Ontario

Groundwater Resources Study 9

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Ontario Geological Survey
Groundwater Resources Study 9

by

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Abstract

An investigation into buried valley aquifer systems in southern Ontario has focused on 3 main locations: 1) in the Caledon East area within Peel Region; 2) in the Schomberg area within York Region; and 3) in the Barrie/Angus area to the west of Kempenfelt Bay on Lake Simcoe. It is recognized that buried valleys in southern Ontario often contain productive aquifers with high-quality groundwater. Despite this, there has been very little systematic scientific work undertaken in southern Ontario to better understand the nature of the buried valleys and their sediment infill. This report describes the investigation of the Caledon East buried valley aquifer system.

The Caledon East buried valley appears to be connected to the Laurentian channel. Spencer (1890) initially inferred the presence of the Laurentian channel network, a broad bedrock depression extending from Georgian Bay to Lake Ontario that is nearly 100 km long and up to 25 km wide. The channel is believed to have an influence on groundwater movement over a large part of southern Ontario.

A combination of seismic geophysical surveys and a continuously cored borehole at the Heart Lake Road were undertaken to assist with the resolution of the subsurface aquifer architecture within the Caledon East buried valley system. Downhole geophysics were also run on the Heart Lake Road borehole to better quantify the response of the subsurface geology and to help in describing the subsurface glacial stratigraphy.

The preliminary results from this study indicate that there is at least 10 to 12 km of sand and gravel in the deeper portions of the Caledon East buried valley system. These deposits appear to be 1 to 2 km wide and 20 to 100 m thick. This coarse sediment is flanked and overlain by silts and sands that are interpreted to extend to the entire width (~2 km to 4 km) of the bedrock valley and to a thickness of 100 m along the length of the valley. A continuous blanket of fine-grained clay-silt rhythmite sediments, at least 20 to 30 m thick, caps the channel-fill sequence. The sedimentological pattern revealed in the Heart Lake Road borehole is consistent with subglacial meltwater activity. There is likely a transfer of groundwater through this buried valley system from the Credit River watershed to the Humber River watershed in the order of 5000 m^3/day.

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Introduction

A systematic study of the hydrogeology and basin analysis of the buried bedrock valley settings in the Laurentian channel area of south-central Ontario began in 2001 (e.g., Sharpe, Dyke et al. 2003; Davies and Holysh 2005). This report describes the investigation of one such buried bedrock valley in the Caledon East area (Figure 1) near the western terminus of the Oak Ridges Moraine at the Niagara Escarpment. There were 3 key factors that coincided to create the impetus for initiating the study:

- in 2001 Credit Valley Conservation was undertaking a study in the area and was looking for a key well that would help to characterize the subsurface geology of the area and that could be used for long term background monitoring;
- Caledon East, which sits on the divide between the Credit and Humber rivers, is in need of additional water supplies to meet demand; and
- the bedrock valley in the area was poorly understood and there was a need to investigate the role of the bedrock valley in moving groundwater between the Credit River and the Humber River watersheds and the potential linkage to the Laurentian channel to the east. The origin of the valley was also of interest.

The study was overseen and coordinated by a coalition of conservation authorities (Conservation Authority Moraine Coalition) and regional municipalities (York, Peel, Durham and Toronto) that are collectively termed CAMC-YPDT. This coalition has combined resources to better understand groundwater conditions in the Oak Ridges Moraine and vicinity (Holysh et al. 2003). The Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC) are also partners in this study.

A variety of mechanisms and hypotheses for the formation and fill of bedrock valleys have been reported (e.g., Scheidegger 1980) and range from preglacial fluvial (e.g., Spencer 1890) to glacial (e.g., Straw 1968) or subglacial fluvial systems (e.g., Kor and Cowell 1998). However, the processes that formed these valleys and deposited the thick sedimentary infills are poorly known, and few critical data have been gathered to test basin models with respect to the valley origin. The dataset gathered as part of this study in the Caledon East area provides an excellent reference with which to examine the buried valley origin and develop a hydrostratigraphic model that can be used for ongoing aquifer mapping.

Study Objectives and Scope

This report examines the geology and hydrostratigraphy of the buried valley identified in the Caledon East area with emphasis on providing a hydrostratigraphic model of the study area. The dataset for this study was initially generated through:

- the drilling of one deep, continuously cored borehole CAMC/YPDT-Heart Lake Road (Figure 2) in the middle of the buried valley (on Heart Lake Road, just north of Old Baseline Road);
- undertaking a complete suite of downhole geophysical logging (including a downhole vertical seismic profile); and
- the completion of 10 line km of reflection seismic data along 3 profiles spaced at intervals of 4 to 6 km (along Heart Lake Road, Mountainview Road and Humber Station Road).

After these results were reviewed, 2 additional boreholes (Figure 2, CAMC/YPDT-Boston Mills Road and CAMC/YPDT-Willoughby Road) were drilled using a mud rotary drill rig. These boreholes were intended to define the bedrock surface and provide preliminary stratigraphic information and confirm seismic stratigraphic interpretations without the expense of drilling and storing a higher-quality PQ-continuously cored borehole. The CAMC/YPDT-Boston Mills Road borehole was drilled on Boston Mills Sideroad just south of the village of Caledon East. The CAMC/YPDT-Willoughby Road borehole was drilled on top of the Niagara Escarpment along the interpreted thalweg of the buried bedrock valley in that area. This borehole was completed in partnership with a private resident who wished to have a domestic well installed. Funds were advanced to cover the costs of advancing this borehole to bedrock beyond the depth necessary to obtain a potable supply.

Several cored boreholes from a nearby landfill investigation of the Interim Waste Authority (IWA sites, Figure 2) provide additional detailed geological context, as did geological and hydrogeological data regarding the municipal well fields available from the Region of Peel. Water well records from the Ontario Ministry of Environment (MOE) water well information system (WWIS) provided additional cursory geological and hydrogeological data.

The location of the sites from which data was collected as part of this study is illustrated in Figure 2.

Previous Studies

GEOLOGICAL MAPPING

White (1975) mapped the Quaternary sediments of the area, thereby providing geological context for the Heart Lake Road borehole near Caledon East (Figure 3). The site occurs at about 277 m asl in Oak Ridges Moraine sediments that are north of the Halton Till plain and south and east of the Singhampton and Paris moraines (*see* Figure 3) (Russell and White 1997). This mapping places local geology into a regional framework and shows that the drill site is situated at the southwestern extent of the Oak Ridges Moraine (Sharpe et al. 1997). The Oak Ridges Moraine comprises 4 major sediment wedges linked by narrow ridges (Barnett et al. 1998): Rice Lake, Pontypool, Uxbridge and Albion Hills wedges. The high-quality PQ-cored borehole (CAMC/YPDT-Heart Lake Road) site is situated in the western-most sediment wedge, Albion Hills, which rests adjacent to the Niagara Escarpment (*see* Figure 3). On a regional scale, Albion Hills sediments tend to be finer grained than sediments of eastern wedges (Russell and Sharpe 2002). Consequently, the borehole site is more distal (perhaps deeper water) in the regional depositional setting (Barnett et al. 1998). Similar coarse-to-fine sediment trends within Oak Ridges Moraine sediment wedges have been noted as upward fining trends in sediment cores across the moraine (Gilbert 1997; Barnett et al. 1998; Russell and Sharpe 2002; Russell, Arnott and Sharpe 2003).

A system of channels is partly eroded into the Niagara Escarpment along its east-facing cuesta at elevations ranging from about 425 to 245 m asl (Chapman and Putnam 1984). These channels afforded southwest meltwater drainage as the Oak Ridges Moraine was forming and therefore controlled water levels during Oak Ridges Moraine sedimentation (Barnett et al. 1998). The Caledon channel near the Forks of the Credit is cut at about 425 m asl and follows one of several re-entrants in the escarpment face. It extends southwest in front of the Paris Moraine, having cross-cut the Singhampton Moraine to the northeast (*see* Figure 3). The Paris and Singhampton moraines appear to record mainly glaciofluvial sedimentation (White 1975; Gwyn and White 1973) at grounding positions of late glacial ice. As these moraines were being deposited, proglacial or subglacial meltwater drainage was likely channelized westward to southwestward between glacier ice and the Niagara Escarpment.

Previous geological mapping in the area still needs to be integrated with new 3-dimensional mapping methods (Sharpe, Russell and Logan 2002), continuous cores (i.e., Russell et al. 2006) and "golden spikes" (Sharpe, Pugin et al. 2003) to provide an updated stratigraphic model of the area.

REGIONAL STRATIGRAPHIC FRAMEWORK

The lithostratigraphy of the region (Karrow 1967; Boyce, Eyles and Pugin 1995) has been reinterpreted using basin analysis principles. The resultant conceptual model (Figure 4; Sharpe et al. 1996) forms the basis of a regional stratigraphic framework of the Oak Ridges Moraine area. A key result is the mapping of a regional unconformity defined by drumlinized Newmarket Till and the beds and banks of tunnel channels (Barnett et al. 1998; Sharpe et al. 2004). To map the regional stratigraphy with low-quality archival data, the stratigraphic framework was simplified to 5 principal units. They are, stratigraphically upward: 1) Paleozoic bedrock; 2) Lower sediment; 3) Newmarket Till; 4) Oak Ridges Moraine and channel sediment; and 5) Halton Till. Lower sediment includes a group of 10 poorly exposed formations representing the middle Wisconsinan glacial period, while older sediments are described mainly from the Scarborough Bluffs (Karrow 1967). Lower sediment has been subdivided to support development of a numerical groundwater model (e.g., Gerber et al. 2004).

INTERIM WASTE AUTHORITY BOLTON INVESTIGATION

In the early 1990s, the Interim Waste Authority (IWA) was established by the provincial government to conduct a search for potential landfill sites to service the Greater Toronto Area. Intensive investigations were completed at 6 candidate sites, one of which was a 122 ha site just west of Bolton (Figure 5). The IWA investigation in the Bolton area was very intensive in terms of the number of boreholes that were drilled to investigate the subsurface conditions. Within the 122 ha site, 17 boreholes were drilled at 5 locations in 1993; while in 1994, 91 boreholes were drilled at 25 locations (Blair 1994). At most of the locations, the deepest borehole was completed using PQ-coring, which provided undisturbed continuous core.

The Bolton IWA investigation defined a consistent sequence of glacial tills and fine-grained glaciolacustrine deposits containing sandy horizons (Blair 1994). A total of 4 main stratigraphic units were identified:

1. The uppermost stratigraphic unit was referred to as the Upper Till Sequence.

2. An upper glaciolacustrine sequence was the next defined unit and consisted of thick, fine-grained silty to clayey sediments containing a distinct water-bearing sand horizon, referred to as the Sand Aquifer.

3. Underlying the upper glaciolacustrine sequence (however, restricted geographically to areas of deep sediment packages in the Humber River valley) was a lower glaciolacustrine sequence. The Bolton municipal wells are screened within this sequence.

4. The glaciolacustrine sequences were underlain by Lower Till Complex, although this till complex was noted to drop substantively in elevation within the deep buried valley system. The till was noted to be predominantly a hard, grey, massive clayey silt with some sand and gravel and occasional boulders.

The high-quality continuous core data from the Bolton IWA study (Blair 1994) have been re-interpreted within the context of the regional stratigraphic model (*see* Figure 4). The results are shown in cross-section in Figure 6 (Russell 2001).

Within the IWA site, the bedrock shales of the Georgian Bay Formation occur at elevations that vary by more than 50 m over the site from a low of about 170 m asl to a high of around 228 m asl. Sediment thickness averages about 80 m, consisting mainly of diamicton below Oak Ridges Moraine and Halton Till sediment. A 1 to 10 m thick, dense, stoney sand till is present on bedrock across most of the IWA site. Due to the presence of Newmarket Till across the Greater Toronto Area, and because Lower sediment is generally absent in borehole records west of the Humber River, the diamicton may be inferred to be Newmarket Till. However, in the Nobleton area (approximately 9 km to the east of the study area), the Newmarket Till overlies Thorncliffe Formation (the upper part of the Lower sediments; *see* Figure 4) at an elevation of about 250 m asl (Sharpe, Pugin et al. 2003). This is much higher than the diamicton unit observed in the IWA boreholes (185 to 205 m asl). Above the lower diamicton, the overlying sediments consist of minor gravel, medium to coarse sand, cross-laminated fine sand and thick sequences of graded fine sand and silt with clay laminae capping fining-upward sets. These beds tend to fill topographic lows (*see* Figure 4). Sedimentary structures include silt rip-up intra-clasts and vertical dewatering features. Examination of similar cores and outcrops across the area indicate that these rapidly deposited beds are likely Oak Ridges Moraine sediments (Russell 2001). The overlying Halton Till sediment consists of about 10 to 30 m of silt diamicton with graded sand interbeds (*see* Figure 6).

SEDIMENTARY PROCESSES

The Oak Ridges Moraine forms the dominant aquifer complex in the region and its sedimentary character is of special significance. In general, Oak Ridges Moraine deposits are interpreted as subglacial, glaciofluvial, transitional to glaciolacustrine subaqueous fan, and delta sediments, deposited in a glacial lake ponded between the ice and the Niagara Escarpment (approximate elevation of 400 m asl) to the west (Barnett et al. 1998).

Observations of Oak Ridges Moraine sediments describe a depositional system characterized by rapid sedimentation from subglacial outburst floods (Barnett et al. 1998). These floods deposited thick, wedge-shaped beds of coarse sediment in an extensive network of large, deep, steep-walled channels (Russell, Arnott and Sharpe 2003). Cross-channel unit geometry is tabular, whereas along-channel sedimentary elements are conformable with undulating longitudinal channel profiles (Pugin, Pullan and Sharpe 1999). Sediment facies may represent a number of local depositional environments that link high-magnitude, episodic events under confined flow through to deep basin discharge. These events produced facies assemblages similar to those in proglacial, glaciofluvial and glaciolacustrine systems, however, subglacial channels commonly have greater flow depths, flow velocities and depositional rates. Associated subglacial bedforms are similar to large cross-beds (Shaw and Gorrell 1991), but larger than those from existing braided-fluvial depositional models (e.g., Walker 1992). The thick massive sand sequences found in subglacial channels are not found in proglacial sequences. These diffusely bedded, fine sand deposits record rapid and voluminous deposition from sediment-laden flows at sites of flow expansion such as those inferred from subaqueous fans (Russell 2001). Fine sand, silt, clay rhythmites were deposited across the basin by low-energy gravity flow from seasonal meltwater discharge (Gilbert 1997; Russell 2001). Oak Ridges Moraine ridge-building sediments have predominant southwestward to westward paleoflow indicators and again relate to high-energy subglacial meltwater floods (Russell and Sharpe 2002).

HYDROGEOLOGY

Dames and Moore Canada (1992, 1996) reported on a comprehensive groundwater study of the municipal well systems in the Region of Peel in the late 1980s and 1990s, including those in Inglewood, Caledon East and Bolton (which are within the study area). AMEC Earth and Environmental Limited (2000) also completed a groundwater study for the Region of Peel in the Inglewood area.

Bolton

Dames and Moore Canada (1996) reported the Bolton Aquifer to be part of a complex of deep, coarse-grained sediments that occur within 3 buried bedrock valleys (note that this is not the current interpretation) that merge just east of Bolton and north and east of the IWA site. The aquifer was deposited either directly on top of shale bedrock or is underlain by till within the valleys. The aquifer sequence was noted to be up to 40 m thick in the centre of the valleys, thinning considerably up the valley slope.

Dames and Moore Canada (1996) essentially identified the same 4 main hydrostratigraphic units that were mapped in the IWA study: an Upper Till Complex (Halton Till); a glaciolacustrine sequence of silt, sand and clay (Oak Ridges Moraine sediment); a Lower Till (Newmarket Till or earlier); and a basal aquifer consisting of sand, gravel and silt (Oak Ridges Moraine channel or Scarborough or Thorncliffe formations). The current interpretation is that the Bolton Aquifer is located within the basal portion of Oak Ridges Moraine channel-fill deposits in areas where the Newmarket Till has been eroded.

Dames and Moore Canada (1996) indicated that recharge to the aquifer was limited in that it was mainly derived from groundwater storage provided by the overlying confining silts, clays and sands of the glaciolacustrine sequence. A simplified 2-dimensional numerical model showed that the municipal pumping (at a rate of about 4700 m^3/day) would result in the long term mining of the aquifer. Partly based on this analysis, it was determined that the wells were incapable of meeting the projected long term water demand and the municipal wells were taken off-line in 2001 and replaced with lake-based servicing. Water levels in the municipal wells have been recovering since that time.

Caledon East

Dames and Moore Canada (1996) noted 2 aquifer systems in the Caledon East area from which the municipal supply is derived: the Caledon East Aquifer, and the Granite Stones Aquifer. The Caledon East Aquifer is reflected on the ground surface by the meltwater channel deposit that extends from Inglewood in the west to just south of Albion in the east (White 1975). The 2 municipal wells drawing water from this aquifer are shallow and extend to only about 20 m depth. The Granite Stones Aquifer refers to a deeper, confined sand and gravel deposit north of the Caledon East Aquifer. The aquifer appears to be confined by Newmarket (or earlier) Till deposits and pinches out completely to the south and east where the till directly overlies bedrock. Recharge to this aquifer likely originates on the upper escarpment flanks to the north, where coarser ice-contact deposits are found at surface and the till unit appears to be thin to absent. Both of these aquifers are located north of the main buried bedrock valley that is the focus of this study. Considering the substantive thickness of finer-grained glaciolacustrine sediment separating the deeper aquifer in the buried valley from the 2 Caledon East aquifers, it is likely that these upper aquifers are hydraulically isolated from the thick gravel sediments found at the base of the Heart Lake Road borehole and inferred to be present in both of the seismic lines completed to the east.

Inglewood

Inglewood originally relied on 2 supply wells located east of the village and just west of the main branch of the Credit River. These wells are located within the main valley of the Credit River near the terminus of the Caledon East meltwater channel (White 1975). Following a test drilling program in the early 1990s, a third well was constructed approximately 1500 m to the north. Test drilling in this area showed the water-bearing sediments to be up to 60 m thick, significantly thicker than in the area of the older wells. Based on water well records, AMEC (2000) interpreted this production well as part of the buried valley aquifer system extending to Caledon East and determined that the aquifer was semi-confined to confined. Current cross-sectional analyses completed as part of this study suggest that the third Inglewood well is set on the flank of the buried valley and the wells are probably screened in either the upper parts of the Thorncliffe Formation or the lower portion of the Caledon East Aquifer (the Caledon East meltwater channel). The aquifer is not likely connected to the deep aquifer at the base of the buried valley as the 2 aquifers are separated by a thick sequence of fine-grained glaciolacustrine sediments.

Site Setting

The study area encompasses the bedrock valley feature from the vicinity of the Niagara Escarpment in the west to its interpreted connection to the Laurentian channel in the vicinity of Bolton in the east. As such, the study area lies entirely within the Regional Municipality of Peel. Given the potential water supply issues in the Town of Caledon East, much of the work has been focused in this area of the buried valley. The East Credit River flows into the main Credit River west of the site, near Highway 10. Centreville Creek, a significant tributary to the Humber River, flows eastward from the area of Caledon East.

The study area is located within the Oak Ridges Moraine region near its western terminus at the Niagara Escarpment. The Oak Ridges Moraine is a regionally significant topographical feature that extends approximately 160 km from the Trenton area west to the Niagara Escarpment. The moraine forms an east-trending belt of undulating, kettled topography between 5 km and 20 km wide. East of the Niagara Escarpment, the moraine forms the surface water drainage divide between Lake Simcoe and Lake Ontario. The elevated sand and gravel deposits of the moraine make it the principal recharge area for regional aquifers (Sibul, Wang and Vallery 1977). The moraine has been traditionally interpreted as an interlobate feature with glaciofluvial and glaciolacustrine deposits. Within the study area, the Oak Ridges Moraine coincides with the Caledon and Albion Hills and the Palgrave Moraine, as mapped by White (1975). At the west end of the buried valley, near the Forks of the Credit, the escarpment is mantled by a considerable thickness of unconsolidated sediment, which is somewhat unique given the steep exposed rock faces that typically characterize the escarpment in other areas.

Geological Setting

BEDROCK GEOLOGY

Precambrian Shield rocks, exposed well north of the study area, carry regional structural trends (Easton 1992), including northwest- and northeast-trending fracture patterns, which have been carried into overlying Paleozoic rocks (Sanford, Thompson and McFall 1985). These structures may have influenced the position and orientation of lakes, valleys and rivers near the Precambrian–Paleozoic contact (Scheidegger 1980). These fracture patterns may also have affected preglacial drainage networks

(Spencer 1881) and the position of the Paleozoic bedrock valleys formed by the preferential erosion of softer shale below the Niagara Escarpment under glacial, glaciofluvial and fluvial conditions.

The study area is underlain by Paleozoic carbonate and clastic sedimentary rocks that form valleys, plateaus and rises leading to the Niagara Escarpment (*see* Figure 5). Georgian Bay Formation shale and interbedded limestone predominantly underlie the Humber River watershed (Sanford 1969) in the east, whereas overlying red Queenston Formation shale predominantly underlies the Credit River valley in the west. Outliers of Queenston Formation shale may also occur in the Humber River watershed. These shale formations gently dip southwest at 10 to 12 m/km. Rocks exposed along the slope and face of the Niagara Escarpment consist of sandstone, carbonate and shale of the overlying Cataract Group. Lockport and Amabel formation dolostones cap the escarpment (Johnson et al. 1992).

Topography

Few wells reach deep bedrock within the buried valley. However, above the escarpment in the upper watersheds of the study area the bedrock appears to consist of dissected upland plateaus with intervening poorly defined valleys. Buried uplands may be similar in form to the Milton upland (White 1975), which is bounded on the north by a re-entrant valley cut into the escarpment face. In fact, the upland area that falls between Mono Mills and Caledon in the northerly part of the study area is very similar in nature to the Milton outlier, in that it appears severely dissected both to the west and north by buried valley features. Elevated uplands west of the escarpment edge have a cap of Amabel Formation dolostone, whereas lower elevation uplands that are found east of the escarpment in the study area have cap rocks of older strata (White 1975).

According to White (1975), preglacial or pre-Wisconsinan valleys separate Amabel Formation outliers from the main escarpment cuesta. Given that structural patterns can be carried upwards from the Precambrian basement rocks, these valleys may have been superimposed on underlying shale by fluvial erosion along joint planes in the original cap rock. This process may explain an apparent rectilinear pattern in bedrock topography. However, White (1975) noted that some valleys have no upstream channels or appear to lack fluvial features, which might suggest other processes at work in addition to pre-Wisconsinan fluvial erosion.

Both the Humber and Credit rivers have narrow, steep-sided valleys cut into the face of the Niagara Escarpment, but the Humber River has been modified by glacial action while the valley of the Credit River has not been greatly affected by glacier erosion (White 1975). White (1975) also notes that the inferred preglacial bedrock topography helped direct ice-flow patterns as well as interstadial and postglacial drainage patterns. As a result, complex sequences of glacial, glaciofluvial and fluvial deposits may occur in the buried valley systems.

LAURENTIAN CHANNEL

Eastern lowlands of the study area appear to be linked to the "Laurentian River" (Spencer 1890) or a broad "Laurentian valley" (White 1975). The regional bedrock topography of the area shows the Laurentian channel as a broad depression extending from Georgian Bay to Lake Ontario (Figure 7). Re-entrant valleys or side valleys of the Niagara Escarpment also appear to be connected to the Laurentian channel system (e.g., Hunter and Associates and Raven Beck 1996; Holysh et al. 2004; Holysh, Davies and Goodyear 2004; Davies and Holysh 2005).

More than 100 years after Spencer (1890) inferred that a Tertiary Laurentian river network played a key formative role in shaping the Great Lakes basin, no clear idea of the geometry, extent and the sedimentary fill in any buried valley in this system has been established. The Laurentian channel (*see* Figure 7), connecting Georgian Bay to Lake Ontario, continues to be characterized from water well records, with little new data contributing to systematic studies of its origin and architecture. The Laurentian channel is more than 25 km wide, about 100 km long, covering an approximate area of 3500 km^2 and, in places, is greater than 100 m deep. A conservative estimate of the sediment-fill volume, about 350 km^3, indicates that it is likely to play a key hydrogeological role in both regional- and watershed-scale flow systems.

Results of Geological Analysis

GEOPHYSICAL DATA

Reflection Seismic Profiles

Land-based, shallow seismic reflection profiling is a technique that gained popularity in glaciated terrains over the last 15 to 20 years. In glaciated terrain, shallow seismic reflection surveys have been shown to be an effective means of delineating the architecture (thickness, 2-dimensional structure and lateral continuity) of the subsurface sediments. Such information is critical in 3-dimensional mapping, especially in areas where sediments are thick and borehole control is sparse. The seismic data collected in this study were obtained using the IVI minivibTM as a source.

The seismic data, collected along 3 lines in the study area (from west to east: Heart Lake Road – Line S-1; Mountainview Road – Line S-2; and Humber Station Road – Line S-3, *see* Figure 2), confirm the presence of, and better delineate, the suspected bedrock valley and its sedimentary fill (Figure 8). The 180 m deep borehole CAMC/YPDT-Heart Lake Road is located on the westernmost line along Heart Lake Road. Seismic reflector patterns show 5 main elements which, in addition to being defined based on the confirmatory drilling in borehole CAMC/YPDT-Heart Lake Road, have also been defined from past drilling and seismic studies undertaken in other areas of the Oak Ridges Moraine (e.g., Pugin, Pullan and Sharpe 1999; Russell, Arnott and Sharpe 2003). A total of 6 seismic facies have been interpreted (*see* Figure 8):

- Seismic facies 1 is a basal, semi-continuous, high-amplitude reflector, interpreted as shale and limey bedrock.
- Seismic facies 2 is a similar high-amplitude reflector that parallels the bedrock reflector on the side of, and adjacent to, the bedrock valley feature. This dense unit may be a thin layer of diamicton. However, at the Heart Lake Road borehole location it was correlated with a coarse gravel layer.
- Seismic facies 3 is an overlying 10 to 100 m thick package of high-amplitude, less continuous, hummocky, truncated and inclined reflectors, interpreted to be stacked sand and gravel sets.
- Seismic facies 4 is an upper 80 m to 150 m thick, low-amplitude, weakly planar reflector, interpreted as sand and silt.
- Seismic facies 5 is a near-surface opaque reflector up to 30 m thick, likely comprising clayey silt sediments.
- Seismic facies 6 is the upper 20 m zone of no data recovery.

Borehole Geophysics

Geophysical logs obtained from borehole CAMC/YPDT-Heart Lake Road include natural gamma, induction log conductivities, magnetic susceptibility, neutron, temperature, far density and seismic (p-wave) velocity measurements (Figure 9). The density measurements are somewhat suspect with the variability in the recorded response likely indicating areas where the PVC piping was nearer or further from the borehole wall. The density tool is the only geophysical tool that is pushed and held against one wall of the PVC pipe as it is run up and down the borehole. Where the PVC pipe is further from the actual borehole wall, the density tool is sampling more of the bentonite grout and the recorded density is lower. Alternately, where the PVC pipe is closer to the borehole wall the density tool samples the true sediment and the recorded density increases.

In the lower part of the borehole, the interval between 100 m and 178 m depth shows a gradual increase in neutron counts, except between the 132 m to 143 m depth. This pattern parallels an increase in mud over the 78 m interval with gravelly sand occurring over the 11 m interval of decreasing neutron counts. The 78 m interval shows a moderately erratic magnetic susceptibility and p-wave velocity pattern, typical of coarser-grained sequences. From 44 m to 100 m depth, gamma, induction log conductivity, p-wave, neutron and magnetic susceptibility logs show a generally uniform response. A variable interval between 60 to 70 m depth likely relates to a sandy interval. Above 44 m depth, gamma shows decreasing and increasing intervals that relate to variations in mud content. Borehole temperature indicates water flow at about 112 m, 138 m and 170 m depths.

Borehole Logging

The drilling of borehole CAMC/YPDT-Heart Lake Road (*see* Figure 2) was completed over 3 weeks in May and June of 2002 by All-Terrain Drilling Limited of Waterloo, Ontario using the PQ mud rotary continuous coring system on a truck-mounted CME 75 drilling rig. A bentonite drilling fluid was used throughout the entire drilling operation to condition the borehole, to control fluid losses and to help ensure that circulation was maintained.

Relatively undisturbed continuous core samples in 1.5 m long PVC core tubes were collected from ground surface to the bottom of borehole CAMC/YPDT-Heart Lake Road, providing an excellent record of the subsurface geology. The borehole drilling was terminated 3 m into bedrock at approximately 180 m below ground surface; 2 monitoring wells were installed in the borehole. A third monitor was installed in a second, shallower borehole, drilled adjacent to the deep bedrock hole.

A total of 117 individual 1.5 m drill runs, with a total depth of about 180.2 m, were logged at a centimetre scale. Logging recorded a number of sedimentary structures: bed thickness, texture, colour, clast size and roundness, disturbance, bed contacts, gradation and density. Core was digitally photographed and sampled for particle size, water content and total organic carbon every 50 cm, or where there was significant textural change (Russell et al. 2006). A graphic log with photo clips provides a complimentary summary drawing based on sediment facies (Figure 10).

Analysis of the core indicates an overall coarsening-upward trend from the bottom of the borehole to the top. The core also shows 3 to 6 similar, variable thickness, fining-upward sedimentary sequences or cycles that rest on bedrock and show a broad transition from gravel and sand to silt to clay (Russell et al. 2006). These sequences represent higher- to lower-energy events, similar to those reported elsewhere within the Oak Ridges Moraine (e.g., Gilbert 1997; Barnett et al. 1998; Russell and Sharpe 2002; Russell, Arnott and Sharpe 2003). The lithologic trends in the CAMC/YPDT-Heart Lake Road borehole core can be linked to identifiable patterns in the borehole geophysics (*see* Figure 9) and seismic facies (*see* Figure 8; Pullan et al. 2004).

Sediment core from CAMC/YPDT-Heart Lake Road can be described using 8 main lithofacies (Russell et al. 2006): gravel; cross-bedded sand; massive sand; cross-laminated fine sand; graded fine sand and silt; graded sandy silt; mud; and clay (*see* Figure 10). The most common sedimentary structures are cross-bedding, cross-lamination, normal grading and lamination. Deformation structures include convolutions, flame structures and other features related to fluidization and dewatering. These sedimentary attributes relate to rapid transitions from high-energy to low-energy waning flow sedimentation, including bedload transport. Waning flow is represented by turbidity currents and suspension sedimentation. This information has been combined to develop a proposed detailed sedimentary model of the Heart Lake Road site (Russell et al. 2006).

Synthesis of Geophysical Data and Borehole Logging

A summary of the main units described in borehole CAMC/YPDT-Heart Lake Road, and within the associated seismic lines, is as follows: 1) Georgian Bay Formation shale; 2) Laurentian channel sediments; 3) Oak Ridge Moraine basin sediments; 4) Oak Ridges Moraine ridge sediments; and 5) Halton Till sediments. A thin reworked sand unit caps the sequence. There is also the lower diamicton unit that was found in the IWA boreholes, but this unit does not appear to persist into the buried valley.

UNIT 1 – GEORGIAN BAY FORMATION

Grey shale, siltstone and limestone beds occur at an elevation of 106 m asl. Recovered core reveals 2 m of thin-bedded soft shale above harder beds.

Geophysical signature: Shale bedrock is confirmed at a depth of 178 m (106 m asl) by high gamma and induction log conductivity readings (*see* Figure 9). Bedrock is well defined as a semi-continuous, high-amplitude reflector. A similar, continuous, high-amplitude seismic reflector parallels the bedrock reflector on the side of and adjacent to the bedrock valley structure. This unit may be a 1 to 10 m thick layer of diamicton, or possibly a coarse gravel layer related to unit 2.

Interpretation: The bedrock valley is better defined and appears to be about 100 m deep and 2 to 4 km wide, and it widens to the northeast. It is possible that the bedrock valley has been eroded by meltwater scouring prior to coarse deposition where bedrock reflectors are directly overlain by seismic facies 3 (*see* lines S-2 and S-3 on Figure 8).

UNIT 2 – LAURENTIAN CHANNEL SEDIMENTS

The lower 78 m unit consists of sequences of sand and gravel. Lower coarse gravel (*see* Figure 10), at 178 m depth, fines up to sand, then to 19 to 25 m of graded beds of clayey silt at 142 m depth. A 10 m thick diamicton unit at around 139 to 148 m depth consists predominantly of laminated to massive gritty silts. Soft-sediment deformation is common within this section and it appears that the unit might represent a slumped bed of abundant contorted, fining-up silt beds, although some small sections have a till-like appearance. A second 2 m thick fining-upward sand and gravel set occurs above graded units at about the 137 m mark. Gravel units include open-work structure with little if any matrix. Precambrian clasts are common and can be greater than 20 cm in diameter but average 4 to 6 cm. Laurentian channel sand is cross-bedded and cross-laminated in medium to fine sand. These units form 2 to 3 m packages that fine up to silty fine sand (*see* Figure 10, 150 m), with occasional clay caps. Fluidization structures indicate rapid sedimentation in sand facies. The graded units are contorted, faulted, fluidized and appear to represent a slump deposit in this coarse sequence.

Geophysical signature: A high-amplitude, semi-continuous, hummocky, truncated and inclined reflector of seismic facies 3 characterizes the lower approximately 25 m gravelly portion of the Laurentian channel sediments. This seismic facies becomes nearly 100 m thick at Mountainview Road and about 45 m thick at Humber Station Road (*see* Figure 8). Similar high-amplitude, hummocky reflectors have been confirmed as Laurentian channel gravel in nearby Oak Ridges Moraine areas (Pugin, Pullan and Sharpe 1999). This seismic facies only occurs within the bedrock valley and pinches out as the bedrock rises out of the valley. Truncation and inclination of seismic reflectors likely indicate cross-bedded and scour-and-fill structures in the sequence. This seismic facies is up to 100 m thick, completely fills the buried valley and forms roughly 35% of the sediment succession along line S-2 Mountainview Road (*see* Figure 8). The Humber Station Road section appears to have an esker or bedform in this hummocky facies. Gravel facies are well delineated by a high downhole p-wave velocity of approximately 2000 metres per second (m/s) (*see* Figure 9). A gradual increase in gamma counts records the fining upward textural pattern in the unit. An erratic and high magnetic susceptibility pattern is typical of such coarse-grained sequences, with a high percentage of magnetics of Canadian Shield origin (Pullan et al. 2000). A clear signal in the temperature log marks the flow of water at the base of the sand–gravel sequence.

Overlying and transitional from the high-amplitude reflectors are moderate- to low-amplitude, horizontal to inclined reflectors that extend across the width of the bedrock valley and beyond. Seismic facies 4 relates to the sandy portion of the channel sequence and is dominated by fine sand and silt.

Interpretation: This gravel–sand sequence is inferred to represent high-energy channel deposition from a subglacial fluvial system. Similar channel sedimentary features are recorded in nearby channel fill settings such as Nobleton (Pugin, Pullan and Sharpe 1999). The rapid transition from gravelly to sandy sediment in thick sequences is typical of subglacial channel sequences (Russell, Arnott and Sharpe 2003).

UNIT 3 – OAK RIDGES MORAINE BASIN SEDIMENTS

An approximately 30 m sequence of rhythmically laminated clayey silt sediment conformably overlies Laurentian channel sand and gravel. From about 83 to 103 m depth the unit consists of laminated silt with clay totalling about 48 clay beds. From 74 to 83 m depth, rhythmites consist of 10 to 25 cm fining-upward beds of silty fine sand, silt and clay. Convolutions and other fluid deformation features indicate rapid sedimentation. About 46 clay caps occur in this sequence (*see* Figure 10, Oak Ridges Moraine basin at 78 m). The clay laminae indicate deep-water sedimentation, potentially over 100 m deep (Gilbert 1997).

Geophysical signature: This unit is not clearly distinguishable on the seismic profiles but it is part of a low-amplitude, weakly to moderately planar seismic facies 4, interpreted as fine sand, silt and clay. The top and bottom of this unit are well displayed on a seismic corridor stack (amalgamation of amplitudes) over a 25 m interval of the profile (Pullan et al. 2004). This unit shows a uniform gamma pattern between 74 and 100 m depth (*see* Figure 9). Magnetic susceptibility trends are very regular.

Interpretation: This unit represents very low-energy, suspension sedimentation in a glaciolacustrine basin. It likely drapes underlying sedimentary structure. Sedimentation is proglacial or possibly subglacial, but the glacial-hydrologic system essentially stopped, particularly when clay caps were deposited from suspension during winter freeze-up. If the clay caps represent annual no-melt seasons, about 100 years of very low-energy activity followed the underlying high-energy channel depositional phase. Similar quiescent intervals have been recorded in cored boreholes across the Oak Ridges Moraine (e.g., Barnett et al. 1998; Russell, Arnott and Sharpe 2003).

UNIT 4 – OAK RIDGES MORAINE RIDGE SEDIMENTS

Unit 4 extends from 33 to 65 m depth and consists of several fining-upward fine sand, silt, clay sequences that represent Oak Ridges Moraine ridge-building sediments. Sets are on the order of 0.2 to 1 m thick and grade upward from ripple cross-laminated fine sand to silty fine sand to clay (*see* Figure 10, Oak Ridges Moraine ridge, 50 m). Cross-laminated silty fine sand is often surrounded by laminated silt and massive clay reflecting the predominance of mud sedimentation. Sand units are convoluted and overturned; clay is brecciated. The soft-sediment deformation relates to high rates of sedimentation and dewatering conditions. The 2 rhythmite intervals near the top of the unit have 19 and 20 clay caps, respectively.

Geophysical signature: This unit shows as low-amplitude, weakly planar seismic facies 4, interpreted as fine sand, silt and clay. This is not distinguishable from seismic facies associated with the upper channel sediments. A few high-amplitude reflectors at the top of this facies appear to mark an acoustic break between sand below and muds above. In addition to the confirmatory data from borehole CAMC/YPDT-Heart Lake Road, similar seismic facies 4 and sediment assignment have been confirmed with continuous core for other upper channel and Oak Ridges Moraine ridge-building sediments (Pugin, Pullan and Sharpe 1999; Russell, Arnott and Sharpe 2003). This seismic facies shows as a continuous unit across all 3 seismic profiles. It also shows some positive and undulating relief considered to represent ice support as this package occurs at 212 to 245 m asl. This unit shows a slightly increasing gamma pattern between 45 and 65 m depth (*see* Figure 9) indicating an increase in clay content. Borehole data show increasing mud content upward to 42 m depth. Sandy sediment intervals are identified by slight increases and moderate perturbations in the magnetic susceptibility signal at 53 to 63 m depth.

Interpretation: This unit represents low-energy underflow sedimentation (turbidity flows) representative of the distal portion of Oak Ridges Moraine ridge deposition (Russell and Sharpe 2002). Paleoflow evidence along the moraine indicates a predominant east to west flow during ridge building (Russell and Sharpe 2002) and, hence, the fine-grained character of Oak Ridges Moraine sediments at the site. The lateral continuity of this unit and the described sediments across several profiles spaced 2 to 3 km apart is in accord with a ridge-building interpretation. About 40 years of aquiescence suspension sedimentation follows the distal Oak Ridges Moraine ridge-building underflows.

UNIT 5 – HALTON TILL SEDIMENTS

Unit 5 extends from 4 to 33 m depth and mainly consists of silt-clay rhythmites. There are a few graded fine sand, silt, clay intervals, particularly near the top of the unit. There is convolution in the sequence, likely due to the liquefaction and fluidization of the sediment. From about 4 to 12 m below surface the interval consists of brecciated, convoluted and contorted clay and silt. Bedding has been destroyed or brecciated and may have originally consisted of silt and clay rhythmites. There are an estimated 130 clay layers in this unit (*see* Figure 10, Halton Till complex, 22 m).

Geophysical signature: Between 20 and 33 m thick, the geophysical signature is an opaque seismic facies 5 that likely relates to clayey silt sediment. From 0 to 20 m there is no seismic data recovery. This unit shows a slightly increasing gamma pattern between 24 and 33 m depth. Sand lenses are marked by small magnetic susceptibility patterns.

Interpretation: This unit represents quiet water suspension sedimentation with occasional low-energy underflow deposition. This succession is interpreted to correlate with Halton Till stratigraphic units. The location of borehole CAMC/YPDT-Heart Lake Road is 1 to 2 km from the mapped margin of Halton Till; however, the Halton Till stratigraphic unit commonly consists of glaciolacustrine fine-grained sediment to the east in the Humber River watershed. In areas with Halton Till diamicton facies, such as the IWA landfill site, the Halton Till sediment is interpreted to represent a grounding-line zone, where reworked glaciolacustrine sediment or till was deposited directly from glacier ice. Sediment gravity flows from the ice margin could explain the occasional underflow sediment that interrupts predominant silt-clay suspension. About 130 years of low-energy seasonal sedimentation likely includes a transition to proglacial lake Peel (*see* "Preliminary Depositional Model").

UNIT 6 – REWORKED SAND

The CAMC/YPDT-Heart Lake Road core log reveals approximately 3.7 m of ripple cross-laminated sand. This appears to represent sand reworked by gullying and possibly groundwater piping from Oak Ridges Moraine sand found upslope of the borehole site.

CHARACTERIZING DEPOSITION INTO SEDIMENTARY CYCLES

Previous studies (e.g., Russell et al. 2006) indicate that the sediment log of borehole CAMC/YPDT-Heart Lake Road can be subdivided into a series of depositional cycles (Figure 11) that relate to pulsating hydrological conditions.

Cycle I (overlying the bedrock surface from 95 to 140 m asl) fines upward from sand and gravel to a 1 m thick silt-clay rhythmite unit. The fine-grained sediments persist from 104 to 135 m asl and contain several metre-scale fining upward, fine sand-silt units. A smaller cycle, (Cycle IIa) trends from gravelly sand to thick silt between 135 and 143 m asl.

Cycle II, a significant sediment trend from 143 to 203 m asl, contains fine to medium sand grading up to an approximately 25 m thick interval of silt-clay rhythmites.

Cycle III, which could include several 2 to 4 m thick sub-cycles, at 203 to 238 m asl, grades from fine to medium sand to an approximately 12 m thick interval of silt to silt-clay rhythmites.

Cycle IV, at 238 to 254 m asl, begins with fine sand and grades to an approximately 10 m thick silt-clay rhythmite interval.

Silt predominates in the upper interval, from 254 to 277 m asl, which includes several fining cycles of fine sand and silt-clay rhythmites (cycle V and possibly VI) and 3 m of silty fine sand at the top.

The cycles can be more generally summed up by identifying 2 major cycles (*see* Figure 11). One large rhythm includes a fining-upward cycle from 95 to 203 m asl. A second large rhythm occurs from 203 to 254 m asl. These 2 thick fining-upward rhythms may correlate with channel sediment fill and ridge-building episodes of Oak Ridges Moraine sedimentation reported in cores to the east (e.g., Barnett et al. 1998). A nondescript fine sediment interval occurs in the upper 21 m of the sediment package and likely represents final ice-supported glaciolacustrine sedimentation that may be a lateral correlative of the Halton Till sediment unit (e.g., Sharpe, Russell and Logan 2002).

STRATIGRAPHIC SUMMARY AND CORRELATION

The high-quality data package from the buried valley within the study area records a detailed account of late glacial architecture, sedimentology and facies variability. The data have been interpreted to indicate that a large subglacial fluvial flood eroded older sediments and scoured the bedrock surface in the area, then deposited high- to low-energy deposits in a sequence that preempted the rapid demise of the Laurentide ice sheet in the region. The evidence for this sequence of events is briefly reviewed using new data and correlations to nearby high-quality data sites (*see* Figure 2).

Based on the high-quality data acquired for the study as well as a detailed cross-sectional analysis, the Upper Till Sequence identified by Blair (1994) at the IWA site is interpreted to be equivalent to the Halton Till complex (*see* Figure 6). Both the Upper and Lower Glaciolacustrine sequences of Blair (1994) represent one or more of the sandy lithofacies and a clay lithofacies (Russell, Sharpe and Arnott 1998) of the Oak Ridges Moraine deposits. The Deep Glaciolacustrine Sequence of Blair (1994) is interpreted to represent fine- and coarse-grained Oak Ridges Moraine channel fill.

At the IWA site, Blair (1994) noted that the Lower Till Complex underlies the Upper Glaciolacustrine Sequence in the uplands outside of the buried valley and the Lower Glaciolacustrine Sequence within the buried valley. Given the considerable elevation difference, and noting the truncation of seismic facies 2 within the valley (*see* Figure 8), it is interpreted that the Lower Till Complex is unlikely to be continuous from the outside of the valley to the lower depths of the buried valley. Rather, it is more likely that the till complex underlying the Upper Glaciolacustrine Sequence has been truncated within the buried valley and a second diamicton unit is found at the lower depths within the valley. At the location of borehole CAMC/YPDT-Heart Lake Road a lower diamicton unit was encountered at considerable depth (about 140 m deep) within the valley and was determined to be a package of massive to laminated gritty silt with pronounced deformation in the lower part. Some thin, till-like units were also present within the diamict sequence. The sequence is interpreted to be a slump of material within the channel deposition stage. However, it is possible that subglacial flood erosion did not uniformly remove all earlier sediment infill, so this diamicton might be correlative with one of the older pre-Newmarket Till diamicts of the Lower sediments, perhaps the diamicton of the Sunnybrook Formation.

Given this re-interpretation of Blair's (1994) stratigraphy to a 2 till/diamict model, it remains uncertain as to whether the upper till complex that is found lying on the bedrock surface outside of the buried valley at the IWA site is correlative with the Newmarket Till, or whether it might be correlative with an older till. Both scenarios are contemplated below. In either scenario, there is no till or diamict unit interpreted to lie above the buried valley; it has been interpreted to have eroded out by tunnel channel activity. The data from borehole CAMC/YPDT-Heart Lake Road confirms that there is no till complex in the upper parts of the buried valley.

The regional stratigraphic model anticipates that a number of stratigraphic units (e.g., Scarborough Formation, Thorncliffe Formation) are found beneath the Newmarket Till within the Lower sediment group. The 3 seismic profiles reveal a thin (10 m) possible diamicton atop bedrock on the upland adjacent to, and on the flanks of, the newly defined bedrock valley (*see* Figure 8). Similarly, a diamicton unit has been detected resting on bedrock in many of the IWA boreholes in the Bolton area just adjacent to the buried valley. One cored IWA borehole (C34B-21 on Figure 6) can be interpreted to show about 20 m of Lower sediment, assuming that the 5 m thick diamicton is Newmarket Till; however, this borehole appears anomalous and serves to highlight the general absence of Lower sediment in the study area. If this lower diamicton sitting on bedrock is indeed Newmarket Till, then there may be no Lower sediment units in the study area. Thus, in the scenario whereby the diamicton is interpreted to be the Newmarket Till, the regional unconformity represents a scoured surface that, outside of the buried valley at both the IWA site and at parts of the seismic lines, did not remove all of the Newmarket Till (*see* Figure 6). This would imply that there was minimal to no deposition of the Lower sediments at the IWA site or that the Newmarket ice removed the Lower sediment deposits in the north Peel area. The diamicton has not been interpreted to extend to the bottom of the bedrock valley in any of the 3 seismic lines. Therefore, within the buried valley it appears that the Newmarket Till has been entirely eroded by the higher velocity events discussed above.

An alternative interpretation of the diamicton at the IWA site and in the seismic lines is that it could be older, potentially as old as the Illinoisian-age York Till, which is a sandy diamicton found resting on shale at Woodbridge, about 20 km to the southeast of the study area (Karrow et al. 2001). On a more regional scale, the Lower sediment is present at elevations up to about 250 m asl at Nobleton, about 9 km to the east of the study area (Sharpe, Pugin et al. 2003; Sharpe et al. 2004). Therefore, it is possible that the Lower sediments could have been deposited at similar elevations in the Caledon East and Bolton areas. Hence, in this scenario, where it is assumed that the Lower sediments were present in the Bolton/Caledon East area, outside of the buried valley, regional erosion (Sharpe et al. 2004) would have removed all Newmarket Till, and probable Lower sediment, leaving only an older till resting near the bedrock surface.

In either of the above scenarios the inferred regional meltwater unconformity eroded existing sediments from the buried valley and adjacent areas. The combined seismic and borehole data are consistent with high-energy subglacial meltwater erosion (Russell, Arnott and Sharpe 2003). It is also possible that meltwater events further eroded part of the bedrock valley where bedrock occurs directly beneath seismic facies 3 (*see* Figure 8).

Coarse-grained deposits overlying the regional unconformity (*see* Figure 4) are interpreted to have formed during diminishing flow following channel erosion (Sharpe et al. 2004). Deposits include a 10 to 100 m thick package of stacked sand and gravel sets highlighted by cut-and-fill and cross-bedding structures. This coarse sediment is inferred to represent high-energy deposition from a subglacial fluvial system. This is consistent with seismic profiles and cored boreholes at Nobleton, Grasshopper Road and Aurora (Pugin, Pullan and Sharpe 1999; Sharpe, Dyke et al. 2003) where similar coarse sediments were confirmed. The possible esker on seismic line S-3 (*see* Figure 8) supports this inference.

An interval of 80 to 150 m of low-energy deposits are interpreted as sand and mud and are correlated with regional Oak Ridges Moraine sediments (Barnett et al. 1998). These sediments are transitional from underlying gravel and sand, and represent waning flow channel sedimentation. This includes a cap of about 100 clay rhythmites that represent a hiatus in meltwater discharge deposition (here identified as Oak Ridges Moraine basin sedimentation) that completes an upper channel-fill sequence (*see* Figure 10). Clay rhythmite intervals in these fining-upward packages contain about 100 years of annual sedimentation, assuming that clay caps are winter events and that the bedrock valley has captured most sediment without slump erosion loss above the regional unconformity. With these conditions, this 100 year time frame of Oak Ridges Moraine basin sedimentation at the Heart Lake Road site corresponds with the 100 year time frame of basin sedimentation at similar sites along the length of the Oak Ridges Moraine.

This quiescent period was followed by distal Oak Ridges Moraine ridge-building meltwater discharge events. At the location of borehole CAMC/YPDT-Heart Lake Road, these events are represented by low-energy underflows and 2 clay rhythmite intervals. These are distal because the Oak Ridges Moraine represents an esker fan complex with east to west paleoflow (Russell and Sharpe 2002). There are about 40 clay rhythmites that are interpreted to record the final phase of this Oak Ridges Moraine ponded sedimentation.

Rhythmically laminated sediments that occur immediately above the Oak Ridges Moraine sediments appear to be transitional. The contact between the Oak Ridges Moraine and Halton Till stratigraphic units in borehole CAMC/YPDT-Heart Lake Road is taken above the last prominent graded fine sandy unit (*see* Figure 10). Adjacent areas with Halton Till diamicton (*see* Figure 6) are inferred to have resulted along a line where the ice was grounded. This produced reworked glaciolacustrine sediment or till units interbedded with sediment gravity flow units. The Halton Till ground-line zone is interpreted to have resulted from ice retreat from earlier events related to drainage of meltwater from the ice sheet (*see* "Preliminary Depositional Model"), not ice advance from the lake basin. The general fining upward of sediments as observed in borehole CAMC/YPDT-Heart Lake Road is more in keeping with gradual ice melt-down (*see* "Preliminary Depositional Model") rather than ice retreat into the Lake Ontario basin and re-advance to the limit of Halton Till (Karrow 1967).

Hydrogeologic Setting

Many of the sediment types found in the Caledon East study area have a strong influence on the hydrogeology. For example, the ice-contact stratified drift deposits extending through the area are typically hummocky accumulations of sand and gravel with a low percentage of fines (clay and silt). As a result of the coarse-grained nature of these deposits, the permeability is high and the sediments typically have high infiltration rates. Infiltration is enhanced by the hummocky nature of these deposits in that runoff is often directed to closed depressions where it accumulates in surface-water ponds that tend to infiltrate water through the coarse materials to the groundwater system. These deposits trend in a northeast band and extend south to the Caledon East meltwater channel (*see* Figure 3).

In contrast, Halton Till deposits mapped below the Niagara Escarpment and south of the ice-contact materials are typically part of a flat to gently undulating till plain. Due to their fine-grained nature, Halton Till deposits have a relatively low permeability and, as a result, infiltration rates are low and overland flow rates are enhanced. These deposits, therefore, are considered less important in terms of their contribution to the groundwater system. Near the northern margin of the till sheet, the topography becomes more undulatory and recharge to the groundwater system is expected to be enhanced, again due to the closed depressions on the landscape.

AQUIFER DEFINITION

A deep confined sand and gravel aquifer system within a buried bedrock valley was identified as part of this study. This buried bedrock valley is a prominent feature of the overburden thickness map of the study area (Figure 12). Additional testing is required to better refine the delineation both of the buried bedrock valley and the aquifer materials within the valley, but preliminary evidence suggests that the buried valley originates above the escarpment to the west of the study area; one branch extending northwards to the Alton area, and a second branch extending westward to the Erin area. These 2 distinct branches meet below the brow of the escarpment to the north of Inglewood (*see* Figure 12). From there, the valley extends eastward, south of Caledon East, and to Bolton, where it merges into the Laurentian channel in the Humber River watershed.

Sedimentological data suggests that the valley was modified by subglacial meltwater activity either prior to, or contemporaneous with the building of the Oak Ridges Moraine. The coarse-grained materials delineated in both borehole CAMC/YPDT-Heart Lake Road and the seismic lines comprise a deep aquifer and represent the base of one or more fining-upwards sequences associated with this subglacial meltwater activity.

Due to the lack of high-quality borehole information along the length of the buried valley, the subdivision of aquifers and aquitards within the buried valley, for the purposes of numerical groundwater modeling, was facilitated by using the stratigraphic model for the Oak Ridges Moraine (*see* Figure 4) and inferring hydrostratigraphic equivalent units where needed. For example, the deep confined sand and gravel unit encountered at the base of borehole CAMC/YPDT-Heart Lake Road was interpreted to be hydrostratigraphically equivalent to the Scarborough Formation, even though its origin might be related to the subglacial meltwater activity. The overlying diamict/slump unit was interpreted to be hydrostratigraphically equivalent to the Sunnybrook Formation. As more information is acquired on the buried valley sediment and interpretations solidified, the hydraulic conductivity of the diamict unit can be adjusted. Above this unit, the sediment package grades from lower sands upwards into predominantly fine-grained glaciolacustrine sediments, which have been interpreted to be part of a channel-fill event and therefore Oak Ridges Moraine equivalent.

WATER TABLE

Figure 13 illustrates that the shallow groundwater system is strongly influenced by topography. Shallow groundwater flows south and east from the escarpment at a gradient of approximately 0.04 into the lower Credit River watershed. The eastern boundary of the Credit River watershed just south of Caledon East generally corresponds to a shallow groundwater flow divide: from that point the shallow groundwater table either slopes gently toward the Credit River in the west at a gradient of about 0.005, or towards the east into the Humber River watershed at a gradient of approximately 0.01. The surface watershed divide continues to be reflected by the divide in the shallow groundwater system to the southwest of Caledon East and east of Inglewood.

Below the Niagara Escarpment, most of the domestic wells that draw water from the water table aquifer are screened in the upper portions of the Oak Ridges Moraine sediments. To the south and east, the Oak Ridges Moraine sediments are overlain by fine-grained Halton Till deposits (*see* Figure 3). In these areas the shallow Oak Ridges Moraine is considered confined to semi-confined.

POTENTIOMETRIC SURFACE

The upper potentiometric surface of the Caledon East area was approximated by interpolating the water levels from wells that were greater than 30 m in depth. The resultant potentiometric surface map is illustrated on Figure 14. The flow system at these depths shows less influence from the local ground topography than the shallow water table flow system (*see* Figure 13). Deeper groundwater flow is still strongly influenced by the Niagara Escarpment, where gradients are approximately 0.03 away from the topographically elevated escarpment. However, the groundwater divide east of Inglewood and southwest of Caledon East is much more subdued at this depth. There are fewer wells available that penetrate to a depth of 30 m. The deep groundwater system shown in Figure 14 reflects a strong component of flow that is southeast towards Lake Ontario. If additional deep wells were drilled along the buried valley the water levels might reflect a more easterly flow of groundwater, parallel to the buried valley.

To assess this, the deeper potentiometric flow system within the buried bedrock valley was further constrained to those wells greater than 75 m in depth and having a bottom elevation of less than 200 m asl. This ensured that only data from deep wells within the valley were used in the assessment. Figure 15 illustrates that deep groundwater flow within the valley system is predominantly west to east along the axis of the buried valley towards Nobleton. This assessment is again limited by the scarcity of deep wells within the valley system, but nevertheless illustrates the likelihood of groundwater flow along the valley from the Credit River watershed to the Humber River watershed. The hydraulic gradient along the valley is a relatively shallow 0.002.

VOLUMETRIC FLUX

The basal sand and gravel aquifer appears to be fairly continuous since it was encountered in the deeper sections of each of the 3 boreholes completed in the buried valley. This deep aquifer might be of interest as a supply of municipal water to Caledon or Caledon East. Based on the reflection seismic surveys completed near Caledon East and Bolton, it is interpreted that this aquifer system extends along the buried bedrock valley from at least Willoughby Road in the west to the Bolton area in the east. Further, this preliminary assessment suggests that the deep aquifer is likely connected to, or continuous with, the Bolton Aquifer (Dames and Moore Canada 1996) and is unlikely to be connected to either of the 2 currently utilized municipal aquifers in the Caledon East area. This suggests that there may be a volumetric transfer of groundwater from the Credit River watershed to the Humber River watershed.

If the aquifer is continuous along the buried valley, a volumetric flux can be approximated near the terminus of this basal aquifer system near Bolton. Assuming an average width of 1200 m, an average depth of 20 m, a relatively flat hydraulic gradient of 0.002 and a hydraulic conductivity of 10^{-3} m/sec, the volumetric flux at Bolton would be calculated as:

$$Q = KiA$$

Where Q is the volumetric flux of groundwater across the designated discharge cross-section, K is the hydraulic conductivity, i is the hydraulic gradient along the designated horizontal flow path and A is the cross-sectional area at the discharge point.

$$Q = 10^{-3} \text{ m/sec} \times 0.002 \times (1200 \text{ m} \times 20 \text{ m})$$

$$Q = 0.048 \text{ m}^3\text{/sec or } 4147 \text{ m}^3\text{/day}$$

Note that the volumetric flux can vary significantly if these input parameters vary within reasonably expected ranges. For example, by increasing the hydraulic conductivity one order of magnitude, the volumetric flux increases 10 fold to over 40 000 m^3/day. As noted above, aquifer mining was predicted to occur in the Bolton wellfield, albeit with a simplified 2D model at less than 5000 m^3/day. Therefore, the estimated flux determined above appears consistent with the modeling analysis.

Discussion

BEDROCK GEOLOGY AND TOPOGRAPHY

The high-quality geological and geophysical data acquired in the Caledon East area confirm the presence of, and better delineate, a significant buried bedrock valley. The valley is about 100 m deep, between 2 and 4 km wide and trends in a northeast direction. It also appears to widen to the northeast. The drilling of the cored borehole, coupled with the seismic survey, provided critical information in delineating this valley.

Origin of the Bedrock Valley

An understanding of the geometry, origin and sedimentary fill of buried bedrock valleys are important to assessing their aquifer potential (Russell et al. 2004). Based on evaluation of the seismic data, the high-energy sedimentary character of the valley fill, the regional bedrock topography of the Laurentian channel (*see* Figure 5) and the ground surface topography, the Caledon East area bedrock valley appears to be connected to the northeast toward the bedrock valley beneath the Holland Marsh. The surprising depth, and the occurrence of Georgian Bay Formation grey shale (rather than Queenston Formation red shale) in borehole CAMC/YPDT-Heart Lake Road core, suggest that the Caledon East bedrock valley is overdeepened. Overdeepening may be due to glacial processes (Straw 1968; White 1975) or it may be due to glaciofluvial processes as demonstrated by Kor and Cowell (1998) with their finding of glaciofluvial overdeepening on the upflow side of the Niagara Escarpment.

The age of the valley is difficult to constrain. Indeed, given the long period of geological time that elapsed subsequent to the bedrock units being deposited in the Ordovician, the valley is likely to have been eroded at different times by various geological processes, including fluvial and glacial. Whether the valley was more recently enhanced by subglacial meltwater events is also difficult to determine. Figure 8 shows that seismic facies 2 (which is interpreted to be either a till unit or a gravel) is not continuous in the bottom of the valley in any of the 3 seismic sections. Rather, seismic facies 3 is interpreted to rest directly on top of bedrock along all 3 seismic lines. This suggests that processes subsequent to the deposition of seismic facies 2 have acted within the valley to erode this unit. Evidence for subglacial meltwater activity within the valley is supported by the presence of thick, high-energy, glaciofluvial channel sediments infilling the valley (*see* Figure 8); high Precambrian content in the gravel component of channel infill; low organic content; and by the fact that the thickest Oak Ridges Moraine channel sediments are oriented northeastward toward the Holland Marsh - a valley considered to be of tunnel channel origin (Russell, Arnott and Sharpe 2003).

Sedimentary Architecture of the Valleys

It is most likely that the Caledon East bedrock valley has a long and complex history. Based on seismic profiling of the Laurentian channel at Nobleton (Pugin, Pullan and Sharpe 1999; Sharpe et al. 2004) and at Schomberg, only 40 to 50% of the bedrock valley floor and cross-sectional area were affected by glaciofluvial processes. The rest of the valley's cross-section area (~60%) comprises large blocks of older, bedded valley infill sediment. On the other hand, despite what appears to be a complex history of valley erosion, the depositional record in the Caledon East valley appears to be young. Glaciofluvial tunnel channel processes likely affected most of the surveyed portions of the valley. Assuming continuity between the seismic profiles across the Caledon East study area, there is at least 10 to 12 km of gravel and sand in the deeper portions of the valley; these sediments are 1 to 2 km wide and 20 to 100 m thick. This coarse sediment is flanked and overlain by sands and silts that are interpreted to extend to the entire width (~2 to 4 km) of the bedrock valley and to a thickness of 100 m along the length of the valley. A continuous blanket of fine-grained clay-silt rhythmite sediments, at least 20 to 30 m thick, caps the channel-fill sequence.

The valley sediments trend to the northeast and are interpreted to have some continuity with the Holland Marsh tunnel channel system (Russell, Arnott and Sharpe 2003). Beyond the controlling influence of the northeast-oriented re-entrant valley at the Niagara Escarpment (where most of the earlier sediment might be removed), more recent glaciofluvial deposits likely dissect older coarse- and fine-grained strata. A glaciofluvial channel-fill scenario is strongly supported by the high-quality data collected for this study. This case study presents a working model for re-entrant bedrock valley fills along the Niagara Escarpment that is compatible with widespread evidence for meltwater flood deposits in the region (Kor and Cowell 1998; Sharpe et al. 2004). Whether this interpretation or alternative interpretations (such as preglacial subaerial deposition) will prevail in the buried valley terrain of the Laurentian channel system will require additional high-quality information and careful analysis of sparse data coverage.

PRELIMINARY DEPOSITIONAL MODEL

Figure 16 shows 4 hypothetical paleogeographic settings that summarize the depositional events recorded in borehole CAMC/YPDT-Heart Lake Road and seismic profiling dataset. The first event in this regional-scale depositional model is not shown because it is not explicitly recorded at the Caledon East site. It is, however, discussed in Sharpe et al. (2004).

Figure 16B) *Tunnel channels*: the end of a tunnel channel cutting-and-filling stage shows the presence of a subglacial lake (SL) in and beyond the Lake Ontario basin. Channel filling is represented by the gravel-to-sand channel-fill event at the Heart Lake Road borehole (*see* Figure 10). The subglacial lake continued to influence channel filling in the upper parts of the channel during the Oak Ridges Moraine (OML) basin stage rhythmite sedimentation, which appears to have been transitional from high-energy sedimentation (*see* Figure 10).

Figure 16C) *Oak Ridges Moraine ridge building*: renewed high-discharge sedimentation along the east-west axis of the Oak Ridges Moraine is interpreted to have occurred under ice-covered conditions, including flow over the Niagara Escarpment (Oak Ridges Moraine ridge sediment package in Figure 10). The ice-grounding line south of Oak Ridges Moraine restricts Oak Ridges Moraine sedimentation to areas north of the subglacial lake.

Figure 16D) *Halton Till*: Ice grounded south of the Oak Ridges Moraine maintains a subglacial lake in the Ontario Lake basin. At the same time, a proglacial lake exists beyond the grounding line to the Oak Ridges Moraine; minor drainage overtops the Niagara Escarpment. This reconstruction is required to explain the persistence of ponded low-energy glaciolacustrine sedimentation at the Caledon area to an elevation of greater than 270 m asl (compare with Halton Till sediments in Figure 10).

Figure 16E) *Peel Pond stage*: proglacial lake stage is lower as ice melts back to lake basin and the lake basin ice lid is close to floating off.

The architecture and sedimentological framework provided by borehole CAMC/YPDT-Heart Lake Road and seismic profile data allow for further delineation and refinement of the buried bedrock valley aquifer system at Caledon East. The sedimentologic–stratigraphic sequence established in Figure 10 can guide aquifer delineation within the bounds of the seismic surveys. Non-cored boreholes and borehole geophysics can be correlated with existing data to identify the stratigraphic and lithological horizons, and to guide placement of piezometers in key aquifer horizons.

The proximity of the buried valley to the community of Caledon East makes it a potential target for additional municipal drinking water capacity for the community. The coarse sediment in the deeper parts of the valley provides an approximately 100 m thick and 2 km wide target for hydraulic testing. Aquifer assessment needs to move to the hydraulic testing stage by establishing a series of monitors to be used in long-term pumping tests for preliminary geochemical analysis.

THE CALEDON VALLEY AS A REGIONAL GEOLOGICAL REFERENCE AREA

The Caledon East study area serves as an excellent regional geological reference for the glaciofluvial buried valley scenario in the west parts of the Oak Ridges Moraine, especially within and along strike of the re-entrant valleys of the Niagara Escarpment. Deep valleys in the area with thick glaciofluvial to glaciolacustrine sediments and no evidence of older organic-rich sediments or correlative strata are also likely to be comparable to the Caledon East case study. The buried valley deposits, including the cyclical nature of the sedimentation pattern, recorded within borehole CAMC/YPDT-Heart Lake Road are somewhat comparable to observations made at several cored boreholes drilled to the east in Durham and York Regions (e.g., Grasshopper Road, Vandorf, Ballantrae, *see* Sharpe, Pugin et al. 2003).

Conclusions

This study of the buried valley in the Caledon East area provides new data that can be used to understand the aquifer system and the Quaternary sedimentology of this part of southern Ontario. From a groundwater perspective, these data assist in understanding the distribution of aquifer materials (sands and gravels) in the sediment package that overlies bedrock in this area. To date, few detailed studies have been undertaken within deep buried valleys to evaluate the infill sediments and the nature of their distribution.

The drilling of the deep borehole CAMC/YPDT-Heart Lake Road at Heart Lake Road identified a valley that was significantly deeper than previously estimated. However, the addition of the bedrock depth information from this single borehole only increased the interpolated valley sediment volume by 1 to 2%. In contrast, adding the bedrock depth estimates from the seismic profile lines increased the estimate of valley volume by 40%. At the location of borehole CAMC/YPDT-Heart Lake Road the coarsest gravel aquifer was only 20 m thick. However, the seismic lines suggest that there could be up to 100 m of coarse-grained sediments. Clearly, both investigative tools (seismic profiling and sediment coring) provide valuable insights into these types of buried bedrock valley deposits.

The buried bedrock valley in the Caledon East area is quite extensive and there remains only 1 key borehole and 3 seismic lines that have intercepted the valley sediments. More data is required to substantiate some of the speculations presented here. Despite this, several key points can be made regarding the outcomes from this study:

- The study has provided the Region of Peel and the community of Caledon East with a target for additional municipal drinking water supplies. The target is a deep gravel and sand aquifer that is very likely not hydraulically connected to the sensitive headwater streams in the Caledon East area. Further hydraulic testing will be needed to confirm this.
- The study has shown that there is very likely a transfer of water from the Credit River watershed into the Humber River watershed through the buried valley. The transfer is likely on the order of 5000 m^3/day. However, additional water level data from new boreholes would help to make this estimate more accurate.
- Buried valleys, such as the one at Caledon East, can be of tremendous significance in terms of understanding groundwater flow systems and making water budgeting exercises more accurate. Modelling exercises that do not account for water movement to and within these features will be inaccurate.

- The study has revealed a sedimentological pattern that is consistent with subglacial meltwater activity. The core from borehole CAMC/YPDT-Heart Lake Road allowed evaluation of the sedimentology associated with the infilling of a deep buried valley near the escarpment face.

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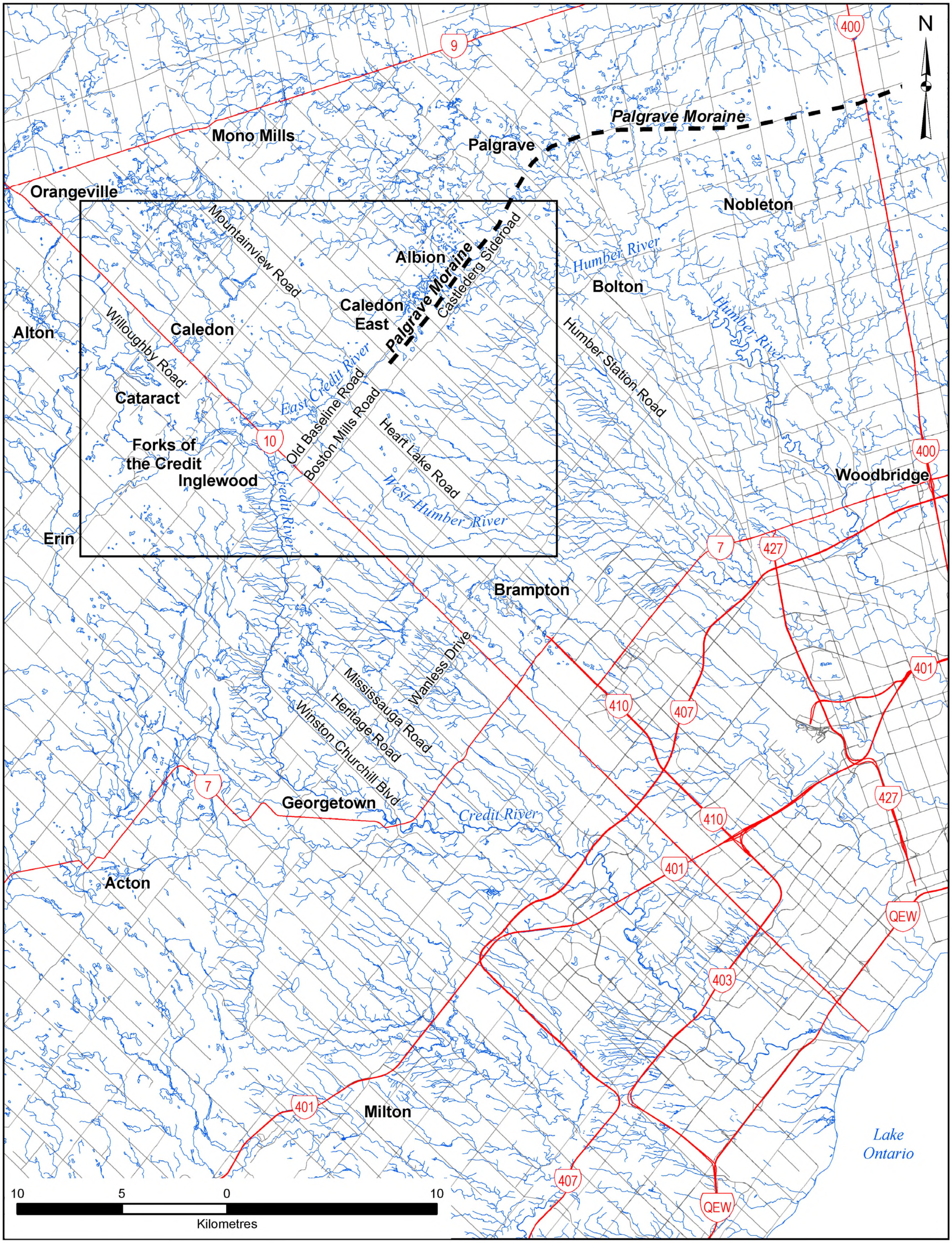

Figure 1. Location map. Solid black line indicates extent of Caledon East study area.

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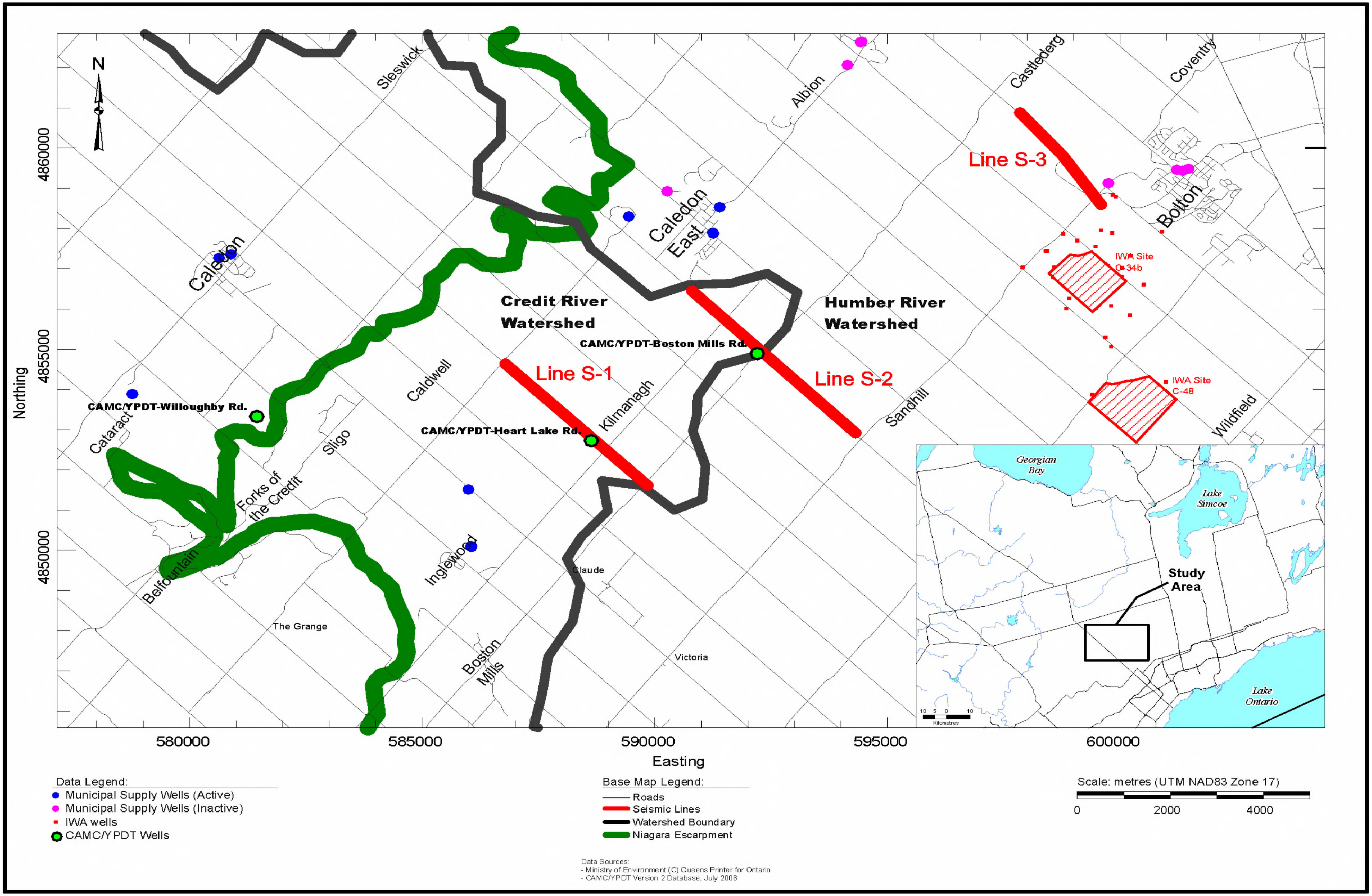

Figure 2. Location of study area showing key data sources, including cored borehole (CAMC/YPDT-Heart Lake Road) and mud rotary boreholes (CAMC/YPDT-Boston Mills Road and CAMC/YPDT-Willoughby Road), seismic profile lines (S-1, S-2 and S-3), and the IWA investigation site near Bolton.

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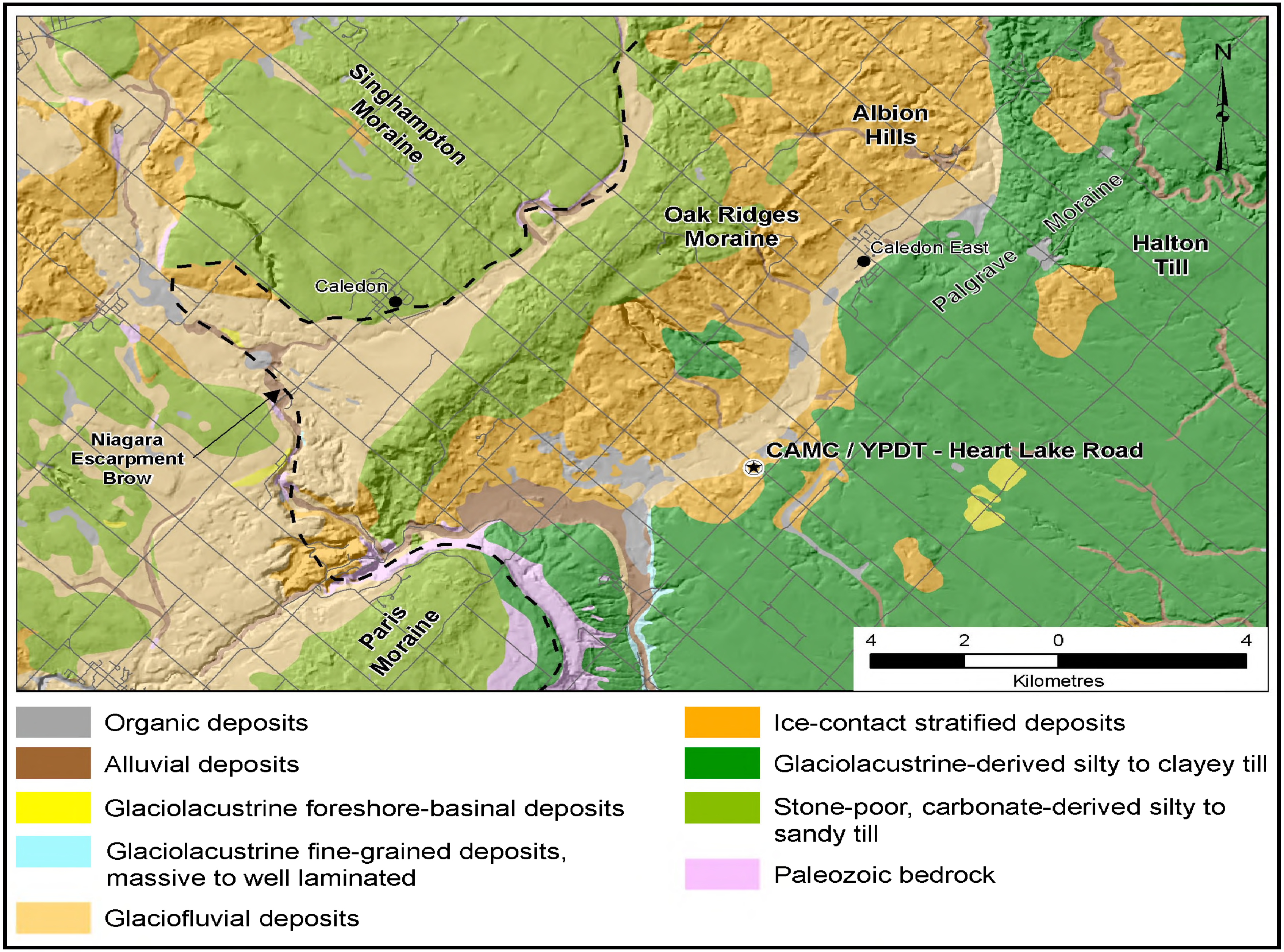

Figure 3. Quaternary geology of the study area.

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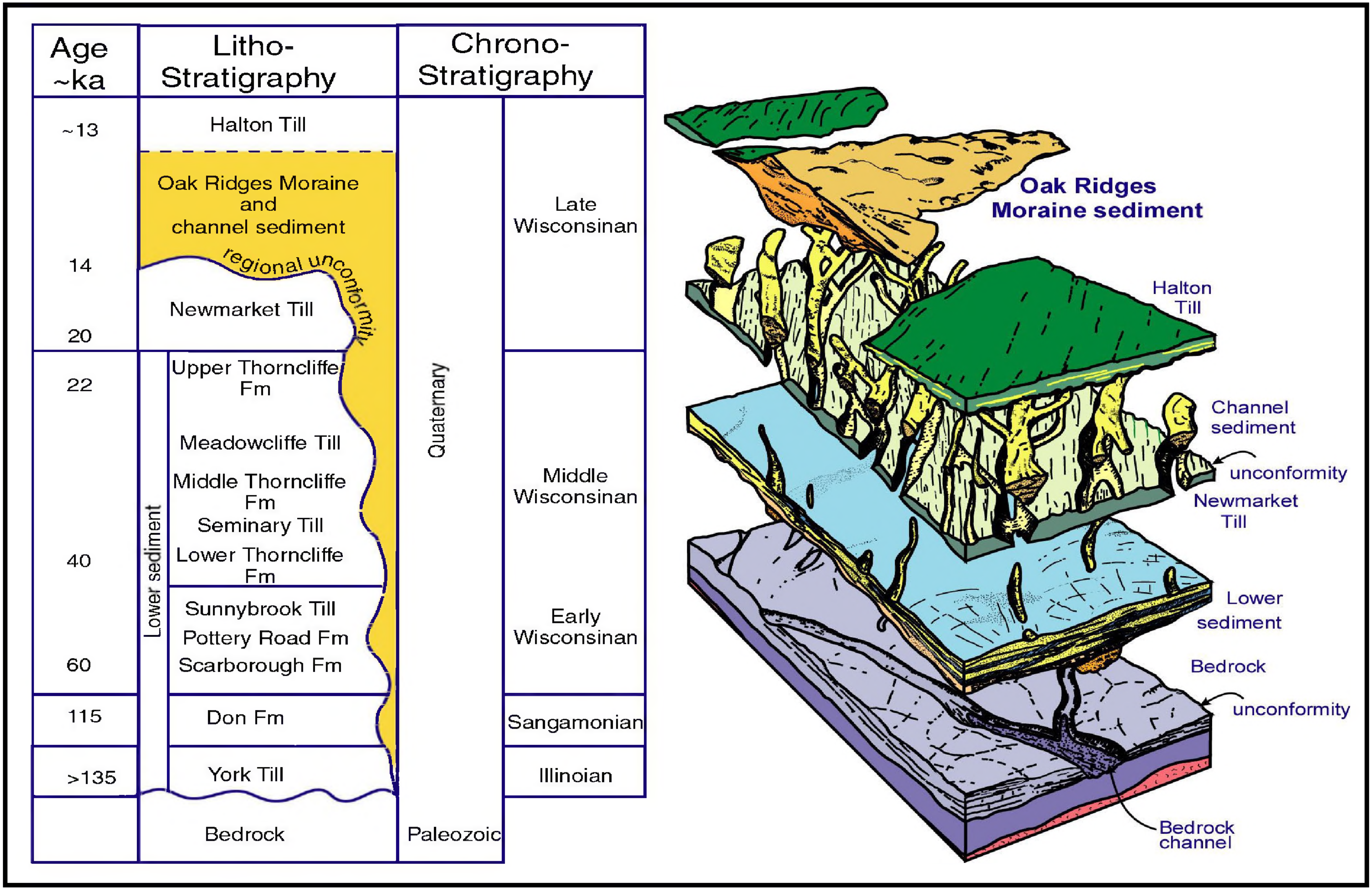

Figure 4. Conceptual stratigraphic model for the Oak Ridges Moraine area (*from* Sharpe et al. 1996).

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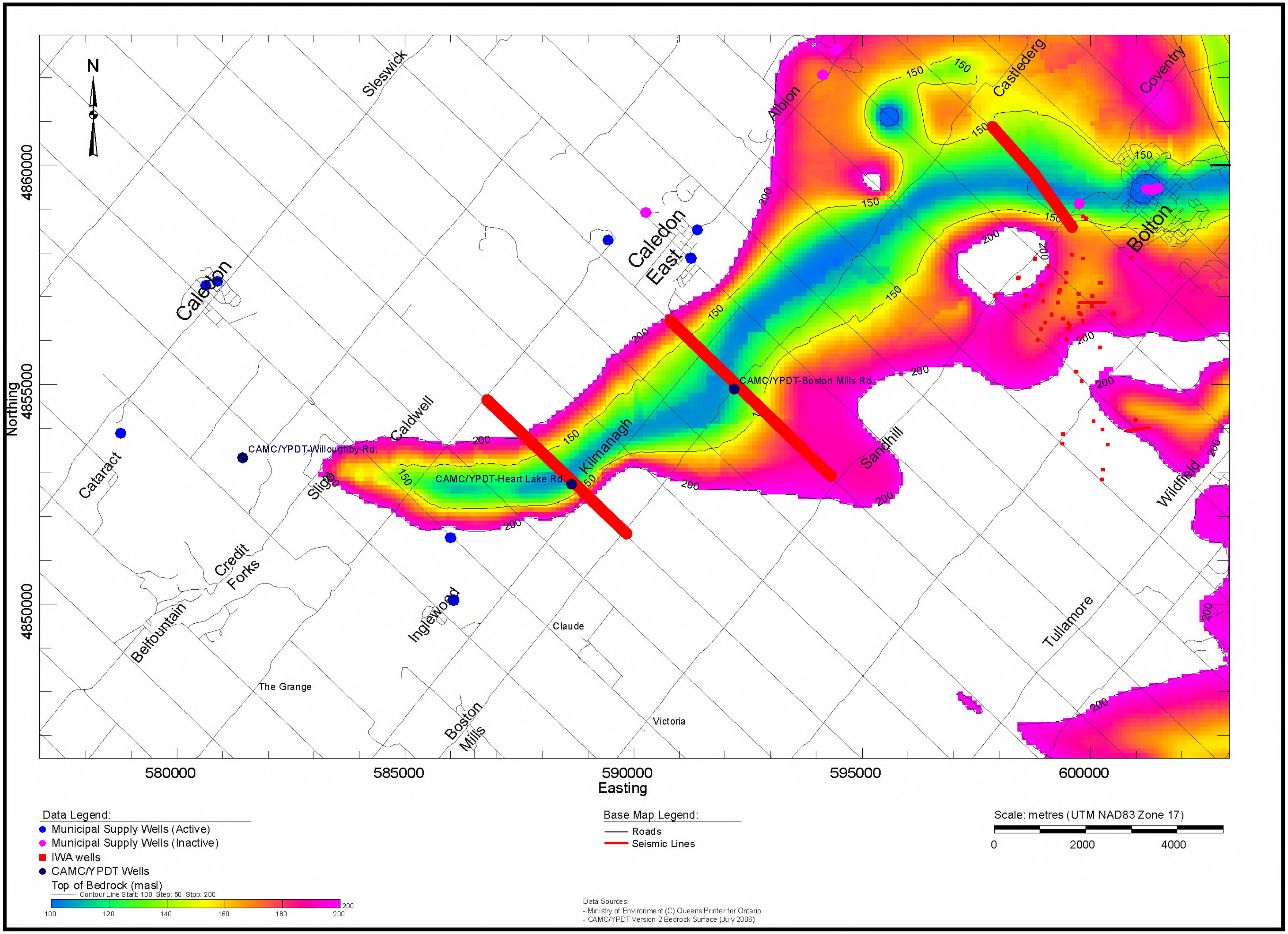

Figure 5. Bedrock surface topography of the study area. The map shows the location of East Caledon buried bedrock valley (blue shading) relative to the IWA investigation site near Bolton.

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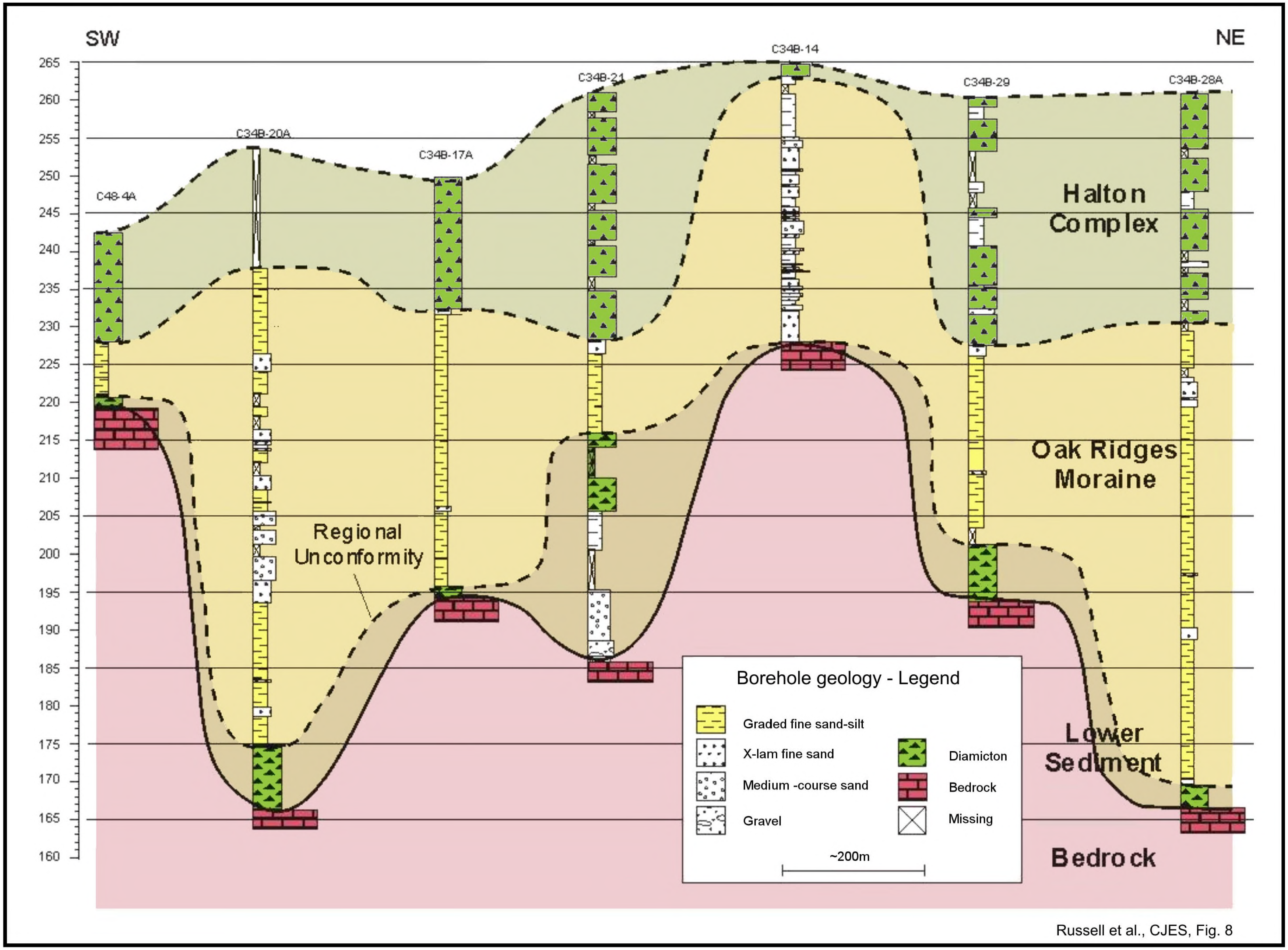

Figure 6. Simplified geological cross-section of the area southwest of Bolton, based on selected borehole geologic logs from the IWA investigation site (re-interpreted by Russell (2001) *after* Blair (1994)).

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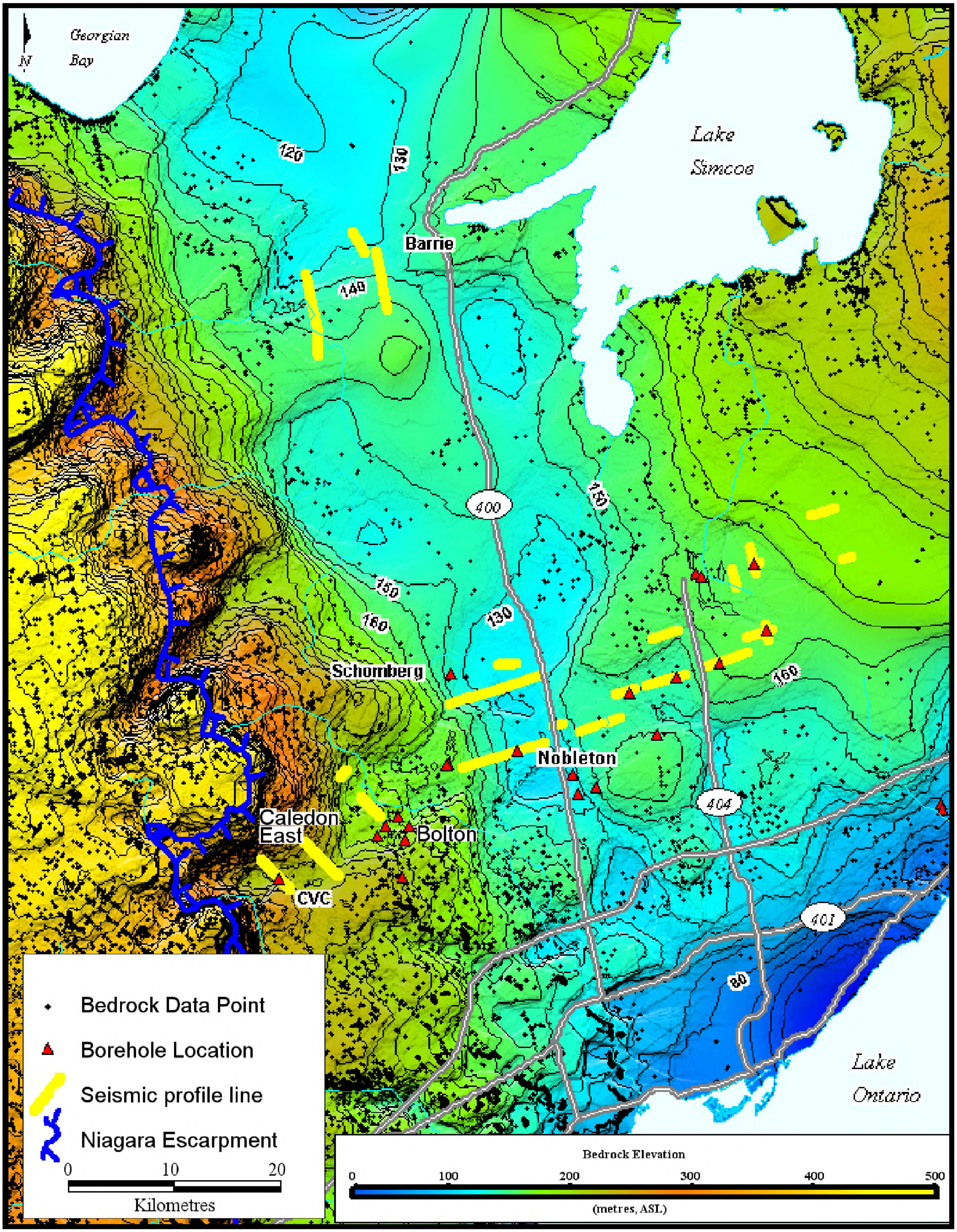

Figure 7. Representation of regional bedrock surface topography. Blue shading between Georgian Bay and Lake Ontario delineates the Laurentian channel.

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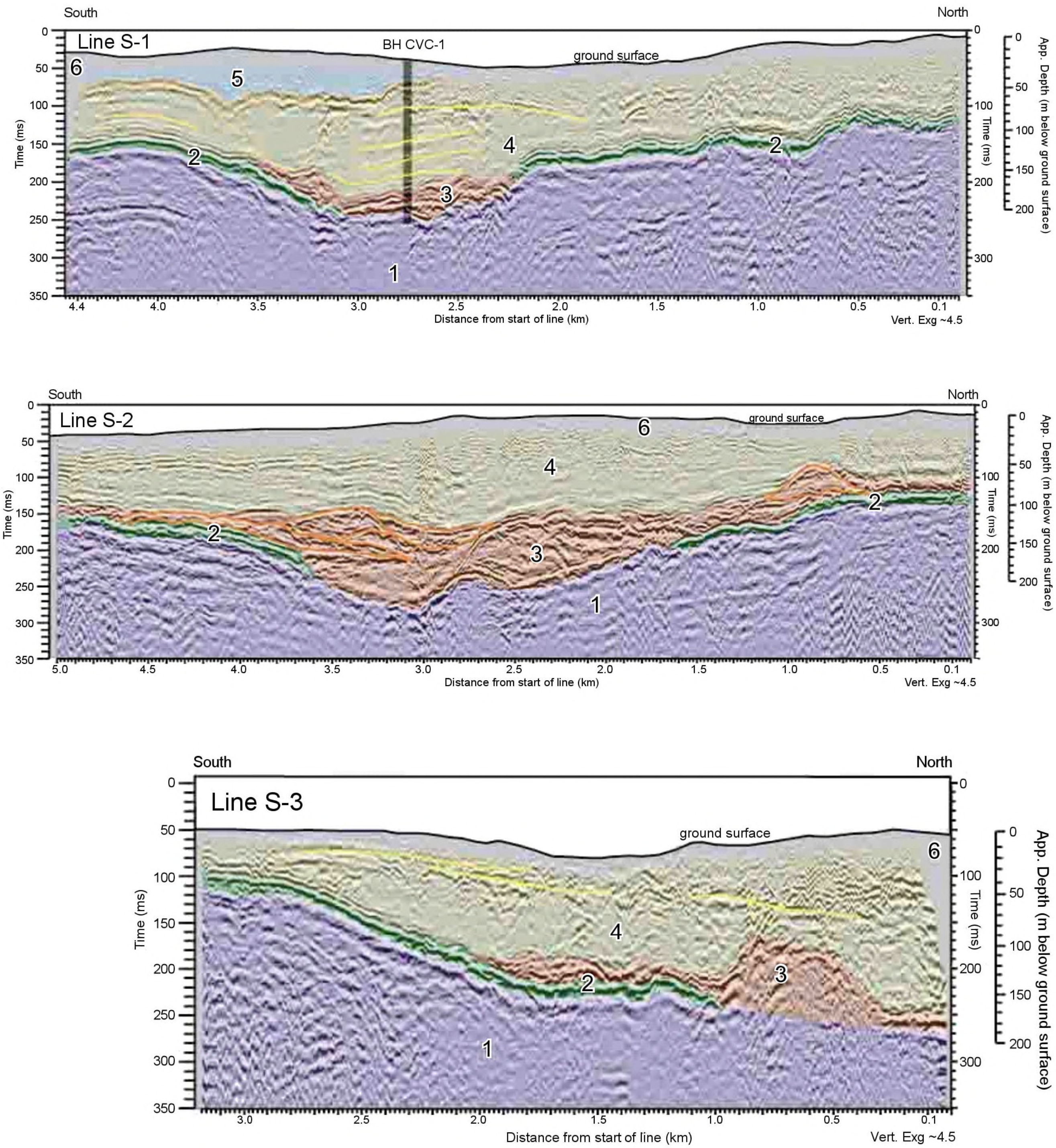

Seismic Facies Legend

1. Georgian Bay Formation (bedrock)
2. Diamicton/gravel
3. Sand and gravel (esker)
4. Sand and silt
5. Silt
6. No data return

Figure 8. Facies interpretations of the seismic profiles of Lines S-1, S-2 and S-3. (See text for more detailed description of seismic facies.)

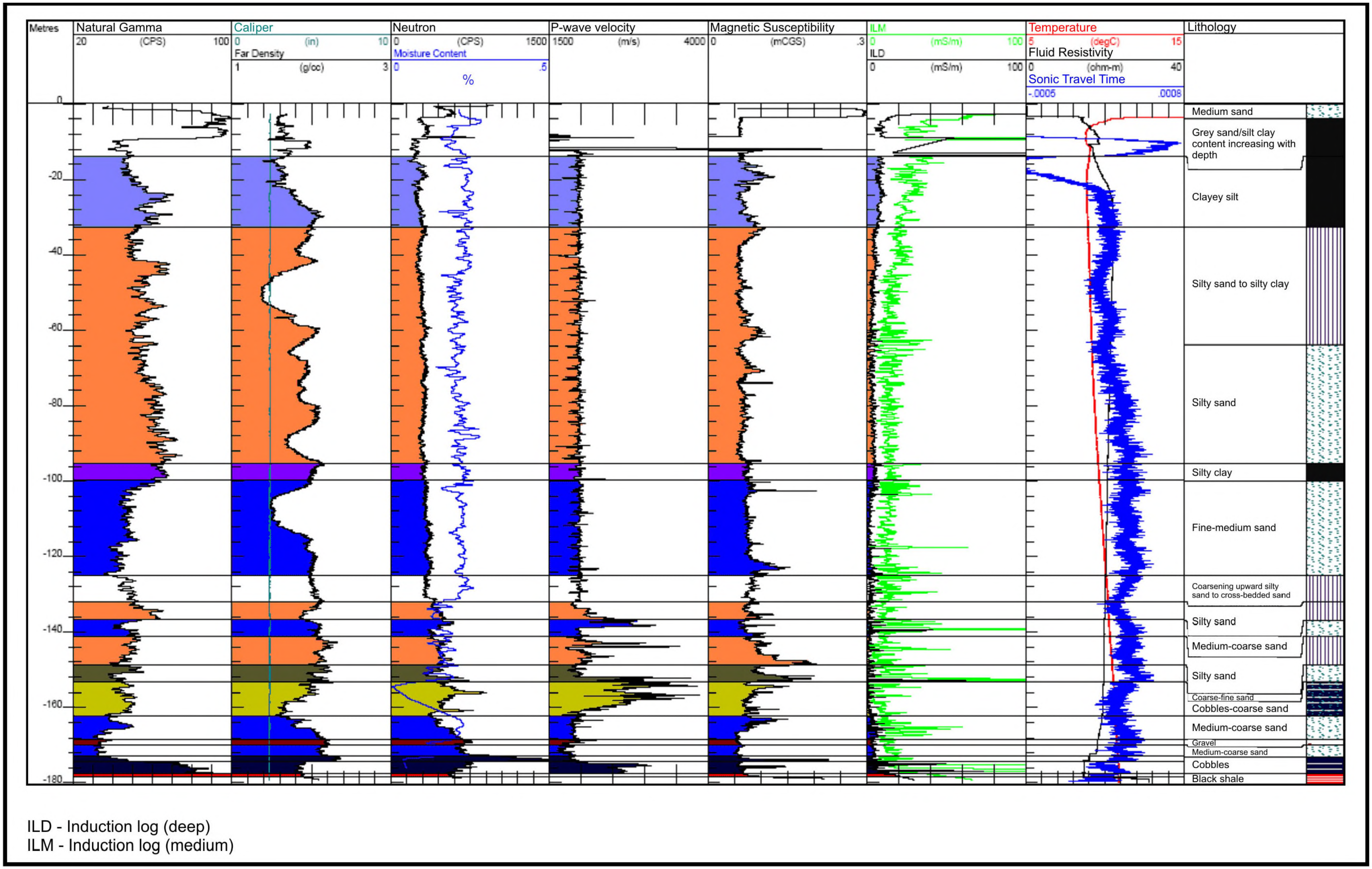

Figure 9. Downhole geophysical logs for borehole CAMC/YPDT-Heart Lake Road. Explanation of units of measure: CPS = counts per second; in = inches; g/cc = grams per cubic centimetre; m/s = metres per second; mCGS = millicentimetres per gram per second; mS/m = milliseconds per metre; degC = degrees Celcius; ohm-m = ohms per metre.

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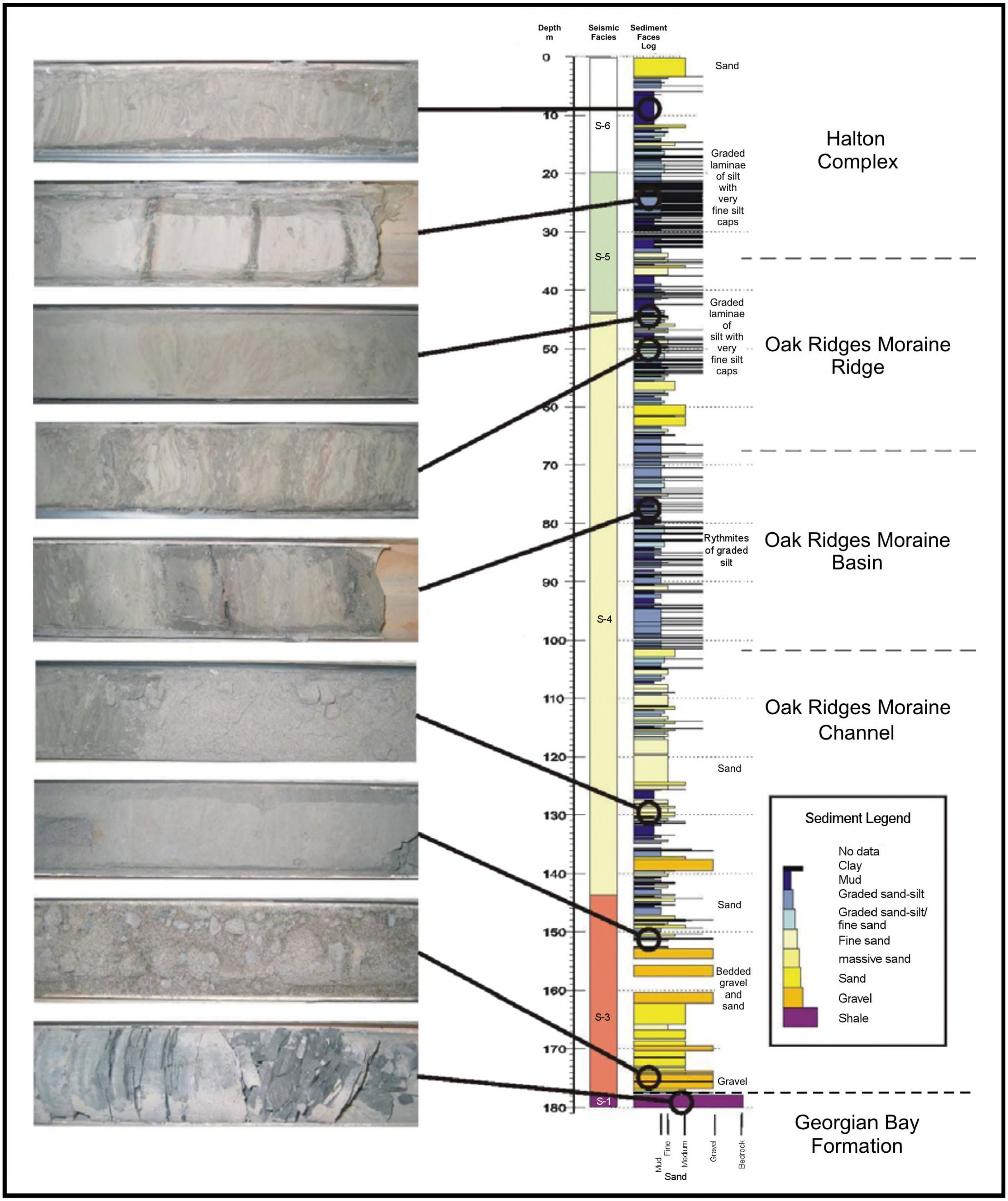

Figure 10. Geologic log of borehole CAMC/YPDT-Heart Lake Road, with photographic images representing regional sedimentary facies. S-1, S-2, etc., refer to the seismic facies determined from the seismic reflection survey, as described in the text.

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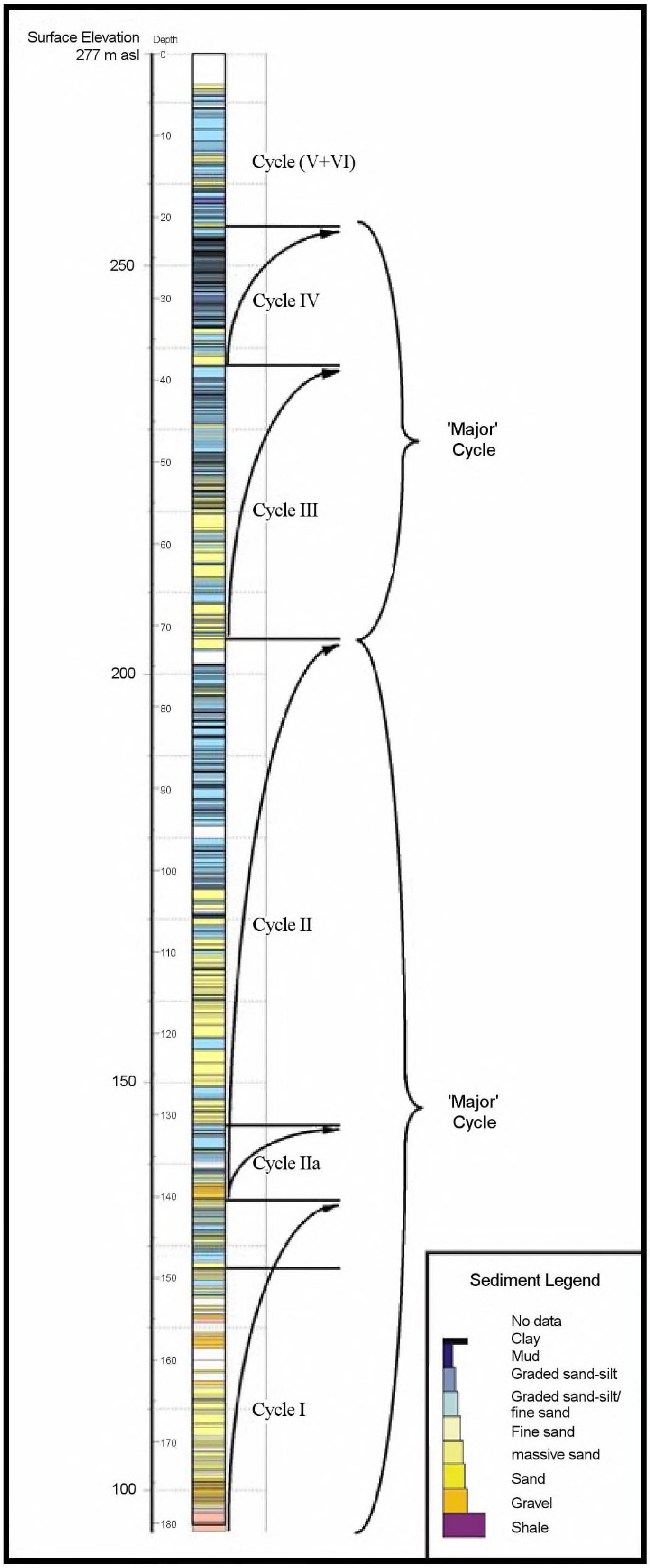

Figure 11. Detailed sediment log of borehole CAMC/YPDT-Heart Lake Road showing depositional cycles.

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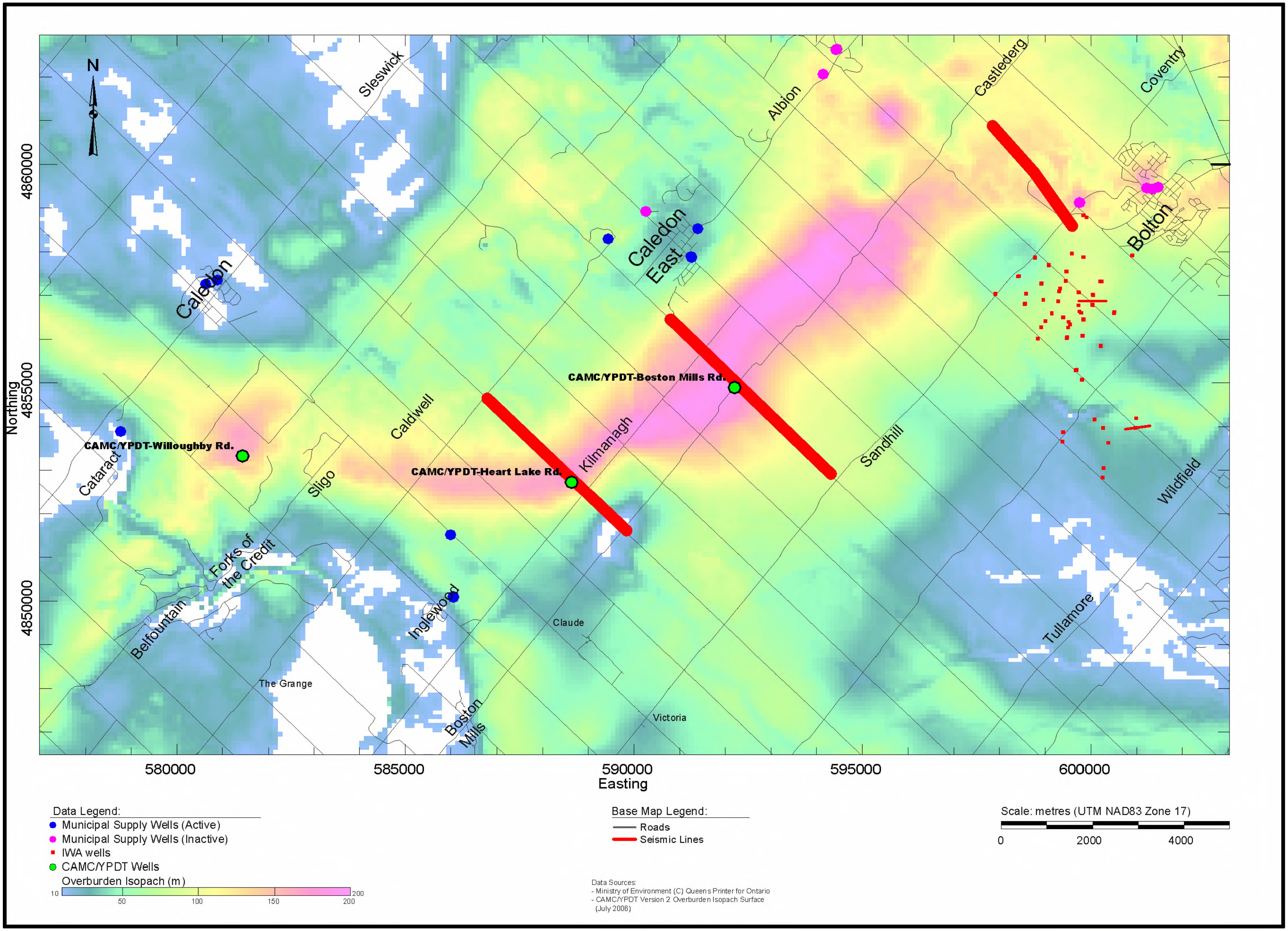

Figure 12. Overburden isopach map of the study area.

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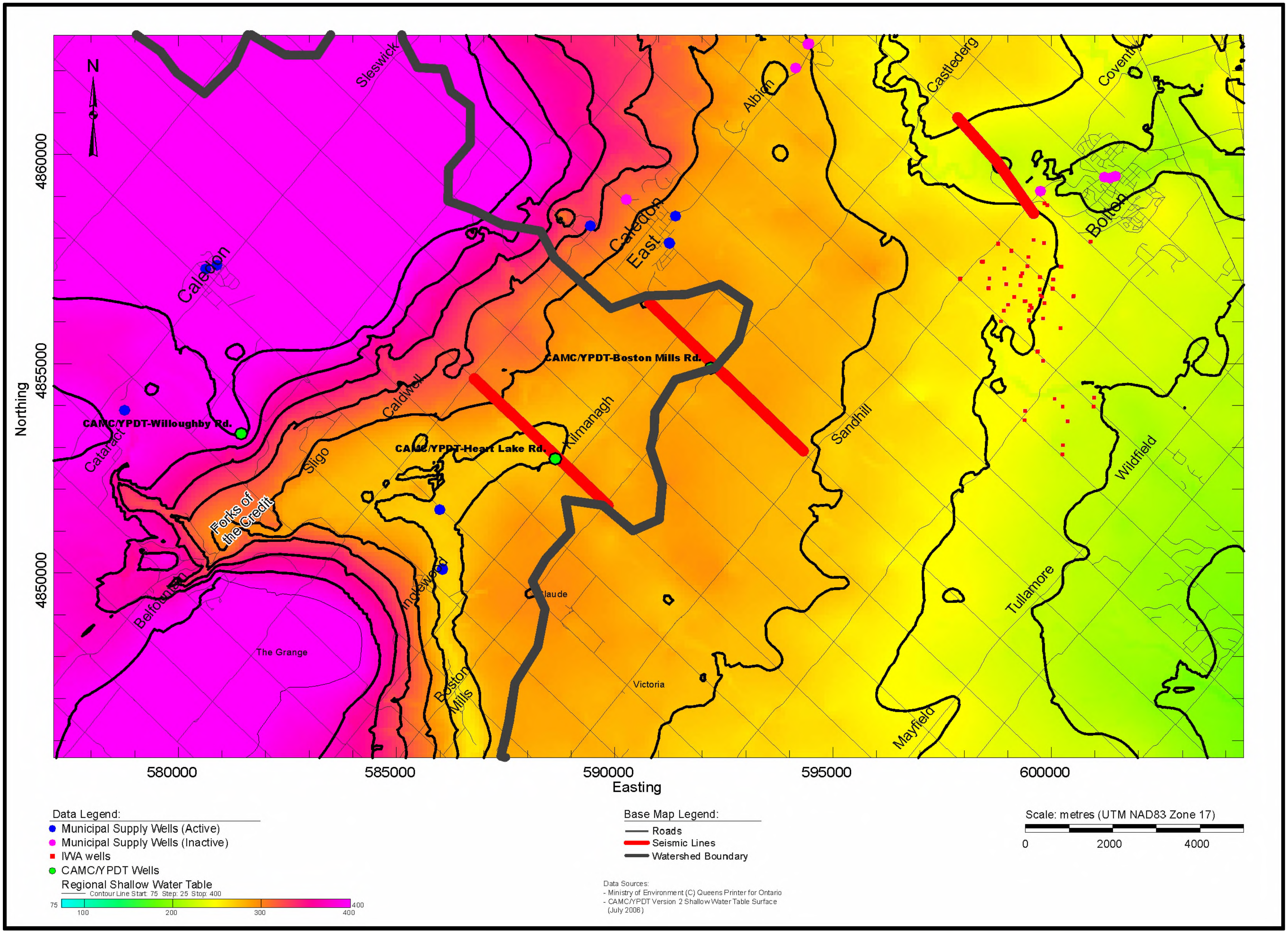

Figure 13. Estimated water table elevations in the Caledon East study area, based on data from water wells with depths <20 m.

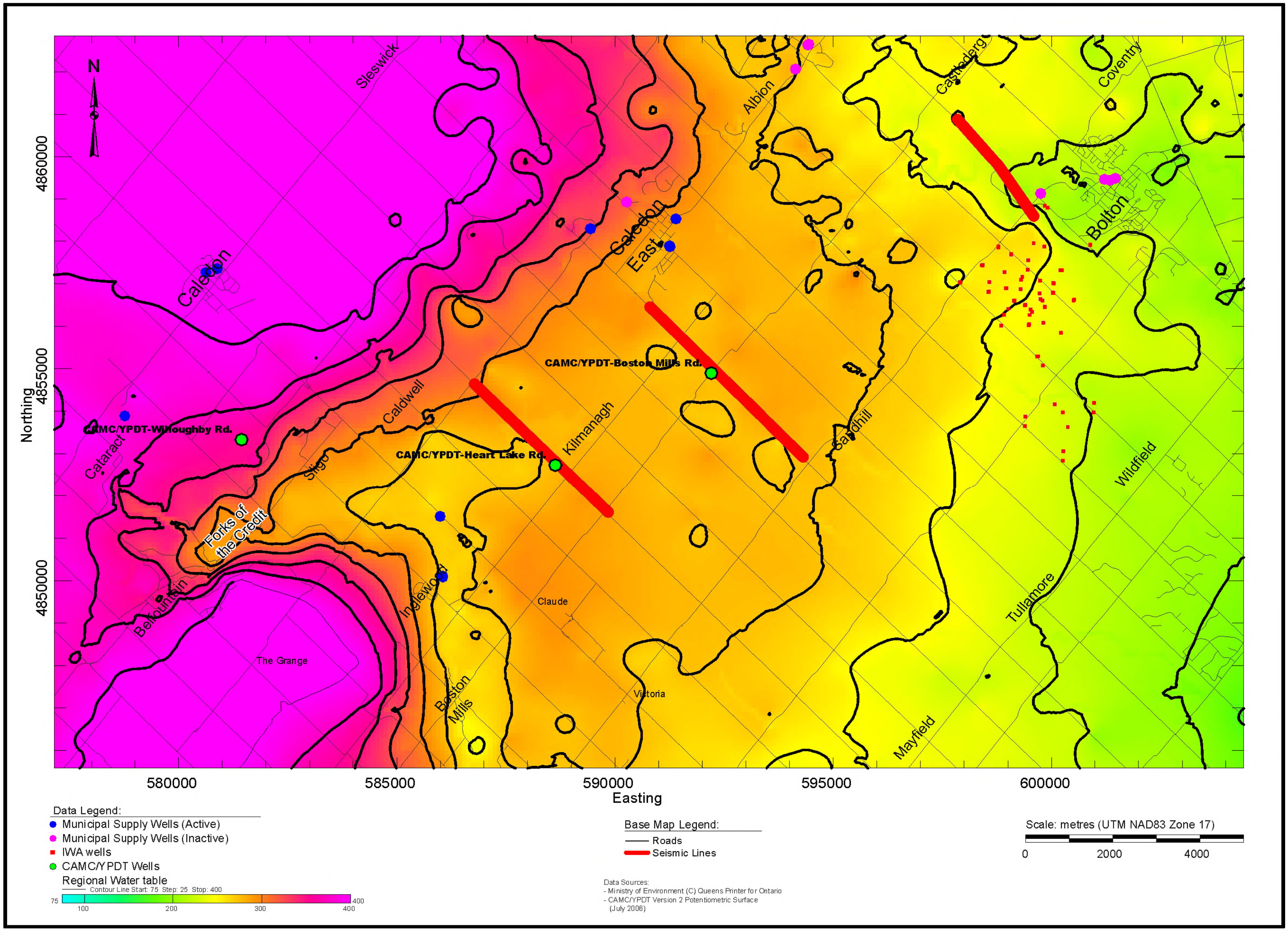

Figure 14. Estimated potentiometric surface elevations in the Caledon East study area, based on wells >30 m in depth.

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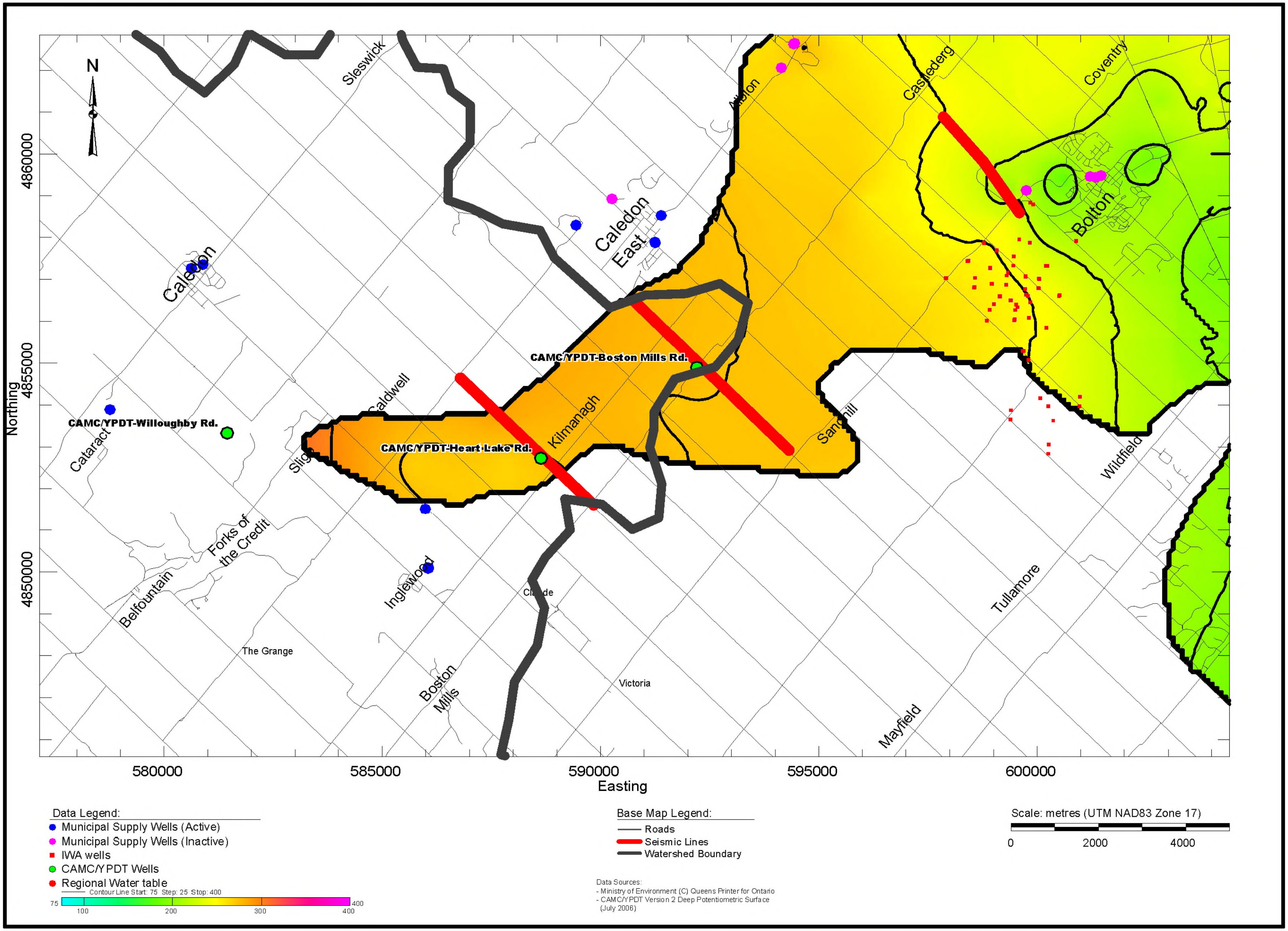

Figure 15. Estimated potentiometric surface elevations within the Caledon East buried bedrock valley.

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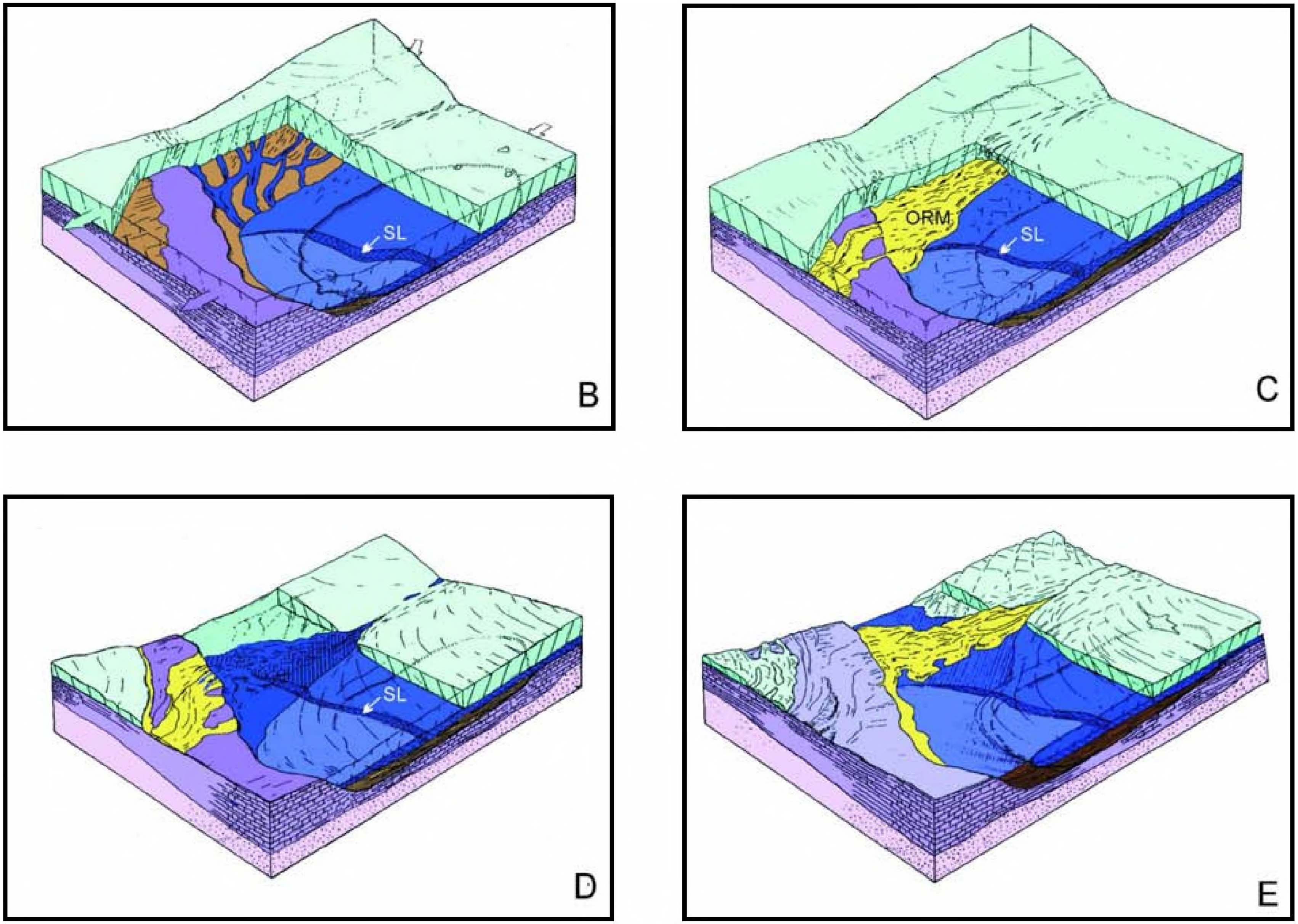

Figure 16. Schematic of sequential regional depositional events in the formation of the Oak Ridges Moraine (*from* Sharpe et al. 2004). Abbreviations: SL = subglacial lake; ORM = Oak Ridges Moraine. B) Tunnel channels event; C) Oak Ridges Moraine ridge building event; D) Halton Till event; E) Peel Pond event. See text for descriptions of these events. (The first event (A) is not shown because it is not recorded in the Heart Lake Road borehole and seismic profile data.)

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Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
			LENGTH		
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
			AREA		
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
			VOLUME		
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
			CAPACITY		
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
			MASS		
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
			CONCENTRATION		
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

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