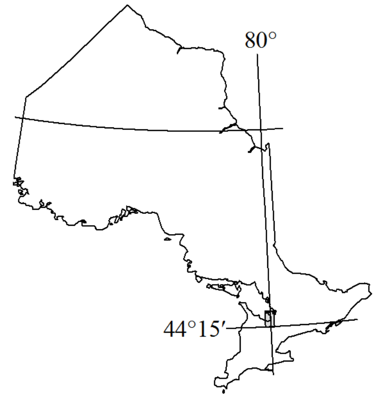
25. Project Unit 14-015. An Update on Subsurface Data Collection for Three-Dimensional Sediment Mapping in the Central Part of the County of Simcoe, Southern Ontario



R.P.M. Mulligan[1]

[1]Earth Resources and Geoscience Mapping Section, Ontario Geological Survey

INTRODUCTION

The Ontario Geological Survey (OGS) has been conducting three-dimensional (3-D) sediment mapping investigations across southern Ontario since 2002. These projects rely heavily on the collection of new, high-quality geological and geophysical data in order to better constrain bedrock topography, drift thickness and to characterize the Quaternary glacial stratigraphy, which, in turn, controls the nature, extent and connectivity of surface and groundwater flow systems in the region. Numerous parallel and complementary studies have been conducted for the current project in the central part of the County of Simcoe (herein referred to as "central Simcoe County"): a ground-based gravity survey was undertaken to better constrain bedrock topography in the region (Rainsford and Biswas 2014), surficial mapping began in 2014 and continued in 2015 (Mulligan 2014, 2015, 2017a, 2017b), sediment drilling programs were conducted in 2015 and 2016 (Mulligan 2016), augmented by seismic reflection surveys and downhole geophysical logging undertaken by the Geological Survey of Canada (GSC) as part of OGS–GSC collaborative efforts (Russell and Dyer 2016; Crow et al. 2017; Pugin et al. 2017). This article focusses on results from continued sediment drilling during the summer of 2017 and introduces plans for future collaborative work on the geophysical and hydrogeological properties of the Quaternary sediments in the vicinity of drilled boreholes.

In 2017, 12 boreholes were drilled in Simcoe County, bringing the number of cored boreholes drilled for this study up to 26, and the number of cored boreholes in the area logged by OGS staff to 32 (Figure 25.1); 5 boreholes were drilled in support of previous mapping in the area (Bajc 1994; *see* Figure 25.1, yellow circles); 1 borehole drilled in support of an MSC thesis (Fitzgerald 1982: "UW-78") and 1 borehole ("Elmvale") was drilled in support of local groundwater studies.

REGIONAL GEOLOGIC SETTING

Central Simcoe County is bounded by Georgian Bay to the north, the Niagara Escarpment to the west, and drumlinized till plain separated by large valleys and flat low-lying plains to the south and east. The area is underlain primarily by Paleozoic bedrock, consisting of Upper Ordovician limestones in the central and northern parts of the study area and Upper Ordovician shales overlain by Lower Silurian dolostones forming the caprock of the Niagara Escarpment in the southwestern part. In the northern part of the study area, several inliers of Precambrian bedrock of the Grenville Province have been intersected in boreholes (Bajc 1994; Armstrong and Carter 2010), including one as much as 34 km south of the nearest known outcrop (Mulligan 2016). To the east of the Niagara Escarpment, the Paleozoic bedrock

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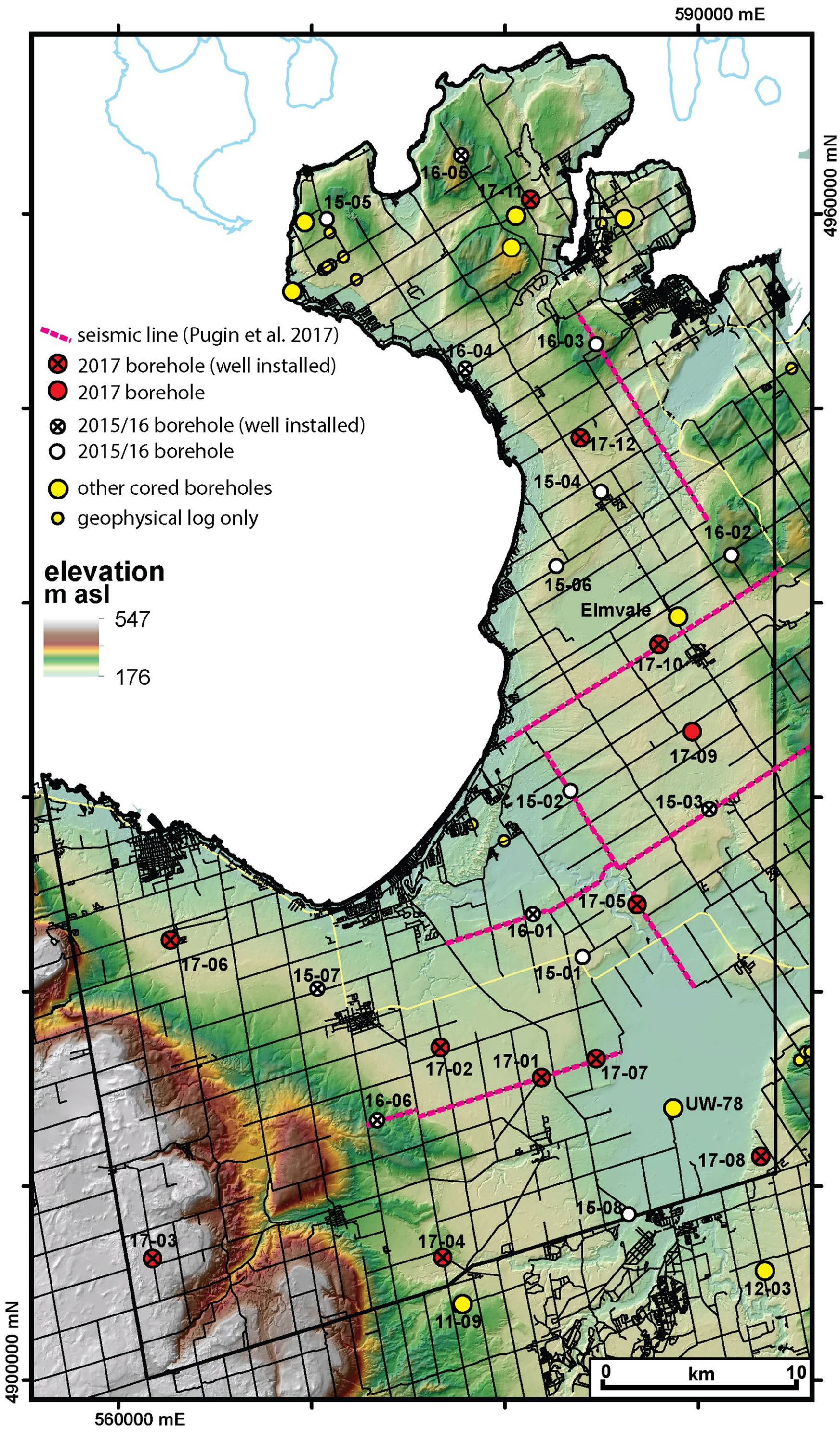

Figure 25.1. Map of subsurface data collected in central Simcoe County. Map shows the locations of boreholes drilled in 2017 (red circles); the locations of boreholes drilled in 2015 and 2016 (white circles); and the locations of previously drilled boreholes (larger yellow circles). Seismic transect data *from* Pugin et al. (2017). Boreholes not drilled as part of this study are *from* Bajc (1994: unlabelled boreholes P92-01–P92-05 (near top of figure)), *from* Bajc et al. (2015: [SS-]11-09 and [SS-]12-03 (near bottom of figure)) and *from* Fitzgerald (1982: UW-78). The Elmvale borehole was drilled to support local field groundwater geochemistry investigations led by Dr. W. Shotyk (R.P.M. Mulligan, unpublished data, 2012–2013). Map features are overlain on digital elevation model (DEM) image (hillshade) (from Ministry of Natural Resources 2010). Universal Transverse Mercator (UTM) co-ordinates are provided using North American Datum 1983 (NAD83) in Zone 17N.

surface is characterized by a broad, but poorly defined, valley up to 40 km wide that appears to extend from southern Georgian Bay southeastward to Lake Ontario. At its deepest known point within the study area, the bedrock is eroded down to 81.25 m above sea level (asl). The valley likely had its origins in a preglacial drainage system (Spencer 1890), which was subsequently enhanced by multiple Quaternary glacial episodes (Gao 2011; Mulligan and Bajc, in press; D.R. Sharpe, Geological Survey of Canada, written communication, 2017).

Overlying the bedrock valley, Quaternary sediments form successions greater than 150 m thick beneath uplands in the north and east and up to 139 m beneath lowlands in the central parts of the study area. Previous drilling by the author has identified 4 major stratigraphic packages overlying bedrock in the study area (Mulligan 2016). These packages bear strong similarities to those identified by previous OGS drilling investigations to the south (Bajc et al. 2015) and east (Burt and Dodge 2011), although the subunits within the sediment groups show significant local variations and their subsurface relationships remain difficult to fully establish. Quaternary sediment successions encountered in 2017 reached a maximum thickness of 138.75 m in borehole CS-17-09 (Figures 25.1 and 25.2), whereas drift thickness is significantly reduced in the bedrock-dominated terrain along the Niagara Escarpment with borehole CS-17-03 (not shown on Figure 25.2) encountering just 6.8 m of sediment overlying bedrock.

RESULTS

Bedrock Topography and Geology

The drilling conducted as part of this study represents the only boreholes and/or wells that reach the bedrock surface across large parts of the study area. Three boreholes (CS-17-11, CS-17-10 and CS-17-09) intersected Precambrian bedrock (*see* Figures 25.1 and 25.2; Photo 25.1A), bringing the total number of new inliers in the area to 5. Of note is that 3 of the 5 intersections of basement rock (boreholes CS-17-10, CS-17-09 and CS-15-03; *see* Figures 25.1 and 25.2) occur in a nearly straight line, oriented north-northwest to south-southeast, located 23 to 30 km south of the nearest surficial exposures of basement rocks. These 3 locations were also the lowest bedrock elevations in the project area and suggest the presence of a significant (but still poorly defined) valley and/or re-entrant eroded into the Paleozoic bedrock surface, which also coincides with a high on the underlying basement.

Quaternary Stratigraphy

LOWER TILLS AND GLACIOLACUSTRINE COMPLEX

The Quaternary stratigraphy is floored by a lower, coarse-grained till that is 2 to 15 m thick. It is commonly encountered directly overlying the bedrock surface and is clast rich with high proportions of Canadian Shield-derived material. Concentrations of green-grey argillaceous dolostone clasts (lower Gull River Formation?) are observed in the till (Photo 25.1B) where it floors the newly discovered bedrock valley incised down to Precambrian basement rock. The lower coarse-grained till is commonly overlain by fine-grained silt–clay rhythmites several metres thick. The rhythmites contain abundant trace fossils and partially bioturbated beds (Photo 25.1C). The rhythmites vary from thicker couplets (2–7 cm) with ice-rafted debris to clast-free, finely laminated clay. Overlying the rhythmites is a fine-grained, pebbly silt to clayey silt till up to 15 m thick (Photo 25.1D). It is widespread in the central and northern part of the study area, but is commonly absent in the south and west, apparently as a result of erosion during younger glacial cycles, although equivalent deposits are encountered extensively farther south (Bajc et al. 2015). The till is locally overlain by silt–clay rhythmites with ice-rafted debris, which are marked by a strong weathering profile, down to as much as 4.5 m through both the rhythmites and the upper part of the till (Photo 25.1E).

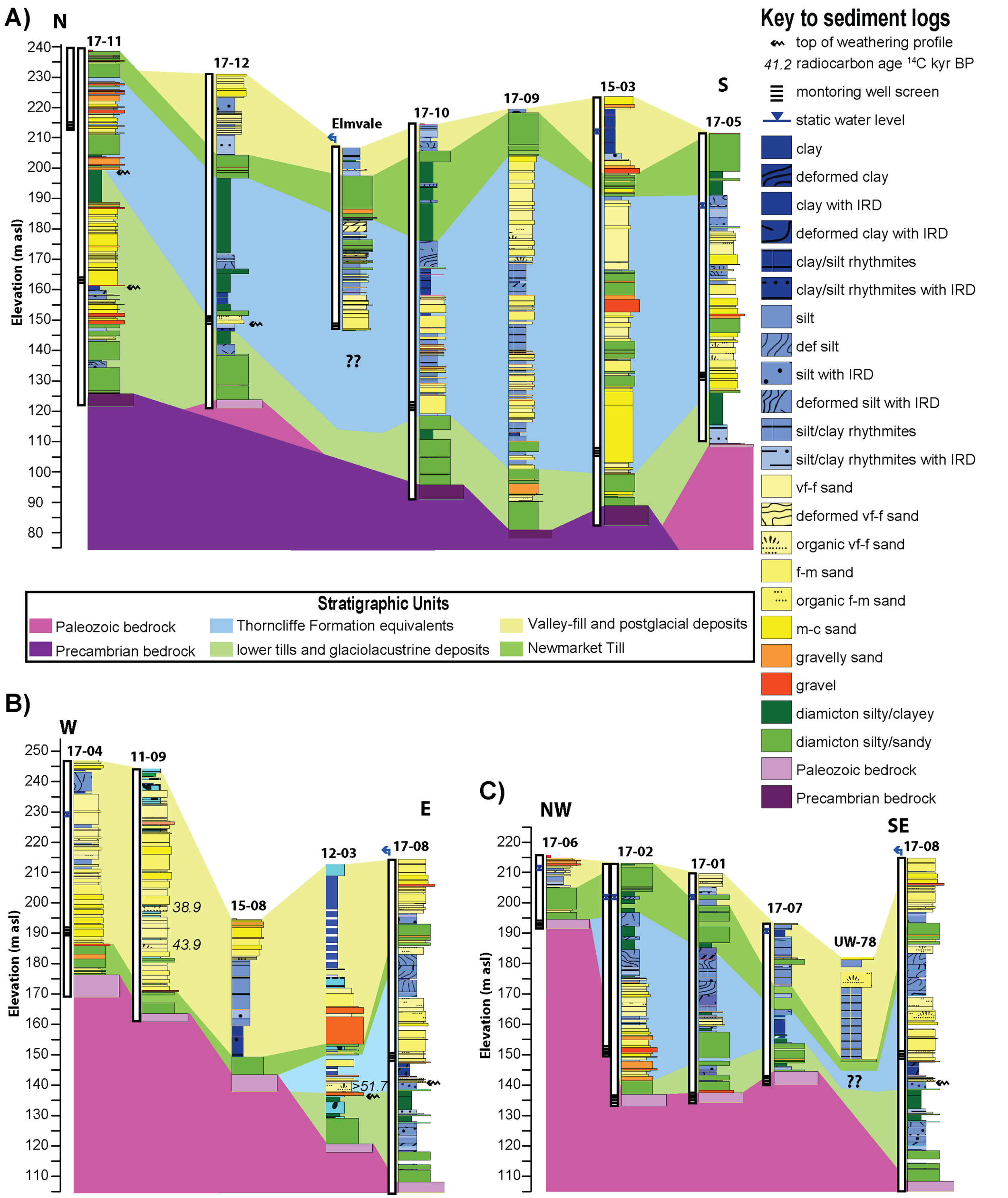

Figure 25.2. Cross-sectional profiles showing the relationship and general architecture of major sediment groups observed within the study area. No horizontal scale. **A**) The cross section extends from the north to the southern part of the study area, covering the relatively flat-lying lowlands to the east of Nottawasaga Bay. **B**) The cross section extends from west to east along the southern boundary of the study area. **C**) The cross section extends from the west to the southeastern corner of the study area. *See* Figure 25.1 for borehole locations; *see also* Mulligan (2016) for logs and relationships of boreholes not shown here. Abbreviations used in "Key to sediment logs": def = deformed; f-m = fine to medium grained; IRD = ice-rafted debris; m-c = medium to coarse grained; vf-f = very fine to fine grained.

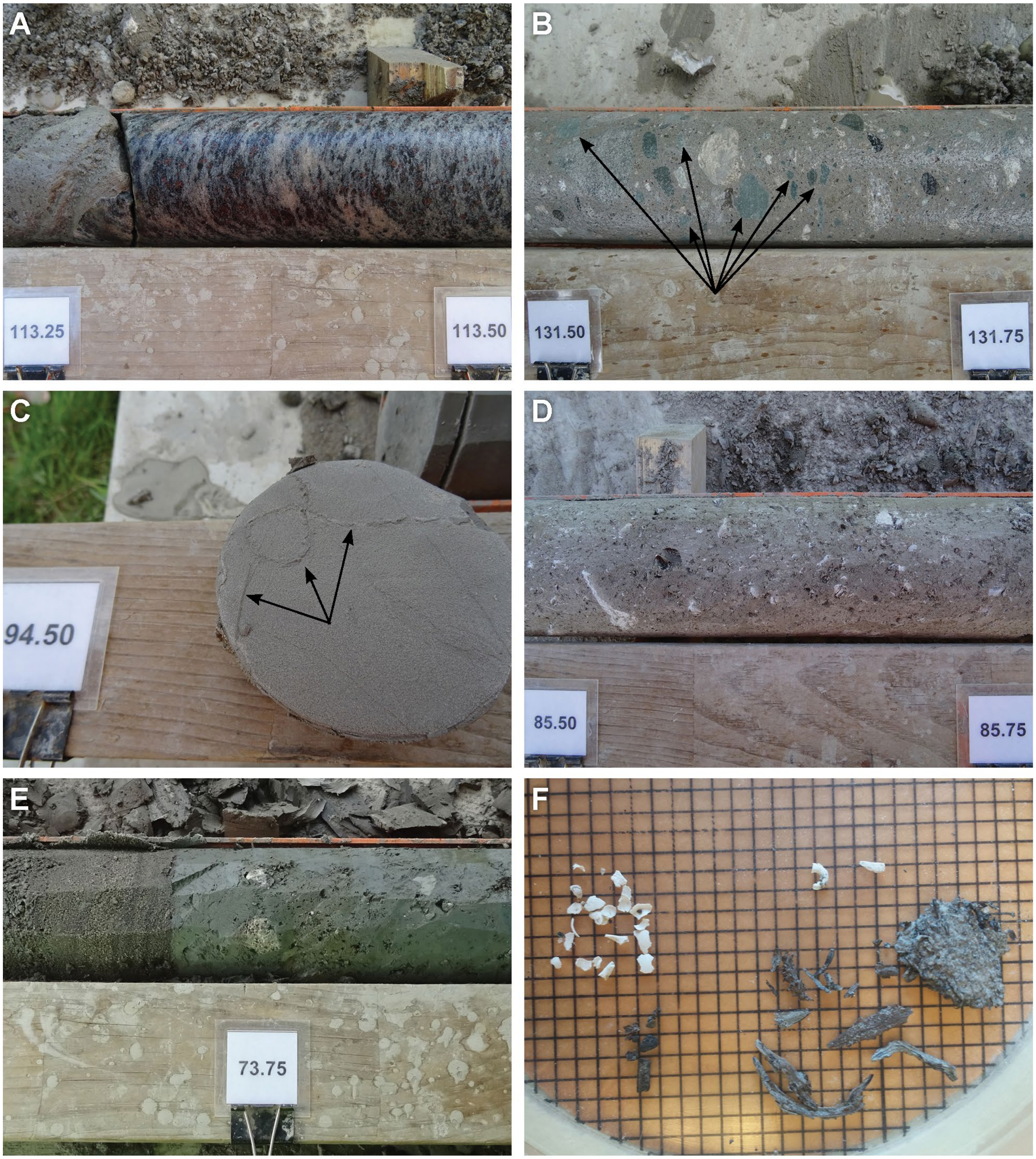

Photo 25.1. Characteristic sediment facies of stratigraphic units identified within the study area. Numbers indicate depth in metres below ground surface; for scale, core diameter is 8.5 cm. **A**) Grenville Province (Proterozoic) granitic gneiss directly overlain by Quaternary (Illinoisan or older) glacial till in borehole CS-17-11. **B**) Clast-rich lower coarse-grained till, rich in greenish clasts (lower Gull River Formation?) (indicated by arrows; borehole CS-17-09). **C**) Sandy parting plane with horizontal trace fossils (upper left part of core, indicated by arrows) in fine-grained rhythmites of the lower glaciolacustrine deposits (borehole CS-17-05). **D**) Gritty, pebbly facies of the lower fine-grained till (borehole CS-17-05). **E**) Oxidized upper part of the lower fine-grained till and overlying glaciolacustrine silt and clays (borehole CS-17-08). **F**) Organic material including shell fragments (unidentified gastropods and pelecypods), wood, leaves and peat mats observed in nonglacial deposits overlying the lower fine-grained till from boreholes CS-17-12 (left) and CS-17-08 (right).

At 2 locations (boreholes CS-17-08 and CS-17-12), fossiliferous sands overlie the weathering profile. Abundant organic material, consisting primarily of wood, twigs, leaves and mosses, was collected (Photo 25.1F); multiple samples were submitted for radiocarbon age determination. Numerous shell fragments (gastropods and pelecypods) were also observed and collected for analysis (*see* Photo 25.1F). The deep weathering profiles underlying the nonglacial sediments are consistent with timescales associated with a full interglacial episode. The presence of molluscs and other organic material indicative of tundra-like paleoenvironments in the nonglacial sediments indicate a transition to glacial conditions. Together, the data suggest this interval provides a record of soil development during the Illinoisan interglacial episode followed by sedimentation along lakes or streams in the colder early to Middle Wisconsin Episode during build-up of the Laurentide Ice Sheet (Mulligan and Bajc, in press).

THORNCLIFFE FORMATION EQUIVALENTS

Thick successions (up to 113 m) of sand, gravel and diamict and/or silt and clay overlie the lower drift sequence. Finely laminated and bioturbated clays occur at the base of the unit (Photo 25.2A), likely marking the beginning of Wisconsin Episode glacial advance into central and southern Ontario. Elsewhere, sand, gravel and diamicton form fining-upward successions at the base of the unit (Photo 25.2B); these

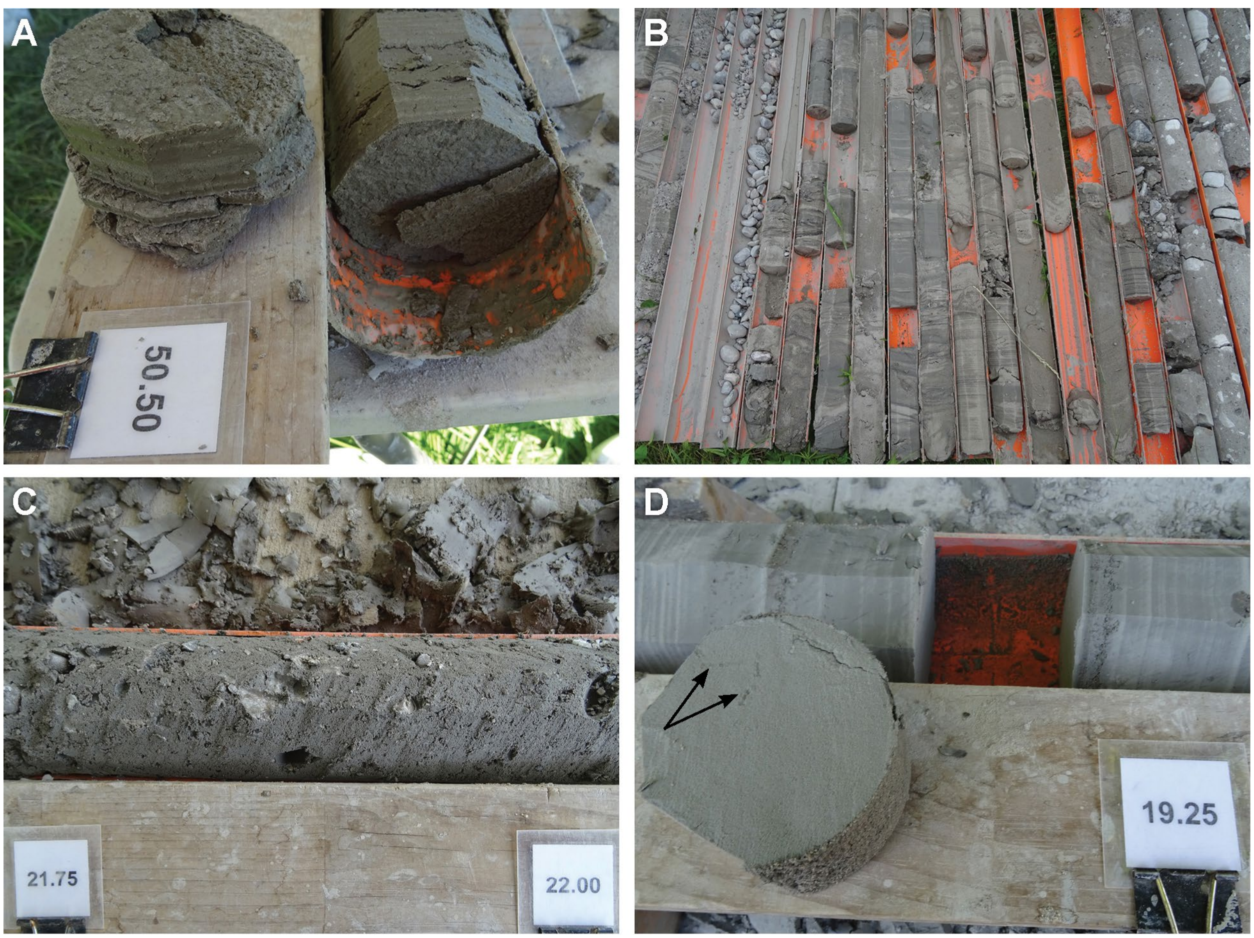

Photo 25.2. **A**) Bioturbated clays within the lower parts of the Thorncliffe Formation equivalents (borehole CS-17-10). **B**) Sand-rich facies of the Thorncliffe Formation equivalents overlying the lower fine-grained till (borehole CS-17-05). Top is in upper left of the photo, base is at lower right of photo. **C**) Sand-rich, well-consolidated and clast-rich facies of Newmarket Till (borehole CS-17-08). **D**) Trace fossils along silt parting planes (indicated by arrows) in silt–clay rhythmites deposited in glacial Lake Algonquin. Numbers indicate depth in metres below ground surface; for scale, core diameter is 8.5 cm.

facies likely record the approach of ice into the study area and erosion of the bioturbated clays, followed by retreat of the ice front, permitting deposition of extensive subaquatic fan sediments in lakes that bordered the ice front and covered the study area. In some areas, sand and gravel comprise the entire sediment package and, in other parts, no significant coarse-grained material was encountered (*see* Figure 25.2). Locally, significant accumulations of detrital organic, typically wood, twigs, leaves and mosses, are observed within sand-rich bodies of this stratigraphic interval. In these zones, the sediment cores have a high gas content and emit a noticeable sulphurous odour. The odour arises from *in situ* decomposition of the buried organic material through natural bacterial activity (Aravena and Wassenaar 1993; Hamilton 2015).

Within this stratigraphic package, there is a high degree of variation and architectural complexity as observed from the boreholes drilled in this study and in preliminary comparisons with surrounding water wells. Subregions within the study area locally host consistent stratigraphic successions, but their correlation with adjacent areas remains challenging in some places. Ongoing analysis of regional seismic reflection profiles collected by the GSC (Pugin et al. 2017) may assist in better assessing sediment architecture.

NEWMARKET TILL

The Newmarket Till was encountered in all boreholes drilled in 2017. It ranges from 7 to 30 m thick and is consistently encountered on uplands, lowlands and on the Niagara Escarpment. Boreholes reveal significant variations in sediment facies and physical properties of the Newmarket Till. It is generally a pebbly to stony, well-consolidated silty sand till (Photo 25.2C) that, toward the north, becomes increasingly enriched in matrix sand content and Precambrian bedrock clasts. In some areas, the till has a silt to clayey silt texture and contains deformed (sheared and folded) silt and clay interbeds (borehole CS-17-10; *see* Figures 25.1 and 25.2A). Elsewhere, a gradational upward transition was observed, changing from laminated to deformed silt and clay of the underlying deposits, into a fine-grained stone-poor diamict that becomes increasingly sandy and clast rich (borehole CS-17-05; *see* Figures 25.1 and 25.2A). The level of matrix consolidation varies greatly: well- to highly consolidated facies predominate, but boreholes drilled on the southern flank of the “Edenvale moraine” encountered softer, crudely stratified, cobble-rich facies. The till sheet has a relatively subdued relief throughout much of the central lowlands (*see* Figure 25.2A), but significant topographic variation is observed between uplands and lowlands, particularly in the vicinity of the Minesing basin (*see* Figures 25.2B and 25.2C). Boreholes drilled in the vicinity intersect Newmarket Till at elevations as low as 144 m asl in CS-15-08 (*see* Figure 25.2B). In borehole CS-17-08, the Newmarket Till is intersected at 189.75 m asl (*see* Figures 25.1, 25.2B and 25.2C), less than 2 km to the east, the till is observed along the flanks of the adjacent uplands at 233 m asl, then can be traced eastward to an elevation of 280 to 284 m asl, where it is observed in a gravel pit 4 km east of borehole CS-17-08 and at higher elevations farther east on the uplands. Total elevation range on the till surface in the vicinity of the Minesing basin exceeds 170 m.

VALLEY-FILL AND POSTGLACIAL DEPOSITS

Locally, thick accumulations of sand with lesser gravel and silt occur within valleys of the study area. These deposits are mapped extensively in the southwest part of the study area along the Niagara Escarpment. They were intersected in borehole CS-17-04 as well as in borehole SS-11-09, which is located 3 km to the south (*see* Figure 25.1; Bajc et al. 2015). These deposits consist primarily of medium- and fine-grained sand, with rarer pebbly or gravelly beds and minor amounts of detrital organic material (*see* Figure 25.2B). These deposits commonly form fining-upward successions and are typically draped by, or interbedded with, fine-grained glaciolacustrine silt–clay rhythmites.

Thick successions of fine-grained silt–clay rhythmites locally overlie either Newmarket Till or sandy, valley-fill sediments at lower elevations (*see* Figure 25.2). Ice-rafted debris is generally concentrated in discrete bands in the lowermost parts of the rhythmites and trace fossils may be encountered throughout (Photo 25.2D). At a few locations, poorly consolidated and crudely stratified silt-rich diamict beds are observed near the base of the fine-grained sediments (boreholes CS-17-01 and CS-17-07; *see* Figures 25.1 and 25.2C). Fine-grained sediments typically coarsen upward toward the ground surface, where, locally, thick accumulations of sand and/or gravel occur. Significant accumulations of detrital organic (wood, moss and well-preserved leaves of *Dryas integrifolia*) were intersected in the lower parts of sands that extend to surface in borehole CS-17-08.

The uppermost sediment package records fluctuating environmental conditions during ice retreat from the region (Deane 1950; R.P.M. Mulligan, Ontario Geological Survey, unpublished data, 2017). The coarse-grained sediment facies directly overlying the Newmarket Till record ice-marginal sedimentation in subaquatic fan settings during the earliest phase of deglaciation in the study area. Fine-grained rhythmites record the prior existence of ice-dammed lakes at elevations greater than 100 m above Georgian Bay. Thin diamictons in the vicinity of the "Edenvale moraine" (Chapman and Putnam 1984; *see also* Mulligan 2014, 2015) record the delivery of poorly sorted sediment to the lake floor by subaqueous debris flows and/or ice rafting associated with late-stage ice advance(s) and/or surge(s) out from the Georgian Bay basin. Coarse-grained deposits capping the sediment sequence mark the final fall of glacial lake levels in the study area.

Hydrogeology

Several boreholes intersected potentially significant buried aquifers (sand, gravel and some bedrock units) and continue to provide valuable data on the hydraulic properties of Quaternary sediments in the region, the distribution of coarse-grained sediment bodies that may be suitable for future groundwater supply, and the locations of potentially significant recharge areas. To better inform questions surrounding the hydrogeologic significance of the Quaternary sediments in the region, monitoring wells were installed at 11 of the 12 boreholes drilled in the summer of 2017 (*see* Figures 25.1 and 25.2). If no significant aquifers were intersected within the sediment succession, a well was screened at the bedrock interface. At 2 locations, a shallow and a deep well were installed to assess the potential connectivity of locally significant groundwater flow systems. Water-level measurements have been recorded by Nottawasaga Valley Conservation Authority staff (*see* Figure 25.2) and data loggers are installed at several locations for long-term monitoring.

FUTURE WORK

Hydrogeology

The OGS is initiating a hydrogeological mapping project of south and central Simcoe County in 2018, building on the 3-D sediment mapping work currently underway. This integrative study is the first of its kind by the OGS, and will involve the integration of physical and hydrochemical data with the 3-D sediment model(s) that are under development. It is anticipated that the integration of physical and hydrochemical data within the sedimentary framework will provide additional data to support the mapping of recharge areas, the identification of hydraulically distinct aquifers and aquitards, and will provide information for the assessment of newly identified aquifers for water supply potential.

Future work will include the integration of existing hydrogeological data sets within the stratigraphic framework, as it is developed. Existing hydrogeological data sets comprise the OGS Ambient Groundwater Geochemistry data, the physical hydrogeological testing results of the local conservation authorities and agencies and any physical hydrogeological data that can be obtained from the water-well information system of the Ministry of Environment and Climate Change. Groundwater sampling of the monitoring wells that have been installed for this project, as well as those for south Simcoe County, is scheduled for the summer of 2018.

Geophysics

Additional downhole geophysical logging of the sediments and bedrock at monitoring well locations will be conducted by the GSC. These data will help integrate geologic and hydrogeologic investigations (Crow et al. 2017) and permit the full integration of seismic reflection surveys into the regional 3-D model (Pugin et al. 2017). These data collected by the GSC in Simcoe County will be prepared and made available to the public by the GSC.

Modelling

Following completion of subsurface data collection for central Simcoe County, the project will shift to database development, model generation and product delivery. Surficial maps for the majority of the area have been released (Mulligan 2017a, 2017b) and new maps for the northernmost part of the study area are in preparation. As with other OGS 3-D sediment mapping projects, all subsurface data will be available for download following completion of all laboratory analyses (Bajc et al. 2015; Burt and Dodge 2016).

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REFERENCES

Aravena, R. and Wassenaar, L.I. 1993. Dissolved organic carbon and methane in a regional confined aquifer, southern Ontario, Canada: Carbon isotope evidence for associated subsurface sources; Applied Geochemistry, v.8, p.483-493.

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Bajc, A.F. 1994. Quaternary geology of the Huntsville–Penetanguishene area, central Ontario; Ontario Geological Survey, Open File Report 5882, 134p.

Bajc, A.F., Mulligan, R.P.M., Rainsford, D.R.B. and Webb, J.L. 2015. Results of 2011–13 overburden drilling programs in the southern part of the County of Simcoe, south-central Ontario; Ontario Geological Survey, Miscellaneous Release—Data 324.

Burt, A.K. and Dodge, J.E.P. 2011. Three-dimensional modelling of surficial deposits in the Barrie–Oro Moraine area of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 11, 125p.

——— 2016. Three-dimensional modelling of surficial deposits in the Orangeville–Fergus area of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 15.

Chapman, L.J. and Putnam, D.F. 1984. The physiography of southern Ontario; Ontario Geological Survey, Special Volume 2, 270p.

Crow, H.L., Olson, L.C., Mulligan, R.P.M., Cartwright, T.J. and Pugin, A.J-M. 2017. Downhole geophysical logs in Quaternary sediments of central Simcoe County, southern Ontario; Geological Survey of Canada, Open File 8251.

Deane, R.E. 1950. Pleistocene geology of the Lake Simcoe district, Ontario; Geological Survey of Canada, Memoir 256, 108p.

Fitzgerald, W.D. 1982. Postglacial history of the Minesing basin, Ontario; unpublished MSc thesis, University of Waterloo, Waterloo, Ontario, 93p.

Gao, C. 2011. Buried bedrock valleys and glacial and subglacial meltwater erosion in southern Ontario, Canada; Canadian Journal of Earth Sciences, v.48, p.801-818.

Hamilton, S.M. 2015. Ambient groundwater geochemistry data for southern Ontario, 2007–2014; Ontario Geological Survey, Miscellaneous Release—Data 283–Revised.

Ministry of Natural Resources 2010. Southwestern Ontario Orthophotography Project (2010) - digital elevation model; Ministry of Natural Resources, Land Information Ontario, Peterborough, Ontario.

Mulligan, R.P.M. 2014. Three-dimensional mapping of Quaternary deposits in the central part of the County of Simcoe, southern Ontario; *in* Summary of Field Work and Other Activities, 2014, Ontario Geological Survey, Open File Report 6300, p.26-1 to 26-19.

——— 2015. An update on three-dimensional mapping of Quaternary deposits in the central part of the County of Simcoe, southern Ontario; *in* Summary of Field Work and Other Activities, 2015, Ontario Geological Survey, Open File Report 6313, p.28-1 to 28-14.

——— 2016. Subsurface data collection for three-dimensional sediment mapping in the central part of the County of Simcoe, southern Ontario; *in* Summary of Field Work and Other Activities, 2016, Ontario Geological Survey, Open File Report 6323, p.31-1 to 31-10.

——— 2017a. Quaternary geology of the Collingwood area; Ontario Geological Survey, Preliminary Map P.3815, scale 1:50 000.

——— 2017b. Quaternary geology of the western half of the Barrie and Elmvale areas; Ontario Geological Survey, Preliminary Map P.3816, scale 1:50 000.

Mulligan, R.P.M. and Bajc, A.F. in press. The pre-Late Wisconsin stratigraphy of southern Simcoe County, Ontario: Implications for ice sheet build-up, decay, and Great Lakes drainage evolution; Canadian Journal of Earth Sciences, doi:10.1139/cjes-2016-0160.

Pugin, A.J-M., Crow, H., Dietiker, B., Rainsford, D.R.B., Mulligan, R.P.M., Burt, A.K. and Russell, H.A.J. 2017. Near surface hydro-geophysics in southern Ontario; *in* Regional-scale groundwater geoscience in southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario open house; Geological Survey of Canada, Open File 8212, p.30, doi:10.4095/299750.

Rainsford, D.R.B. and Biswas, S. 2014. Summary of geophysical projects and activities; *in* Summary of Field Work and Other Activities, 2014, Ontario Geological Survey, Open File Report 6300, p.18-1 to 18-7.

Russell, H.A.J. and Dyer, R.D. 2016. Ontario Geological Survey–Geological Survey of Canada groundwater geoscience collaboration: Southern Ontario 2015–2019; *in* Summary of Field Work and Other Activities, 2016, Ontario Geological Survey, Open File Report 6323, p.35-1 to 35-15.

Spencer, J.W. 1890. Origin of the basins of the Great Lakes of America; Quarterly Journal of The Geological Society, v.46, no.1-4, p.300-337.