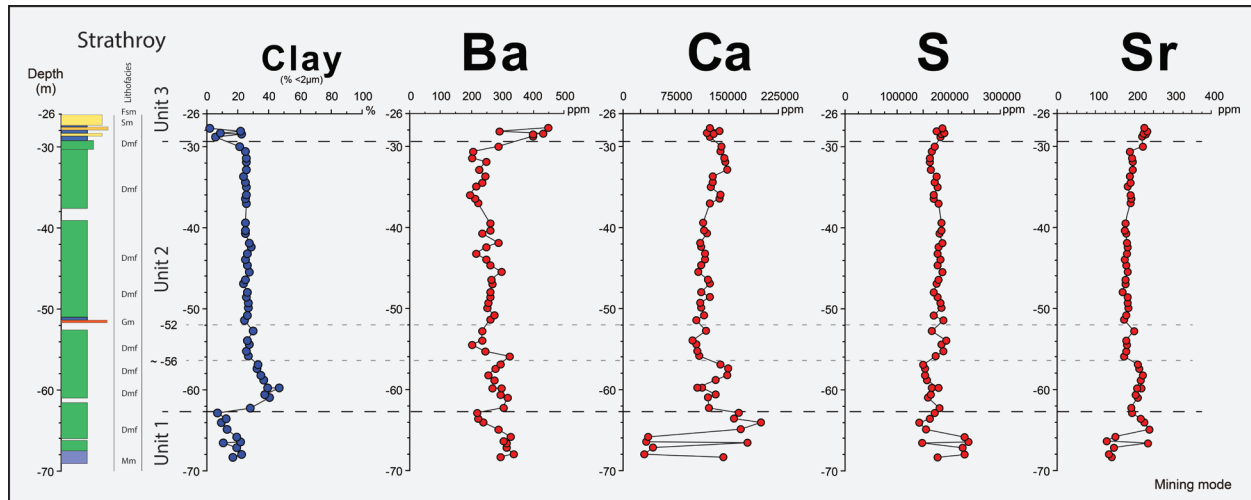


Figure 16: Relationship between clay content and Ba, Ca, S, and Sr concentration.

Unit 3 - 29.0 – 17.2m

The contact between unit 3 and the underlying unit 2 is shown by an increase in silt content and a corresponding decrease in clay however the sand content remains similar for ~2m above the contact (Appendix B). Geochemically the contact is defined by a marked decrease in Al, As (to below D.L.; Fig. 17), Ca, Fe, K, Rb, and Si with an increase in concentration of Ba, Mn (to above D.L.), Sr, and Zr (Fig. 17). For some Th, Ti, and Zn, concentrations do not vary greatly between the units however the variability in concentration is greater in unit3 than in the underlying unit 2 sediments. Silt content of the unit fluctuates between samples (Fig. 17) and is not reflected in elemental concentration fluctuations that appear to be controlled by the fluctuations in the clay content. Note that the clay content of unit 3 is less than unit 2.

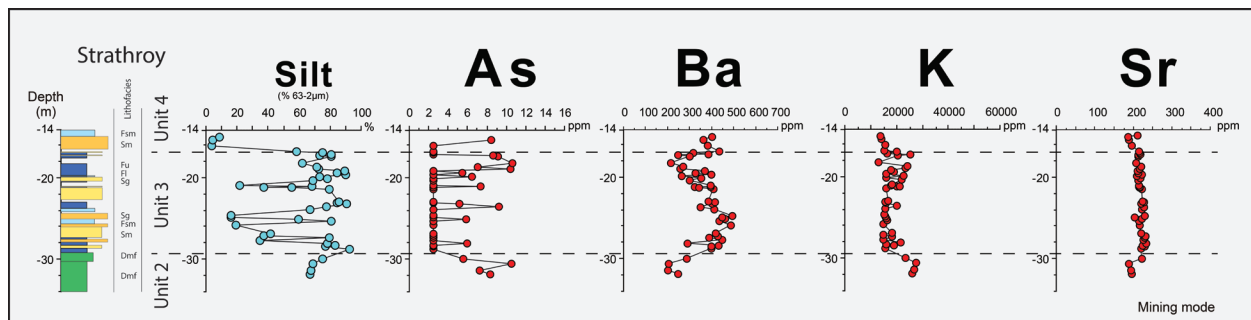


Figure 17: Relationship between silt content and As, Ba, K, and Sr concentration.

Unit 4 - 17.2 – 4.0m

Clay and silt content of unit 2 decreases compared to unit 3 sediments. Sand content of unit 2 higher than both the underlying and overlying sediments. Several elements show little variation through unit 3, 2, and 1 (e.g., Al, Ba, K, Fe, Rb, Sr). Concentrations of Mn (Fig. 18) increase compared to underlying unit 3 sediments. Minor fluctuations are shown in a slight decrease in Sr concentrations from unit 3 to unit 4 and larger variability in Zn and Zr concentrations (Fig. 18).

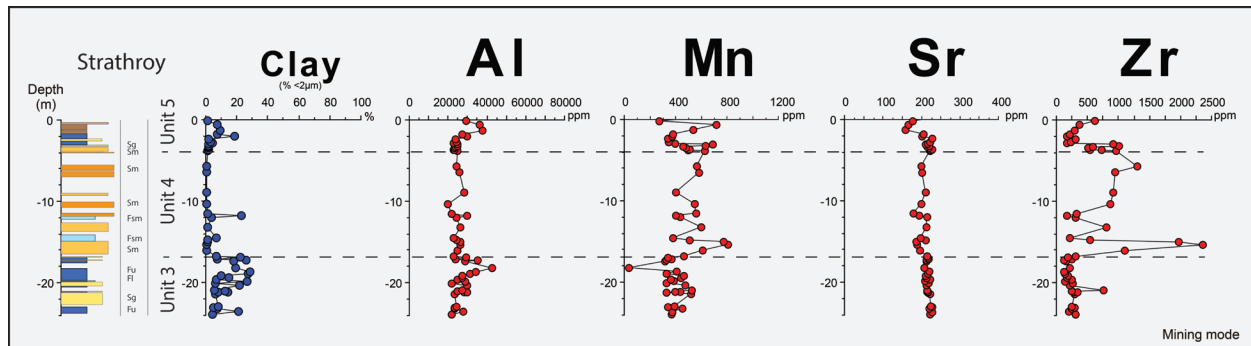


Figure18: Relationship between clay content and Al, Mn, Sr, and Zr concentration.

Unit 5 – 4.0m – top of borehole

From the base of unit 5 to the top of the borehole (excluding the uppermost 3 samples) there is a general decrease in sand content with a corresponding increase in silt content (Fig.19) and a minor increase in clay content. These trends in grain size are not necessarily reflected in elemental concentrations. For example, Al, Ca, K, Rb, S, Sr, and Zr (Fig.19) show little change in the lower two meters of the unit but show an increase towards the top of the borehole.

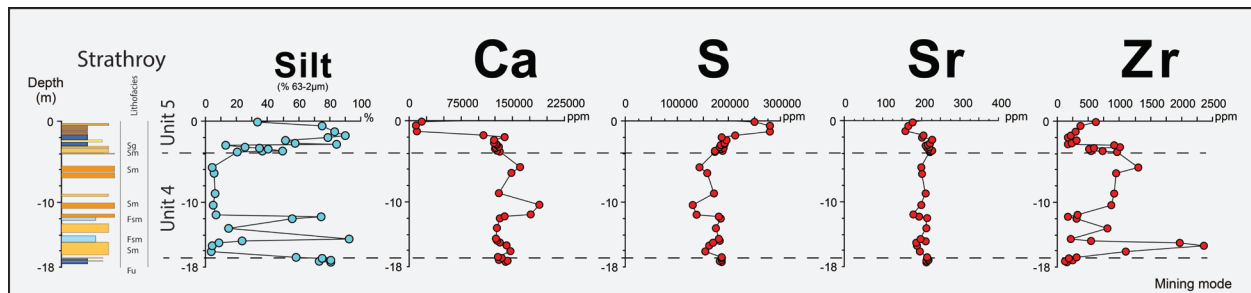


Figure 19: Relationship between silt content and Ca, S, Sr, and Zr concentration.

Chemostratigraphy - Westminster

The Westminster borehole consists of interstratified diamicton and unconsolidated sediments ranging from mud to gravel overlying limestone bedrock (Fig. 5). Following descriptions are based on data collected in Mining mode. The sediment package can be divided into 5 units based on relative changes in elemental concentrations (e.g., K, Rb, Sr). No grain size data is available for the Westminster borehole. Elemental analyses were not carried out on the limestone bedrock.

Unit 1 – base of borehole - 48.2m

Variations in lithology and associated grain size of unit 1 sediments are reflected in the variable elemental concentrations of Al, Ba, Fe, K, Rb, Sr, Th and Zn (Fig. 9). However, elements such as Ca, Si, Y, and Zr show a relative consistency throughout the unit with excursions associated with lithological changes. Concentrations of S at a depth of 54 m and above are consistent with overlying unit 2 sediments reflecting a change in lithology from underlying diamicton to variable thickness of interstratified diamicton sand and silt (Fig. 20).

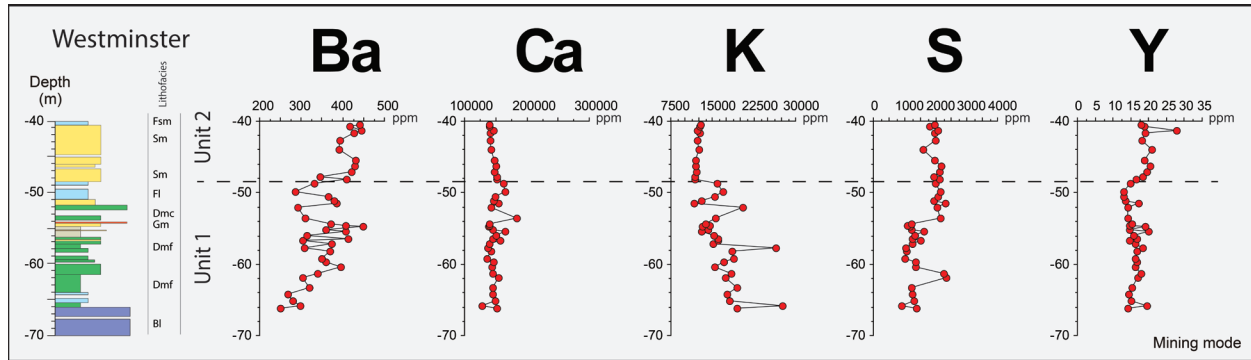


Figure 20: Lithology and elemental concentrations for Ba, Ca, K, S, and Y.

Unit 2 – 48.2 - 22m

Contact between unit 1 and unit 2 is sharp as shown with elements K (Fig. 20), Al and Rb (Fig. 21), and Sr (Appendix B) that also show a consistent concentration throughout unit 2. At the base of the unit there is an upwards increase in concentration over 3-5 samples shown with Ti, Y, and Zr. Between a depth of 31 m to 33 m there is a sharp increase in Ca and a decrease in Si (Fig. 21) associated with a course to very coarse sand unit. Other than this deviation, many elements such as Al, Ca, Fe, K, Pb, Rb, Sr, and Ti show little change in concentration throughout the unit even though numerous changes in grain size occur in the units' sediments. Some elements such as Al, Ba, Si, and to a lesser degree S and Sr show that there may be an upper and lower division in the unit at a depth of approximately 36 m where the medium to coarse sand horizons occur (Figs. 20, 21).

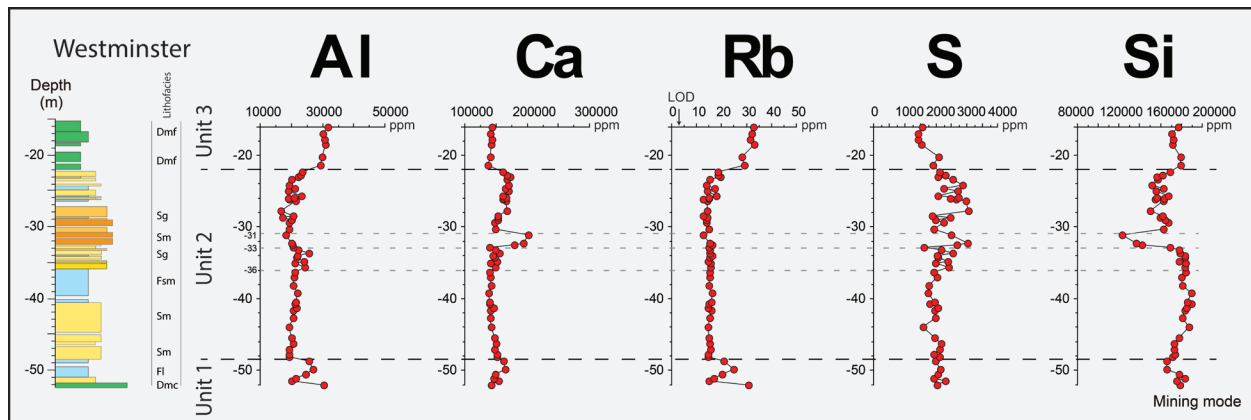


Figure 21: Lithology and elemental concentrations for Al, Ca, Rb, S, and Si.

Unit 3 – 22 - 13.5m

Unit 3 diamicton is distinguished from underlying unit 2 and overlying unit 4 sands by a sharp decrease in Ca and Zr with a corresponding increase in concentration of Al, Fe, K, Rb, Si, Sr, Ti, and Zn (Fig. 22, Appendix B).

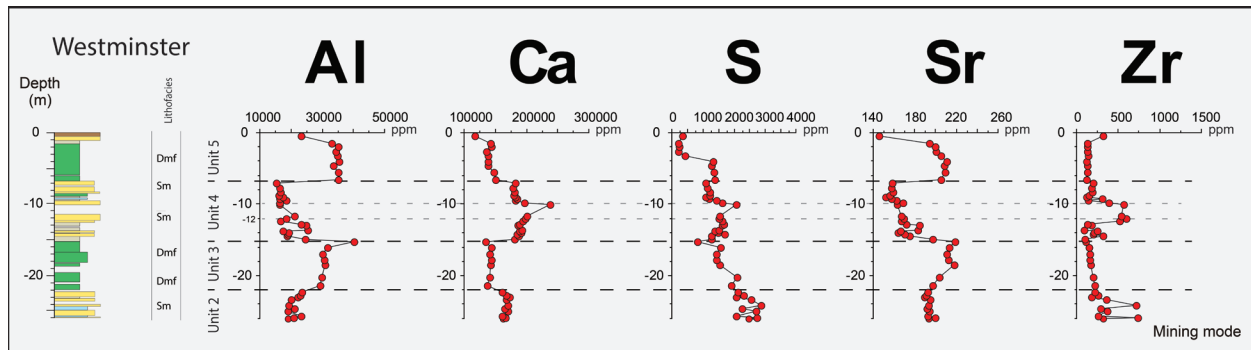


Figure 22: Lithology and elemental concentrations for Al, Ca, S, Sr, and Zr.

Unit 4 – 13.5 - 6.5m

Very fine to medium sand of unit 4 shows a significant decrease in Al, Fe, K, Pb, Rb, Si, Sr, and Zn and an increase in Ca from the underlying and overlying diamicton (Fig. 22, Appendix B). Between 10 and 12 m depth there is a zone of no recovery shown on the stratigraphic section however samples provided for analyses show an increase in concentration for Ca, Th, Ti, Zn, and Zr (Fig. 22, Appendix B) with decrease in concentration for Si. Concentrations for many elements (i.e., Ca, Si, Zr) show little change above or below this horizon however other elements such as Fe show concentration differences while some show (i.e., K) more variability in the sediments below 12 m compared to those above 10 m (Appendix B).

Unit 5 – 6.5 – 2m

Unit 5 diamicton shows consistent concentrations throughout the unit that are similar to those of unit 3. Some elements such as Fe, Rb, and Ti show a minor change in concentration in the lower few meters of the unit compared to the upper few meters. S however shows significant differences in concentration between the lower and upper few meters of the unit (Fig. 22). Zr remains similar in concentration throughout the unit (Fig. 22). One sample at the top of unit 5 shows a departure in concentration for many elements from the underlying sediments (Fig. 22). These results are most likely a reflection of anthropogenic activities.

5.0 Discussion

For southern Ontario, Sharpe et al., (2020) discuss the origins of geochemical variation in surficial unconsolidated deposits in terms of bedrock provenance, mineralogy, weathering, and soil formation processes. Their data show that regional-scale geochemical variation of these sediments is largely derived from associated bedrock sources. For southern Ontario these sources include shield terrane comprised of metamorphic volcanic, intrusive, and sedimentary rock types, of variable geochemical composition and marine carbonate, sandstone, and shale of Cambrian to Silurian ages.

Key elements indicative of Precambrian Shield terrane include Si, Al, Na, Fe, and K whereas terrain composed of Paleozoic carbonate-dominated sedimentary rock are represented by Mg and Ca.

Strathroy borehole

Lowermost diamicton of the Strathroy borehole is assigned to the massive, clay to silt matrix, Port Stanley Till. For discussion purposes we have assign informal geochemical units where the diamicton can be separated into 2 units. The lowermost unit 1 sediments are differentiated from overlying sediments by higher sand and lower clay content. Sand content of the lowermost diamicton varies throughout the unit and differs from the overlying unit 2 diamicton where sand content is consistent. These changes in grain size are reflected in the geochemical signature of the sediments (Appendix B). For example, Ca, and Si content are variable in unit 1 with considerably less variability in unit 2. Subtle changes in elemental concentrations of unit 2 sediments occurring over several samples suggest some variability or fluctuations in mineralogy that correspond to changes in the clay content.

Overlying clay to coarse sand sediments (0 to 29m) are divided into 3 units based on changes in both grain size and geochemistry. The geochemical signature of these units differs from the underlying diamicton (units 1 and 2) suggesting a provenance not directly sourced from the diamicton but from a sedimentary mineral assemblage where Zr is concentrated in the heavy mineral fraction (Appendix B). This is shown in the increase Zr content compared to the diamicton where Zr is constantly low in concentration. Similar relationships hold for many other elements including Al, Ba, K, Mg, Rb, Si, and Sr where the geochemical signature of the diamicton (units 1 - 2) differs from that of the overlying sediments (units 3-5).

Westminster borehole

Sediments from the Westminster borehole can be differentiated based on lithology and chemostratigraphy. Diamicton occurs as three distinct stratigraphic horizons (unit 1, 3 and 5) separated by mud, silt, and variable grain-sized sand (unit 2 and 4). The lowermost diamicton shows variable concentrations for many elements, with Ca (Fig. 20), Si, Y, and Zr remaining consistent. This varies from the remaining 2 diamicton horizons (unit 3 and 5) that show relatively consistent concentrations for some elements e.g., Al and Ca (Fig. 22). Unit 4 unconsolidated sediments show consistent geochemical signature for some elements (i.e., Al, Ca, K, Rb) with one deviation, regardless of variability in grain size.

6.0 Assessment of elements potentially hazardous to human health

Data presented in this open file help establish a basis to characterize geochemical background variation in glacially derived sediment of southern Ontario. These sediments have the potential to host elements that may be harmful to human health through food or water contamination. The Ontario Ministry of Environment, Conservation and Parks provides “Rules for Soil Management and Excess Soil Quality Standards” (Ontario Ministry of the Environment (OME), 2020). The OME document provides tables that represent 1) upper limits of typical province-wide background concentrations in soil that is not contaminated by point sources and, 2) upper limits of stratified soil used for agriculture, residential, and/or industrial/commercial use in a potable groundwater area (see Tables 1 and 4 OME, 2020). Summary data for potentially hazardous elements (As, Cd, Cr, Cu, Hg, Pb, and Zn) detected in this study

are shown in Table 3 along with OME data. Chemostratigraphic data for As, Cu, Pb, S, and Zn are shown for the Strathroy borehole in figure 23 and for the Westminster borehole in figure 24.

All analyses for As, Cd, Hg, Pb, and Zn were below limits identified in OME - Rules for Soil Management and Excess Soil Quality Standards, (2020). One sample analysis for Cr in soil mode was detected from the Strathroy borehole at the lower limit for province-wide background concentrations. The sample was collected at a depth of 67.94 m near the base of the borehole. Two sample analyses for Cu in soil mode were detected from the Strathroy borehole above the lower limit for province-wide background concentrations with values of 74.5 ppm at a depth of 64.05 m and 67.45 ppm at a depth of 15.32 m All sample analyses for U detected in soil and mining modes for both boreholes (Appendix A) are above the upper limits for province-wide background concentrations but below the limits for potable water stratified soils. It should be sated that concentrations reported in the Provincial wide guidelines are determined using an analytical procedure other than pXRF and thus a comparison of concentrations reported by different analytical methods should not be considered definitive.

Table 3. Summary data for potentially hazardous elements

Strathroy - 119 samples								
Soil mode	As	Cd	Cr	Cu	Hg	Pb	U	Zn
Count	26	0	33	117	6	15	118	127
Minimum	7		22	13	9	8	4	30
Maximum	12		67	75	12	21	15	133
Mean	8		31	24	10	12	8	55
Std dev	1.13		11.99	10.60	1.24	3.58	2.25	15.96
%RSD	725		255	223	816	322	348	345
Limits of Detection SiO ₂ + Fe + Ca	7	12	22	13	9	8	4	10
Mining mode	As	Cd	Cr	Cu	Hg	Pb	U	Zn
Count	79	0	0	2	N/A	69	35	125
Minimum	5			28		10	4	6
Maximum	14			55		30	10	10
Mean	8			41		14	5	8
Std dev	2.15			19.54		4.14	1.30	0.56
%RSD	382			212		337	369	1331
Limits of Detection SiO ₂ + Fe + Ca	5			15		10		
Westminster - 108 samples								
Soil mode	As	Cd	Cr	Cu	Hg	Pb	U	Zn
Count	85	2	15	94	33	5	94	108
Minimum	3	8	8	11	6	4	4	16
Maximum	8	9	18	32	8	8	15	84
Mean	5	9	13	17	7	6	7	40
Std dev	1.20	0.49	2.94	4.22	0.60	1.53	2.12	14.01
%RSD	26	6	23	24	9	27	32	35
Limits of Detection SiO ₂ + Fe + Ca	7	12	22	13	9	8	4	10
Mining mode	As	Cd	Cr	Cu	Hg	Pb	U	Zn
Count	28	0	0	0	N/A	101	11	107
Minimum	5					5	4	18
Maximum	11					17	7	86
Mean	7					9	5	41
Std dev	1.22					2.19	1.00	13.57
%RSD	19					26	22	33
Limits of Detection SiO ₂ + Fe + Ca	5					5		15
Upper limits of province-wide background*	11 - 18	1 - 1.2	67 - 70	62 - 92	0.16 - 0.27	45 - 120	1.9 - 2.5	290
Upper limits of potable water stratified soils**	18	1.2 - 7.9	160 - 11000	140 - 1900	0.27 - 1.9	120 - 1000	23 - 300	340 - 15000

Numbers in italics and blue were detected near or below the recommended limit of detection for the Niton spectrometer

Numbers in red are at or above values presented in OME data table 2 and/or 4

* data obtained from Table 1 OME, (2020)

** data obtained from Table 4 OME, (2020)

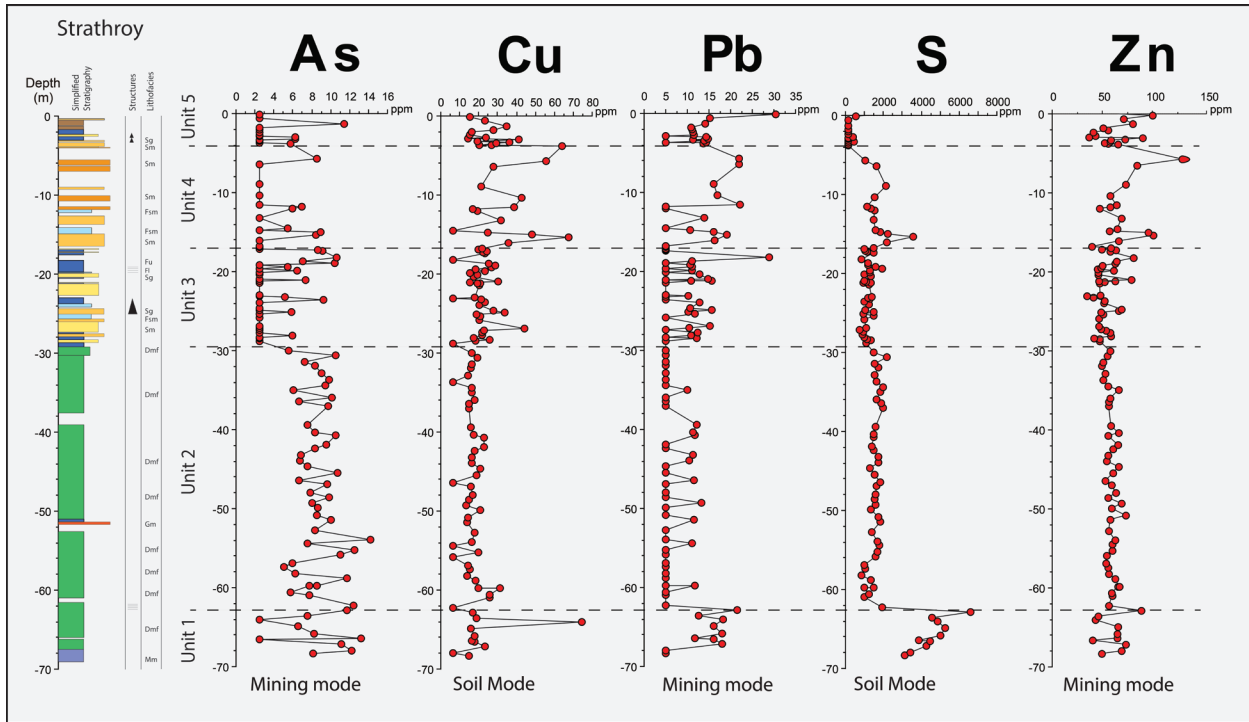


Figure 23: Strathroy borehole chemostratigraphy for As, Cu, Pb, S, and Zn.

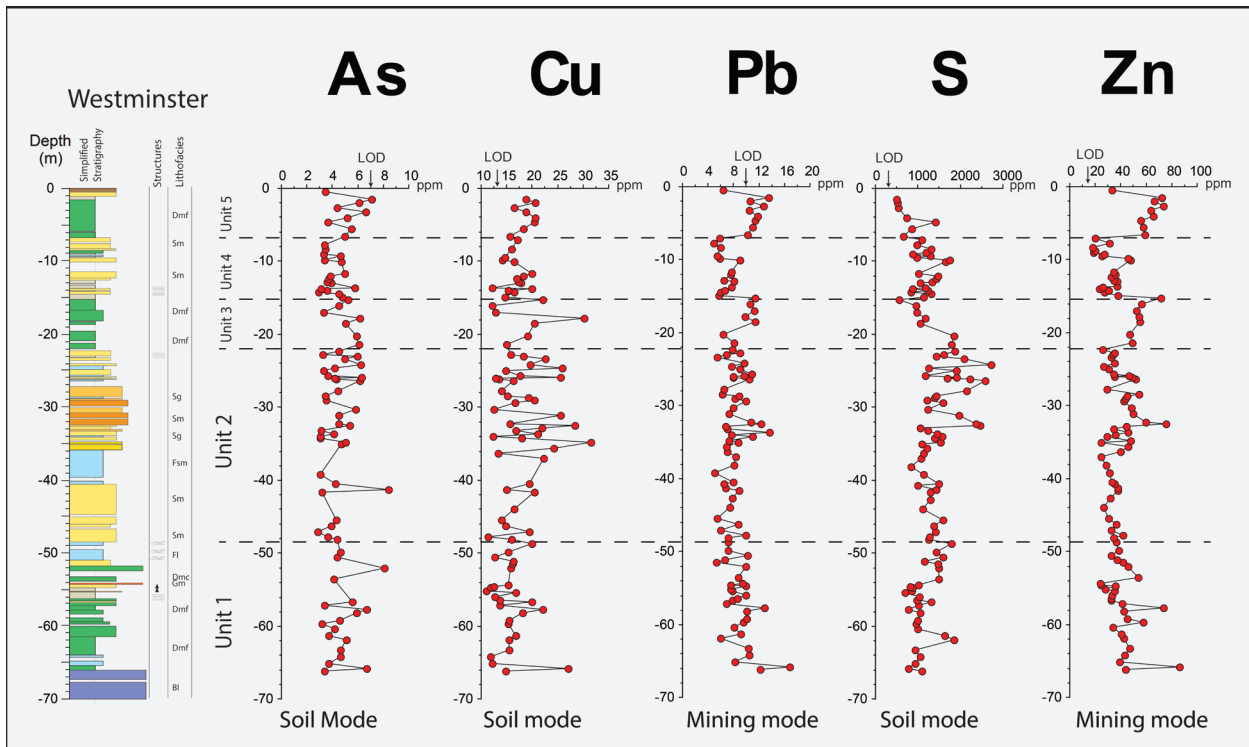


Figure 24: Westminster borehole chemostratigraphy for As, Cu, Pb, S, and Zn.

7.0 Acknowledgements

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