Oak Ridges Moraine, Ontario: extent, architecture, sedimentary facies and origin of valley settings in the ORM region.

Oak Ridges Moraine region, southern Ontario, Canada
76th Annual reunion of the Northeastern
Friends of the Pleistocene

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Trip Leaders

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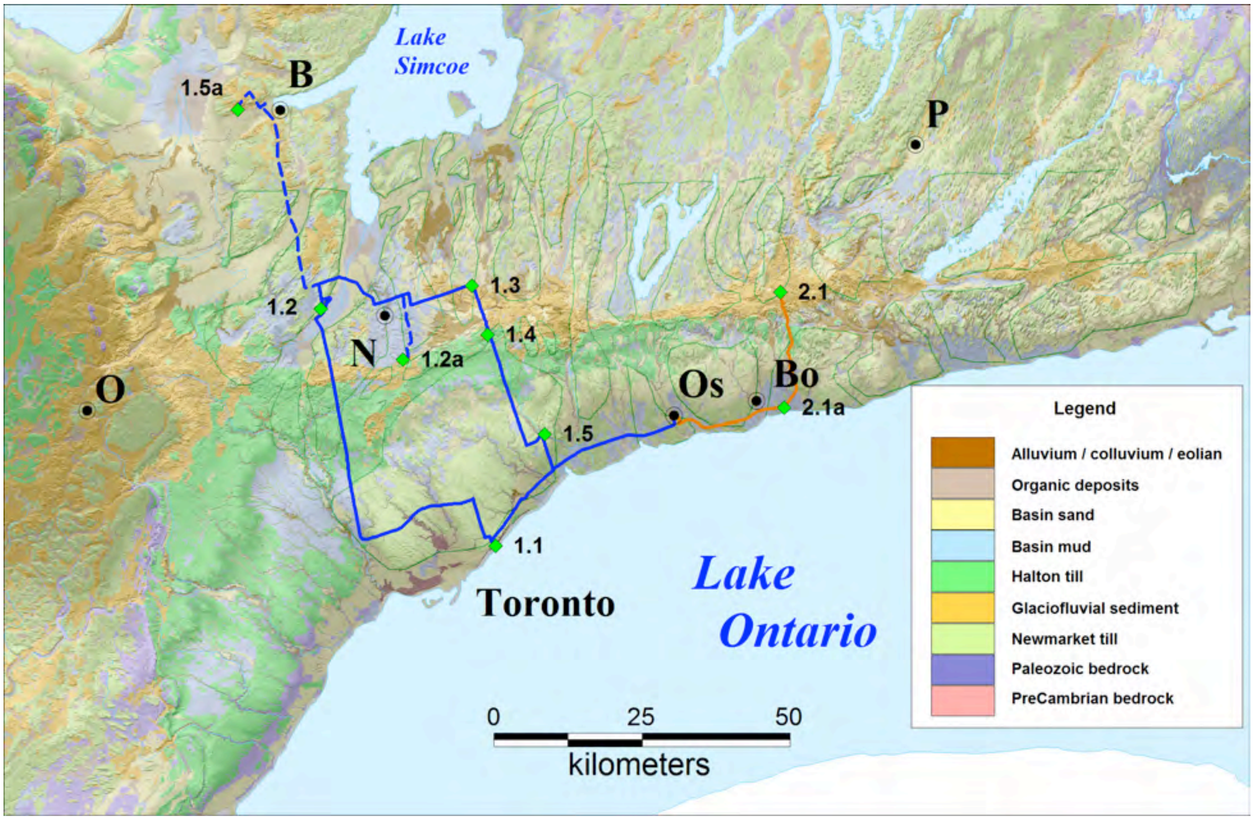
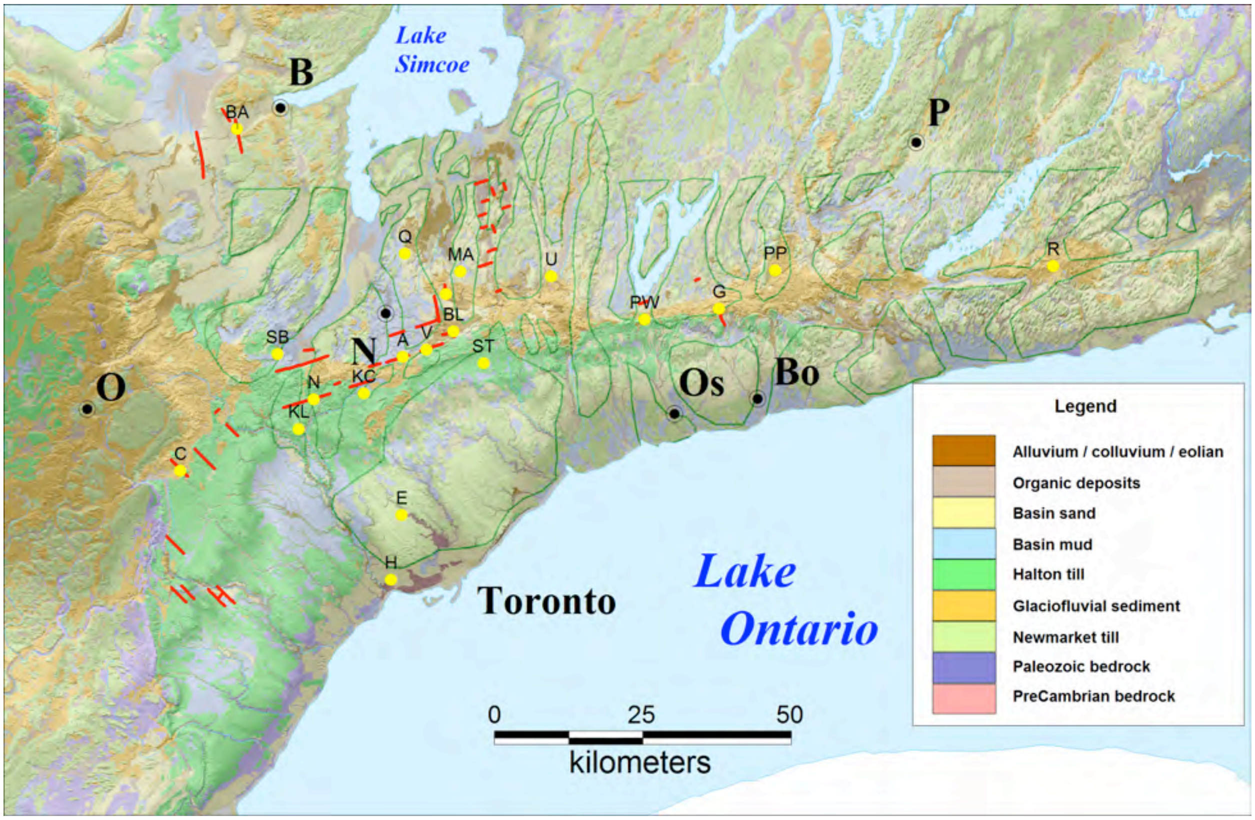


Map 1. Trip stops are shown on a background of the surficial geology overlain on a digital elevation model. Stops with a 1.2a designation are optional; they are in the guide but may not be visited.



Map 2. Daily trip route plan in the ORM / GTA area. Trip stops and daily route shown on a background of the surficial geology overlain on a digital elevation model. Green lines delimit uplands of Newmarket Till.

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Table of Contents

ABSTRACT

The fieldtrip traverses the glaciated landscape of southeastern Ontario from the Niagara Escarpment to Rice Lake. The focus of the trip is on the glacial geology of a continental basin and tunnel valleys hosted within the glacial stratigraphy of the Oak Ridges Moraine region. Using digital elevation models, and detailed geological mapping, a system of anabraching valleys has been classified on the basis of length, width and depth. The valleys have been traced beneath the Oak Ridges Moraine using high-quality shallow reflection seismic and continuous borehole data. The trip presents a suite of subsurface data with outcrop sedimentology in support of meltwater process models and depositional environments. Process models are considered to relate to regional subglacial landscapes and are used to explain the origin of regional unconformities and the formation of tunnel valleys. Depositional process models, such as high-energy models, will be discussed to interpret key sedimentary facies and evidence for hydraulic jumps where rapid flow meets standing bodies of water.

The trip starts at the famous Scarborough Bluffs on Lake Ontario, to discuss regional glacial stratigraphy and unconformities. Subsequent stops highlight inter-valley sediments beneath ORM and outcrop sediments of the ORM interpreted as subaqueous fans. We also review the surface expression of tunnel valleys, eskers, seismic mapping of buried valleys and regional meltwater concepts for tunnel valley formation. We consider the ORM buried valley dataset as a world-class analogue for ancient (tunnel) valleys with oil and gas reservoir potential.

The principal objective of the fieldtrip is to assess a 200 m thick glacial basin with tunnel valleys and fills with respect to its reservoir analogue potential for similar ancient glaciogenic deposits. The secondary trip objective is to demonstrate the field support for a range of methods and process-based sedimentary models for tunnel valley formation and deposition of related channel-fill facies.

1. FOP FIELDTRIP

1.1. Field trip goals

The fieldtrip will highlight the glacial geology of the Oak Ridges Moraine (ORM) and the Greater Toronto area (GTA) with an emphasis on:

1. Geological history of a continental glacial basin.

2. Buried valley network of the region and the regional stratigraphic architecture for buried valleys (specifically tunnel valleys / channels).

3. Glacial sedimentary facies in outcrop and sediment process models.

2. INTRODUCTION

The trip is based on work for a regional hydrogeological study of the Oak Ridges Moraine (ORM), a sandy east-west glacial landform that extends 160 km eastward from the Niagara Escarpment north of Lake Ontario (Fig. 1), by the Geological Survey of Canada and a number of partner agencies (Ref.). Applying basin analysis methods, the work resulted in a regional geological and hydrogeological framework. Local agencies are using the resulting conceptual and 3D models for numerical analysis of groundwater assessment and management at the watershed scale. Ongoing evaluation of the ORM aquifer complex provides an opportunity to re-assess the regional groundwater data with respect to its potential to serve as a glacial reservoir analogue. We include varying factors such as basin lithology, glacial settings across Canada, sediment thickness and preservation in reviewing elements of analogue suitability.

The basin analysis study approach and sequence stratigraphy of the ORM glaciated terrain is reviewed to help establish key principles for reservoir appraisal. This includes a brief assessment of channel body character, geometry and fills in global settings so as to frame our interest in glacial tunnel valleys.

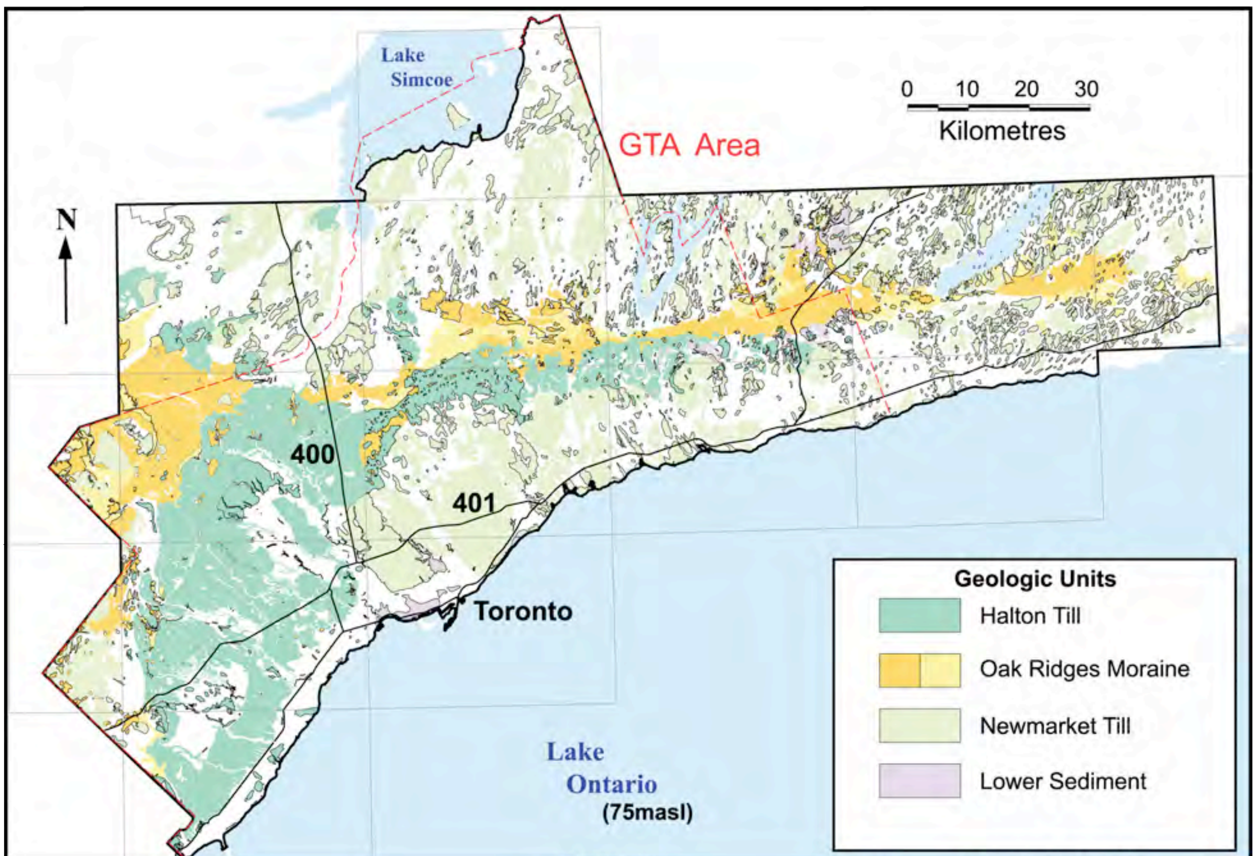


Figure 1. Simplified geology of the ORM area. Note: Newmarket Till and intervening white areas north of ORM represent tunnel channels.

Specific process models that relate to regional subglacial landscapes and the origin of regional unconformities and formation of tunnel valleys are discussed. This is based on a well-constrained 3D geological models of the ORM developed from high-quality geophysics, terrain, core and sedimentary data.

2.1. Basin analysis in regional studies

To manage Canada's groundwater resources in a sustainable way and similarly to assess hydrocarbon potential, there is a need for regional knowledge of aquifer /reservoir systems. Improving regional knowledge, in light of scant (hydro)-geological data, requires a multidisciplinary approach that advances the geological understanding of a basin. Basin analysis - mapping and characterizing the reservoir potential of sedimentary basins as applied in petroleum exploration - provides an approach that is directly applicable to regional hydrogeology studies (Sharpe et al., 2002). Basin analysis was applied to this glaciated terrain by integrating data from a variety of sources and scales of investigations to develop a (hydro)geological model of the Oak Ridges Moraine Area (ORM), southern Ontario (Logan et al., 2006).

Basin analysis supports the progression from data compilation and geological conceptualization to model development, and ultimately, towards quantitative flow system analysis. This progression is achieved notably by developing primary geological models of the stratigraphy, sedimentary architecture and origin of deposits of the ORM area (e.g. Russell et al., 2003). Analysis outlined two regional elements highly significant to groundwater flow, and reservoir potential, in the area: i) regional till uplands form principal aquitards, and ii) channels that breach the uplands form important channel-fill aquifers /reservoir types. The important channel aquifer setting had not been previously recognized since its identification required a geological framework based on high-quality topographic, geological and geophysical data (e.g., Pugin et al., 1999; Knight et al., 2008). Development of the regional geological knowledge would not have been possible using plentiful, yet poor-quality water well records alone. A numerical model was used to illustrate the significance of vertical and horizontal flow/ connectivity in /through generic channels (Sharpe et al., 2002; Inspec-Sol_CRA, 2010).

2.2. Sequence stratigraphy in glaciated terrain

Stratigraphic patterns have long been studied in sedimentary basins as they reveal the evolution of the basin over time. Well-known patterns generated by the classic river-delta-deep sea fan depositional systems, for example, can be used to find natural resources, such as groundwater, mineral resources, and petroleum. Research driven by petroleum exploration has resulted in advanced process–response models that now form the basis for interpreting most stratigraphic records (e.g. Walker, 1992), both locally (facies models) and regionally (sequence stratigraphy). Stratigraphic patterns in glaciated basins, by contrast, are less well understood, primarily because glacial deposits contain fewer petroleum reserves and the fresh-water aquifer resource is not a price-driven commodity. Glacial facies models have been developed, in some cases quite well (e.g., Ashley et al., 1985), but they are unfinished in comparison to their non-glacial counterparts, especially for sub-glacial environments (e.g., eskers, till, tunnel channels) where quantifiable process and stratigraphic response models are difficult to obtain.

What would be helpful is a glacial sequence stratigraphic approach (Cummings et al., 2010, 2012). Sequence stratigraphy is process-oriented sedimentology on a large scale. Although it has been applied successfully to the analysis of glaciated basins (e.g., Corner, 2006), its terminology does not transfer well because sea-level change is the implied main driver (cf. Brookfield and Martini, 1999). Hence, sequence stratigraphy or related simple process–response conceptual models have not caught on in glacial geology. What has been undervalued is that stratigraphic patterns and key surfaces in sedimentary basins are generated by the interplay between, i) sediment supply, and ii) depositional space for sediment.

If the central supply-space principle is appropriately applied, it can improve analysis of glacial depositional systems just as it has for river-delta-deep fan depositional systems (Posamentier and Allen, 1999), carbonate depositional systems (Eberli et al., 2001), coal depositional systems, (Bohacs and Suter, 1997), and aeolian depositional systems (Kocurek, 1999). The terms sediment supply and accommodation space may offer glacial geologists a simplified vocabulary with which to assess complex stratigraphic phenomena in glaciated basins. Nevertheless, process models and event sequences are important in glacial settings like the ORM, particularly related to the importance of slow, gradual processes versus rapid, episodic processes in glaciated-basin filling, and where thick glacial sequences may occur.

2.3. *Channels bodies and valley fills*

The three-dimensional geometry of fluvial channels and valley fills provide suitable fluvial analogues for analyses of the geometry of subsurface (aquifer/ reservoir) bodies (Gibling, 2006). Channel-body geometry has been widely linked to sequence stratigraphic concepts of base-level change and accommodation, yet there is a need to evaluate the influence of local geomorphic controls, a situation presented by the glacial setting of the ORM channel examples detailed later. Gibling reviewed the literature on > 1500 bedrock and Quaternary fluvial bodies, including glacial valleys, for which channel-body geometry, width (W) and thickness (T) are recorded. Twelve types of channel bodies and valley fills are distinguished based on their geomorphic setting, geometry, and internal structure. Log-log plots of W against T allow comparison of each type (Fig. 2).

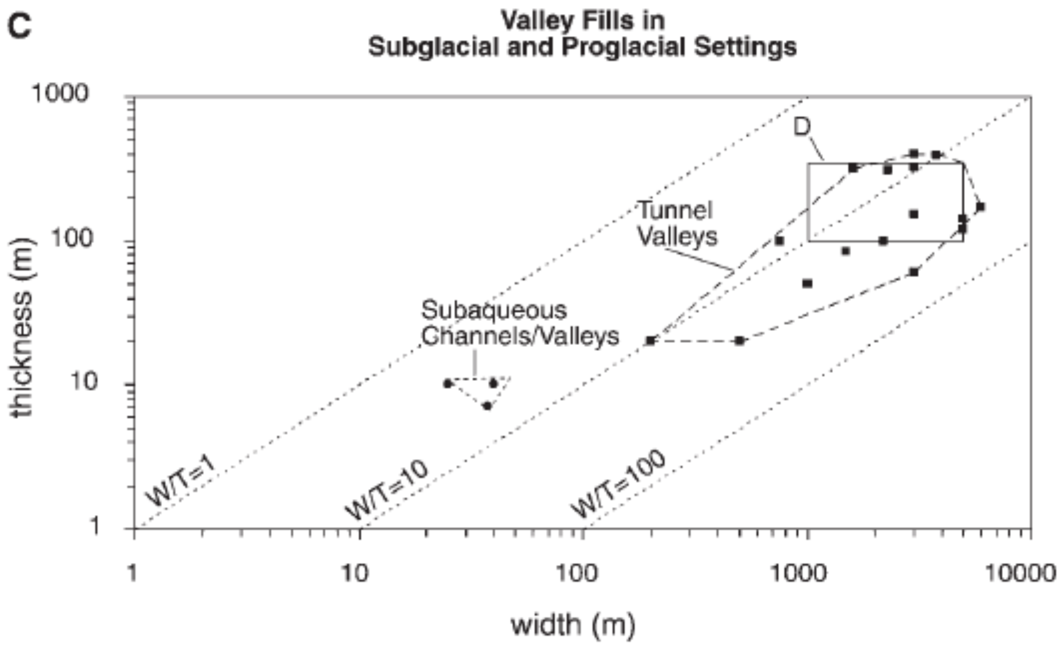


Figure 2. Width : thickness plot for valley fills in subglacial and proglacial settings. Box 'D' highlights tunnel valleys from offshore Denmark (from Gibling, 2006).

Narrow and broad ribbons (W/T, 5 and 5–15, respectively) and narrow, broad, and very broad sheets (W/T 15–100, 100–1000, and 1000, respectively) are distinguished. The dataset allows an informed selection of analogues for subsurface applications. Mobile-channel belts are mainly the deposits of braided and low-sinuosity rivers, which may exceed 1 km in composite thickness and 1300 km in width. Their overwhelming dominance throughout geological time reflects their link to tectonic activity, exhumation events, and high sediment supply.

Some deposits that rest on flat-lying bedrock unconformities cover areas of 70,000 km^2. In contrast, meandering river bodies are generally, 38 m thick and 15 km wide, and the organized flow conditions necessary for their development may have been unusual and they do not appear to have built basin-scale deposits. Fixed channels and poorly-channelized systems are divided into distributary systems (channels on megafans, deltas, and distal alluvial fans, and in crevasse systems and avulsion deposits), through-going rivers, and channels in eolian settings. The width/ maximum depth of many modern alluvial channels is between 5 m and 15m, hence, these bodies probably record an initial aspect ratio followed by modest widening prior to filling or avulsion. The narrow form (W/T, ~15) commonly reflects bank resistance and rapid filling, although some are associated with base-level rise. Exceptionally narrow bodies (W/T, ~1) may additionally reflect very deep incision, compaction thickening, filling by mass-flow deposits, balanced aggradation of natural levees and channels, thawing of frozen substrates, and channel reoccupation.

Within marine and alluvial strata, upper Paleozoic valley fills appear larger than Mesozoic examples, possibly reflecting the influence of large glacio-eustatic fluctuations in the Paleozoic. Valley fills in sub-glacial and proglacial settings are relatively narrow (W/T as low as 2.5) due to incision from catastrophic meltwater flows. The width: thickness plots for valley fills in subglacial and proglacial settings show these types as being greater than 10 with the tunnel valleys in offshore Denmark plotting in the deeper and wider portions of this comparison. Large tunnel channels in the ORM region plot in a similar portion of these plots as the offshore Denmark examples, although there are smaller valleys that plot toward the smaller portion of the field (Fig. 2). The overlap in dimensions between channel bodies and valley fills, suggests that many braided and meandering channel bodies in the rock record occupy paleo-valleys.

Avulsion frequency, sedimentation rate, and the ratio of channel belt and floodplain width help determine channel-body connectedness (Fig. 2). Although these controls strongly influence mobile channel belts, they are less effective in fixed-channel systems, for which many examples testify to the influence of local geomorphic factors that include bank strength and channel aggradation. There are few examples of highly connected suites of fixed-channel bodies, despite their abundance in many formations. Whereas accommodation is paramount for preservation, its influence is mediated through geomorphic factors, thus complicating inferences about base-level controls and rapidly varying lengths in glacial settings.

3. GLACIAL GEOLOGY

3.1. Glacial basins across Canada

Most of Canada has been glaciated several times during the Quaternary (~ last 2 million years), but only a few places preserve thick glacial sediments from both earlier and more recent glacial episodes (e.g. Shilts et al., 1987). The Glacial Map of Canada (GMC; Prest et al., 1968) provides a quick overview of potential basins that may record and preserve glaciolacustrine and glaciomarine sequences, and which are candidates for preserving thick glacial sequences. The areas of glaciolacustrine sediment (green on GMC, Fig.3) largely coincide with areas that are upflow of terrain that drains to the sea (e.g. Hudson Bay) in inter-glacial times, and where drainage is blocked during glacial episodes as ice advanced.

Geology is also a major control on sediment thickness. Areas of crystalline shield (see broad area of eskers on the GMC, Fig. 3) with a predominance of hard silicate rocks, produces little glacial detritus (sediment). This contrasts with areas underlain or immediately downflow of sedimentary basins with carbonate, shale and sandstones. The Western Canadian Sedimentary Basin and eastern Paleozoic basins are noteworthy in this regard with areas of up to, or greater than, 200 m of glacigenic sediment. Most of these areas correspond to ice-marginal glaciolacustrine basins. Eskers are prominent on the Shield landscape as there is little other glacial sediment to cover them. Eskers record a concentration of the latest glacial sediment captured within the subglacial drainage system during the final stages of the Laurentide ice sheet (Shilts et al., 1989). Most of the glaciolacustrine and glaciomarine terrain on the GMC is considered to be pro-glacial in origin. Increased knowledge of subglacial lakes beneath Antarctic (e.g. Siegert et al., 2007) is providing a new analogue for interpretation of some glaciolacustrine deposits within a subglacial model for the Laurentide Ice Sheet (Evatt et al; 2006). Hudson Bay and topographic depressions on the Canadian Shield and particularly along the Shield margin with the sedimentary basin cover are good candidates for preservation of subglacial glaciolacustrine deposits (e.g., Great Slave Lake). An example in Southern Ontario is the Niagara Escarpment and Laurentian valley parts of which will be reviewed on this field trip (see figure. 4b).

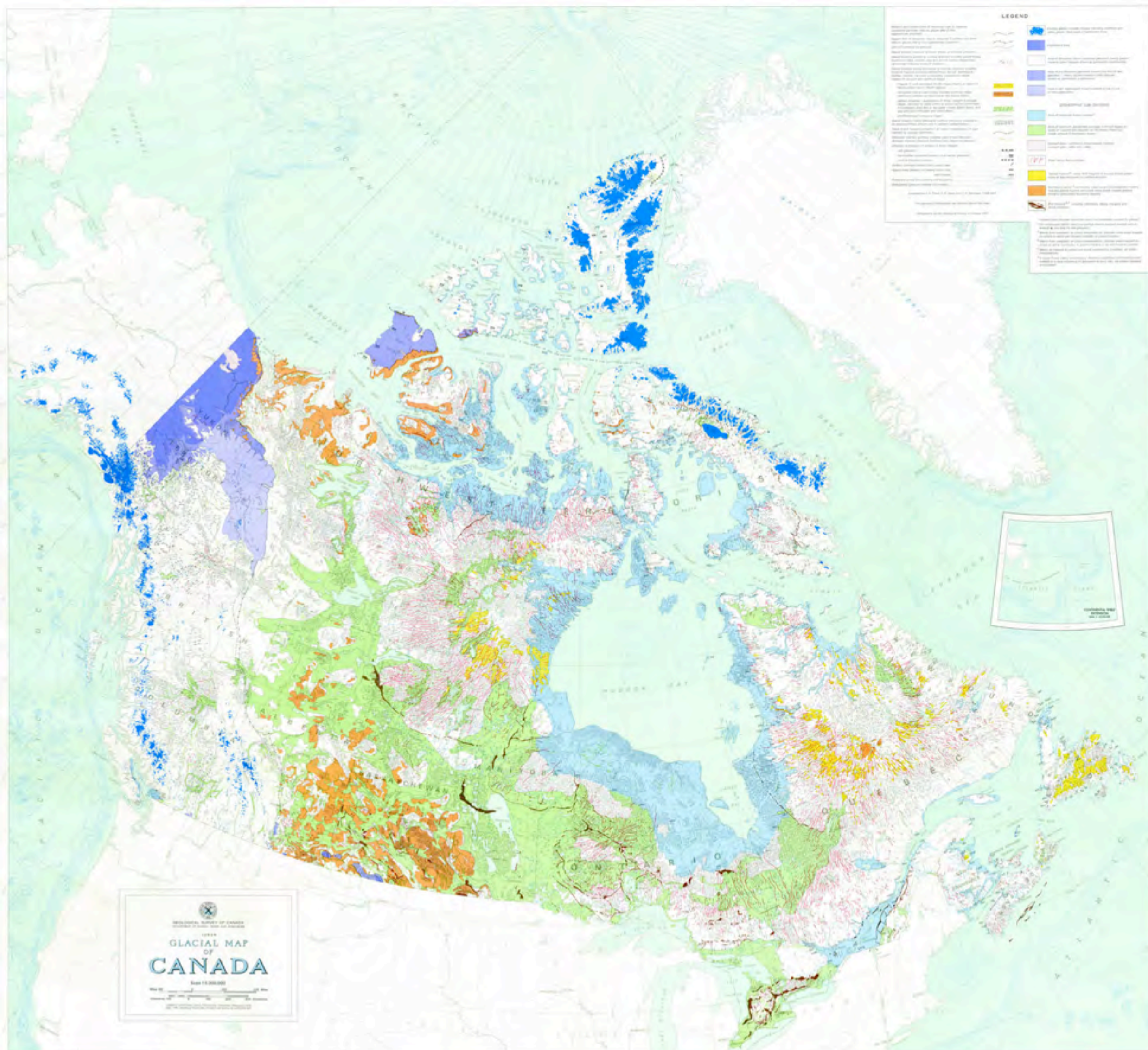


Figure 3. Glacial map of Canada highlighting ice-marginal glaciolacustrine deposits (green), glaciomarine (blue) and esker network (red) on the shield. Note that ORM (brown) is one of only a few stratified moraines in Canada. (Prest et al., 1967)

3.2. Glacial geology of Ontario

Southern Ontario is underlain by Paleozoic and Precambrian bedrock that is extensively covered by glacial sediment south of Shield margin. Areas of thick sediment are in part dependent on bedrock topography and rock type. For example, silicate rocks of the Canadian Shield are 3-4 orders of magnitude harder than the predominant carbonate rocks of the Paleozoic basin. There is thin (~1-10 m) discontinuous glacial sediment on Shield terrain compared to Paleozoic terrain where glacial and related sediment is ~10-200 m thick. The erosion history of the areas has produced a number of escarpments; two of which are noteworthy, one at the Shield-Paleozoic contact and a second within the Paleozoic, where shale rocks were preferentially eroded relative to capping carbonate rocks of the Niagara Escarpment (Fig. 4a, b). The bedrock topography map of southern Ontario clearly shows a major depression below (east of) the Niagara Escarpment (Fig. 4b, LV). This depression has the thickest glacial sediments in southern Ontario. The glacial geology can be summarized in basic terrain features:

glacial basin sediment (muds, sands) and upland sediment (muddy and coarse tills; Fig. 4c). This wedge of glacial sediment, ~150 km by 50 km, covers an NW-SE oriented basin that is ~200 m thick, spanning last inter-glacial sediments to most recent glacial sediments. Of interest here is where buried valleys, and glacial valleys with fill sequences occur in these terrains/ sequences. Sand and mud plains across southern Ontario also contain thick glacial sequences but not as thick (<100m) and widespread (~100 km^2) as the thickest strata that occur east of the Niagara Escarpment (Fig. 4b).

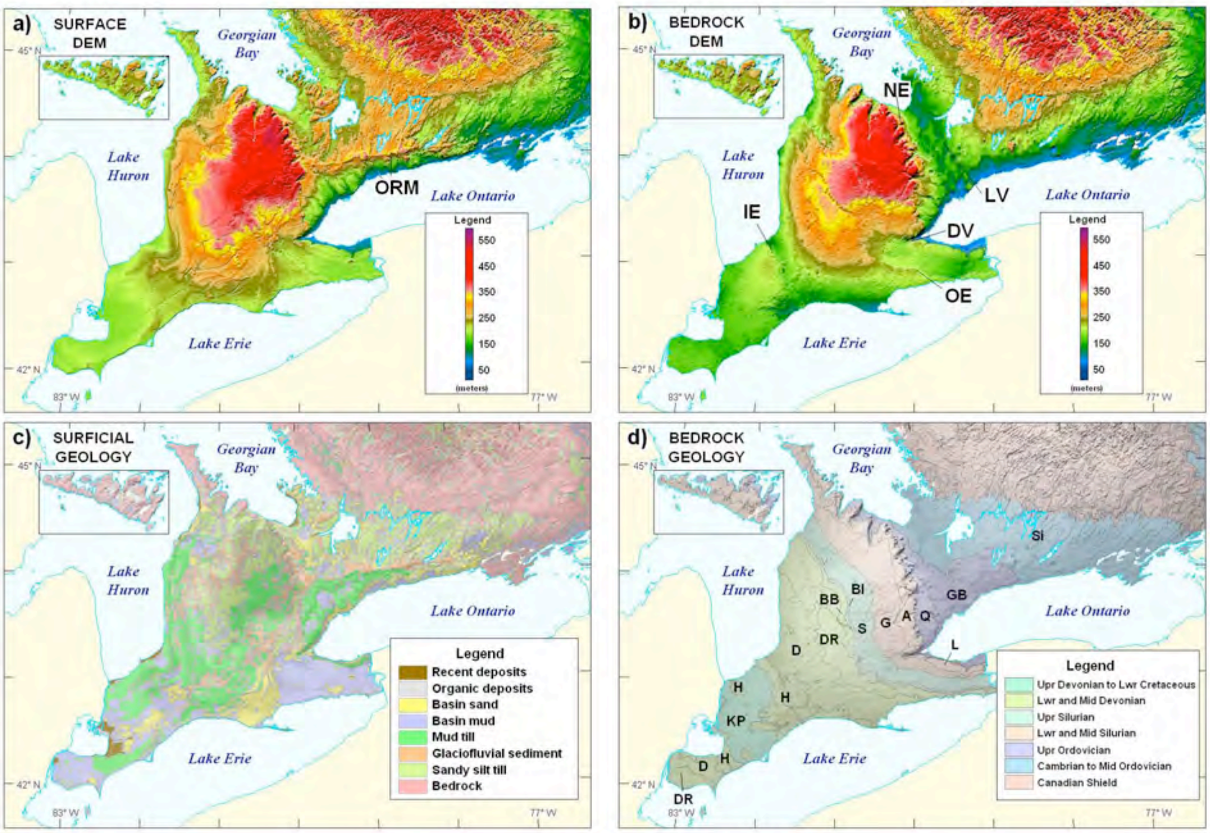


Figure 4. Attribute maps for Southern Ontario. a) Digital elevation model (DEM) of the ground surface (data source: Gao et al., 2006 modified from OMNR, 2006). ORM= Oak Ridges Moraine. b) DEM of the bedrock surface (data source: Gao et al., 2006). LV= Laurentian Valley, DV= Dundas Valley, NE= Niagara Escarpment, OE= Onandaga Escarpment, IE= Ipperwash Escarpment. c) Simplified surficial geology with a ground surface DEM drape (modified from Barnett et al., 1991; OGS, 1997). d) Bedrock geology with a bedrock surface DEM drape. Letters designate major Formations or Groups. Si= Simcoe, GB= Georgian Bay, Q= Queenston, L= Lockport, A= Amabel, G= Guelph, S= Salina, BI= Bass Island, BB= Bois Blanc, DR= Detroit River, D= Dundee, H= Hamilton, KP= Kettle Point (data sources: OGS, 1991, 1993, Gao et al., 2006). Figure modified from Hinton et al., 2007.

3.3. Geological setting of the ORM region

The Oak Ridges Moraine forms an elevated ridge of sediment ~250-300 m above Lake Ontario and Georgian Bay, extending 160 km from the Niagara Escarpment to east of Rice Lake (Figs. 4a, 1). It is a sandy, complex glaciofluvial-glaciolacustrine landform resting unconformably on a regional till sheet, lower sediments and, in places, directly on gently-dipping bedrock.

The ORM and underlying sediments unconformably overlie relatively thin Paleozoic platform strata that in turn unconformably overlie Precambrian Shield rocks that are exposed north of the area (Fig. 4d). Paleozoic rocks in the area are predominantly Ordovician limestone, in the east, and minor sandstone and shale in the west. The Niagara Escarpment on the western margin of the area is capped by Silurian dolostone (Fig. 4d).

A broad control on groundwater resources, reservoir potential and flow patterns in the area is the structure of Precambrian, Paleozoic and Pleistocene strata. A major northeast trending structure in Shield rocks (Easton, 1992) may control the position of lakes on the edge of the Precambrian / Paleozoic contact (Fig. 4a) and possibly the orientation of the bedrock valleys that occur in the northern ORM area (Scheidegger, 1980; Eyles et al., 1995). Paleozoic bedrock valleys are also align with northwest and northeast trending fracture patterns (Sanford et al., 1985), and likely pre-glacial drainage networks that preferentially eroded softer shale (Spencer, 1881). These lakes and structures have likely been enhanced by glaciofluvial erosion (Gilbert and Shaw, 1994). In addition, a network of valleys or channels occurs in the thick glacial sediment of the ORM area (Russell et al., 2003). Underlying structure and bedrock morphology are controls on regional channel network of the ORM.

Early work on the ORM did not explicitly recognize the large glacial channels (e.g., Duckworth 1979 and Chapman, 1985), despite the fact that basin analysis methods were employed (Eyles et al., 1985). Groundwater studies relied on early use of water wells and geologic mapping (e.g. Karrow, 1959; 1963; 1967). Early work (Spencer, 1897; and Scarborough Bluffs) that recognized buried valleys, attributed these valleys to low base level and non-glacial conditions (e.g. Karrow, 1967 and refs therein; Stop 1.1).

3.4. Glacial history for the Oak Ridges Moraine region

The last major ice advance (Late Wisconsinan (last glacial); ~25 000 to 12 000 years BP) was from the northeast (Fig. 5) and along the axis of the Great Lake basins. During this interval the ice deposited a thick widespread till sheet or amalgamated sheets (Newmarket Till; stops 1-1, 1-2, 1-5). This till overlies thick lower channel and inter-channel deposits and both sequences continue under the ORM. This regional till sheet is variable in thickness (Sharpe et al., 2005); and has been eroded by meltwater events to form a regional unconformity consisting mainly of drumlins and a network of channels (Sharpe et al., 2004). The ORM rests on this eroded terrain and formed ~12 000-13 000 years ago (Gwyn and Cowan, 1978).

The ORM occurs as thick stratified sediments, partly capped by thin Halton Till along its southern flank (Fig. 6). The ORM sediments were deposited rapidly in tunnel channels and a glacial lake (e.g. Gilbert, 1997; Barnett et al., 1998; Russell et al, 2003; 2004) set in a re-entrant or cavity between/under thick ice of the Laurentide Ice Sheet to the north and low-relief ice occupying the Lake Ontario basin to the south. ORM deposits may be part of a larger system of ice-controlled meltwater deposition during final deglaciation that includes stratified moraines west of the ORM and above the Niagara Escarpment (Chapman and Putnam, 1943).

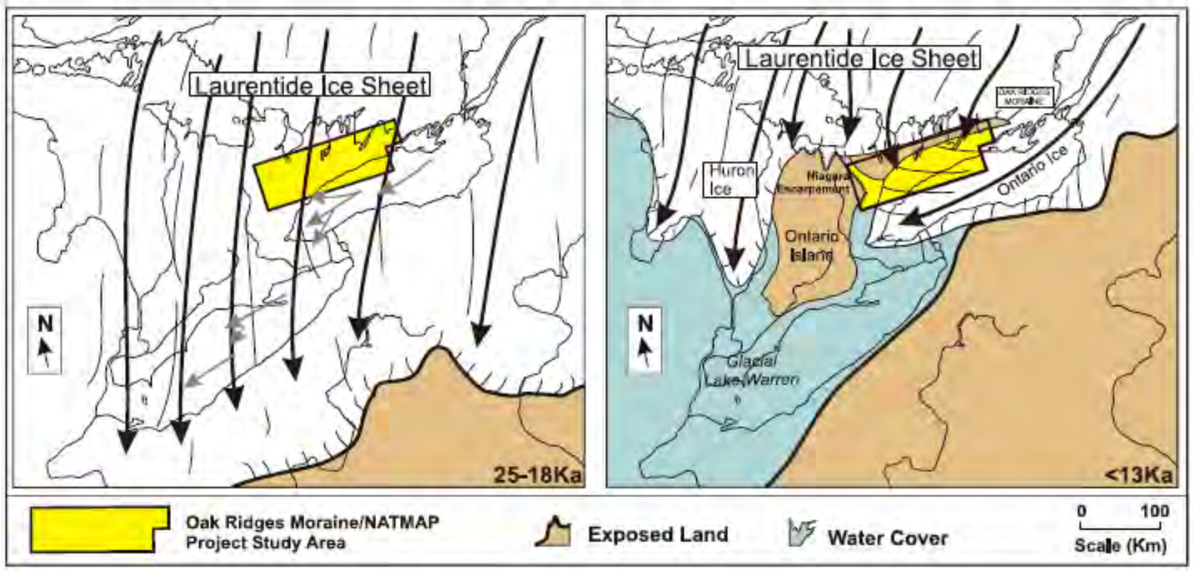


Figure 5. Ice flow directions during late glacial maximum (20 ka) and deglaciation (13 ka) (After Barnett et al., 1991).

3.5. Stratigraphic framework for ORM region

Based on geological mapping (Sharpe et al., 1997) and a need to generalize the geological history of the area, four major units and two erosional surfaces (regional unconformities) are identified and described (Fig. 6; Sharpe et al., 2004). The unconformities are important as they allow us to correlate stratigraphic units across the area and they often mark major changes in hydraulic properties across their boundaries.

1. Bedrock surface: This surface forms a regional unconformity separating rock from sediment (Fig. 4b). The general location of valleys on this surface has been mapped (e.g., Eyles et al., 1993). The best documented of these buried valleys, the Laurentian Channel (Russell et al., 2004), extends from Georgian Bay to Lake Ontario (Spencer, 1881) and is buried by sediment up to 200 m thick. The geometry of the bedrock surface is poorly constrained, as few wells intersect bedrock. Investigations using location-corrected water-wells (e.g., Kenny, 1997), hydrogeological borehole data, and seismic reflection profiles indicate a trunk and tributary valley system (Brennand et al., 1997). Near Bolton, valleys erode into the Niagara Escarpment and form tributary valleys to the main Laurentian valley. These bedrock valleys may contain productive aquifers and serve as poorly-known reservoir analogues.

2. Lower sediments: Lower sediment occurs stratigraphically below Newmarket Till and is a group of the ten formations of Illinoian to mid-Wisconsinan age (~30-50 Ka; Fig. 6). It forms ~70% of total sediment volume in the area and is up to 150 m thick (Fig. 7; Sharpe et al., 2005a). Lower sediment is identified in 100 m high lake bluffs and in seismic profiles. It also has a planar upper surface and a horizontal internal architecture (e.g., Pugin et al., 1999; stops 1.1;1.2). This tabular geometry is truncated where tunnel channels incise bedrock (Fig. 6b). Lower sediment becomes thinner where bedrock rises towards Niagara sediment (Sharpe et al., 2007) comprises sand, silt and clay, till, and distinctive organic-rich and fossil-bearing beds important for regional correlation (Karrow, 1967). Silt-clay rhythmite units are commonly 20-30 m thick and intercalated with 20-30 m thick sand units. Lower sediment hosts a number of key regional aquifers (e.g. Thorncliffe Formation, stops 1.2; 1.5) that have prolific yields; however, the aquifer-aquitard system is poorly known. Sandy formations form regional aquifers used for municipal water supply (Sibul et al., 1977), and act to transmit inter-watershed flow (Sharpe et al., 2002).

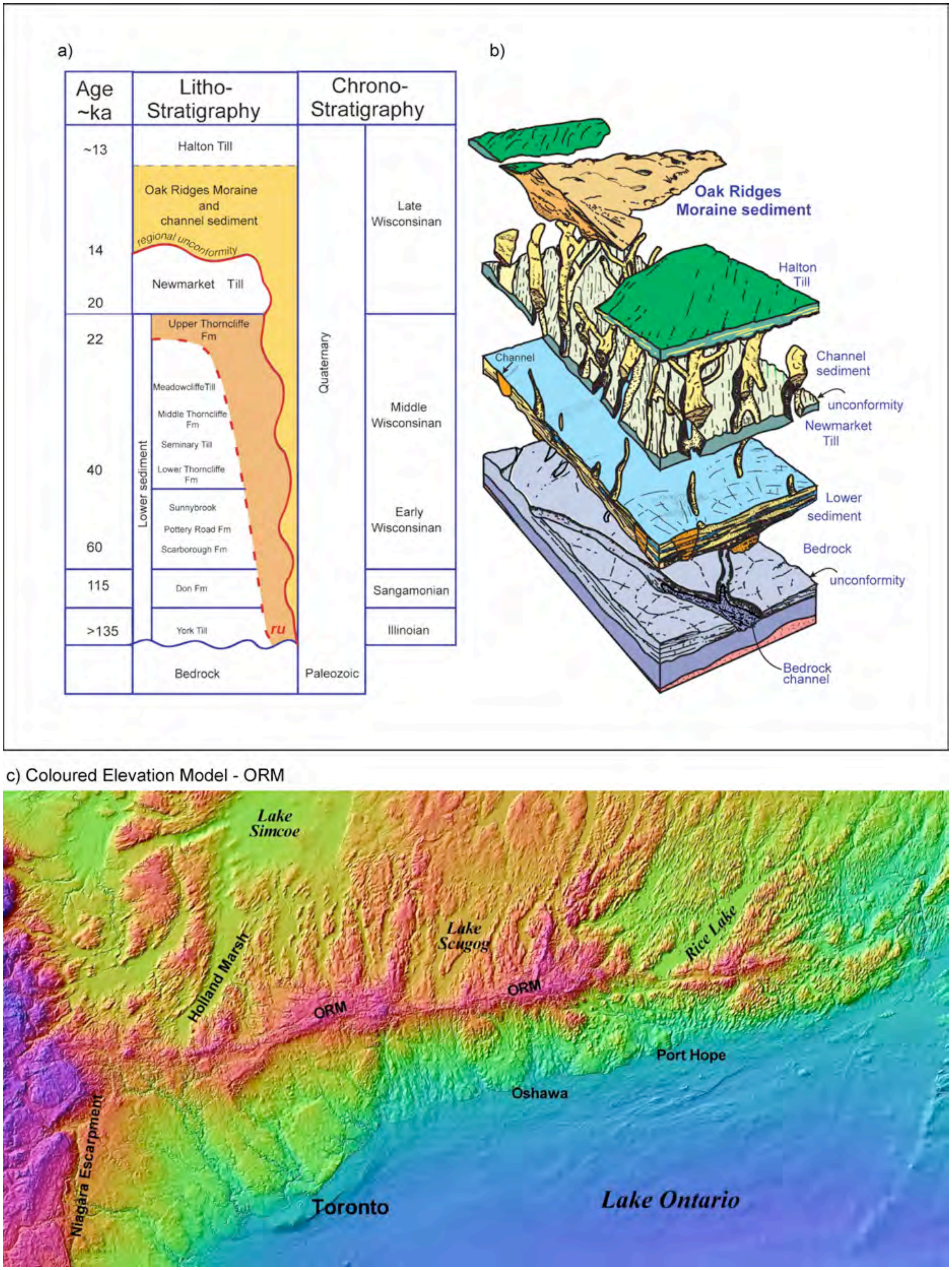


Figure 6. Regional stratigraphy of the ORM area (a) as shown within conceptual stratigraphic architectural drawing of the stratigraphy (b). A digital elevation model of the area (c) guided these models. Two ages of channel cutting are shown in a) (Sharpe et al., 2013).

3. Newmarket Till: A dense, stony, silty sand diamicton regionally extensive drumlinized unit (stops 1.1; 1.5; and 1.3) that is up to 50 m thick (Fig. 8). It forms the surface unit north and south of the ORM and has been traced lithologically beneath the moraine (e.g., Barnett et al., 1991). The basal contact is commonly planar and generally undeformed. Beneath the central part of the ORM the base of the unit typically occurs ~200-220 m asl (Sharpe et al., 2002; 2005). It contains locally significant (1-2 m; up to 5 m) sandy inter-beds (stop 1.5). Distinct stone horizons occur within the unit. The Newmarket Till also contains rare horizons of thin rhythmites or isolated clay laminae. Newmarket Till is characterized by high seismic velocities in downhole seismic logs obtained over wide areas, and the contrast in velocities between it (2000-3000 m/s) and overlying sediments (1500-2000 m/s) makes it a prominent reflector on seismic profiles (Pullan et al., 1994; Boyce et al. 1995; Pugin et al., 1999). Newmarket Till is a regional aquitard separating near-surface aquifers from deeper, lower aquifers/ reservoirs (Fig. 8; x-section).

The sedimentary character of this till indicates some loading from overlying ice but not enough to rearrange underlying, widespread fine sedimentary structure (Stop 1-5). The unit appears to have been deposited by subglacial and meltout or debris flow processes (Sharpe et al., 2005). Discontinuous boulder pavements may be found with striated upper surfaces suggesting subglacial processes (scouring?). Elsewhere the diamicton is locally interbedded and appears to have formed as debris flows.

4. Unconformity: The Newmarket Till surface undulates north of the ORM and carries both drumlins and channels as part of a regional unconformity (Sharpe et al., 2004; stops 1-1 and 1-2). This erosional surface is considered to have been formed by subglacial sheetflows, producing drumlins (Shaw and Sharpe, 1987; stop 1-3) followed by waning-stage, entrenched flow, producing channels (Brennand and Shaw, 1994; Russell et al., 2003; see stop 1-2, 1-3, for discussion).

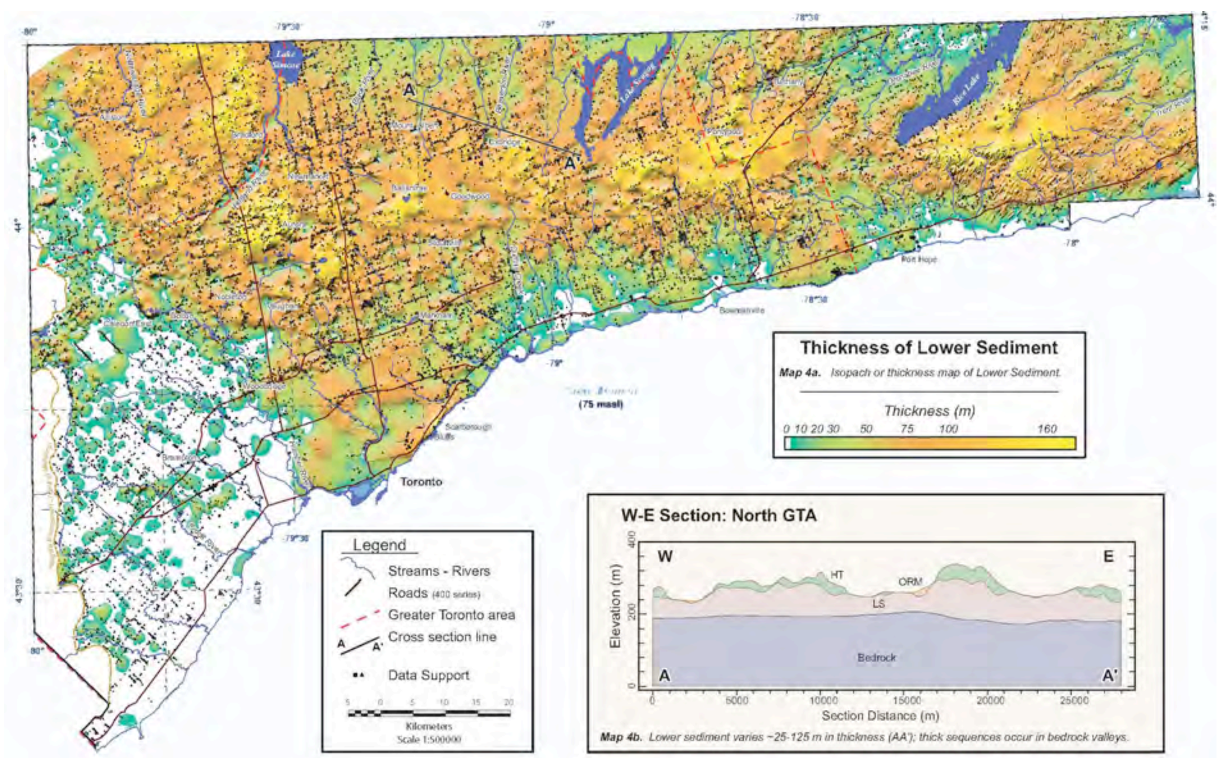


Figure 7. Sediment isopach map for Lower sediment shows thicknesses >100 m for most of the area east of the Niagara Escarpment (white area to extreme west); from Sharpe et al., 2005.

A network of south-southwest-oriented channels that occurs north of the Oak Ridges Moraine (Fig. 1) cuts into Newmarket Till. The surface expression of the channels disappears beneath the ORM. Mapping, drilling, and seismic reflection profiling (e.g., Pugin et al., 1999) show that channels continue beneath the ORM. The channels may be confined within Newmarket Till, or may have eroded through it into lower sediments (Figs. 7,8). The channels at surface are 1-5 km wide and 10-50 m deep. In the subsurface, their geometry is 1-2 km wide and 10-150 m deep (Pugin et al., 1999). The lowest, coarse sediment fills show NE-SW trends (parallel to surface channels, Fig. 13). The channels mainly contain sandy sediments (Russell et al., 1998; 2003); however, some channels contain thick (10-15 m), cross-bedded gravels (Shaw and Gorrell, 1991; Pugin et al., 1999; Sharpe et al., 2003), and are capped by 10-20 m mud intervals (Russell et al., 2003). The channel network is attributed to subglacial floods (e.g. Barnett, 1990; Shaw and Gilbert, 1990; Barnett, et al., 1998) and the fill is attributed to waning flow (e.g. Shaw and Gorrell, 1991). These channels may be hydrogeologically significant as high-yield aquifers /reservoirs (e.g., Ballantrae; Desbarats et al., 2001; Sharpe et al., 2002; Figs. 17, 18) or as hydraulic connections to lower beds.

5. Oak Ridges Moraine sediments: The ORM is an extensive stratified sediment complex 160 km long and 5-20 km wide, arranged as four sediment wedges (see Fig. 1-4.1, stop 1-4), each widening westward. The wedges sit distal to large channels extending from: 1) Holland Marsh, 2) Lake Scugog, and 3) Rice Lake (Figs. 4d, 6). The ORM is more extensive and reaches thicknesses of150 m in the subsurface (Fig. 9), particularly beneath Halton sediments (Russell et al., 2005). The lower contact of the ORM sits on a channelized, regional unconformity on lower sediment or on bedrock (Figs. 6, 9, inset). ORM sediments occur primarily within fan-shaped bodies on the scale of 10-100 m thick, 100-5000 m long and 10-1000 m wide; they are arranged from coarse to fine downflow and upsection (Fig.1-4.8; stop 1-4). Core logging indicates that moraine sediments consist of 2-3 fining-upward sequences (Gilbert, 1997; Barnett, et al., 1998; Russell et al., 2002). Rhythmically interbedded fine sands and silts are dominant, but coarse, diffusely-bedded sands and heterogeneous gravels are prominent locally, at the apex of fans and at depth in channels. ORM sediments have predominant NE-SW to E-W paleoflow indicators (Sharpe and Russell, 2005). The deposits are interpreted as glaciofluvial, transitional to glaciolacustrine subaqueous fan, and minor delta sediments, deposited in a glacial lake ponded between the ice and the >400-m asl high Niagara Escarpment to the west (Fig. 4b). The ORM forms the dominant aquifer and recharge-discharge complex in the region.

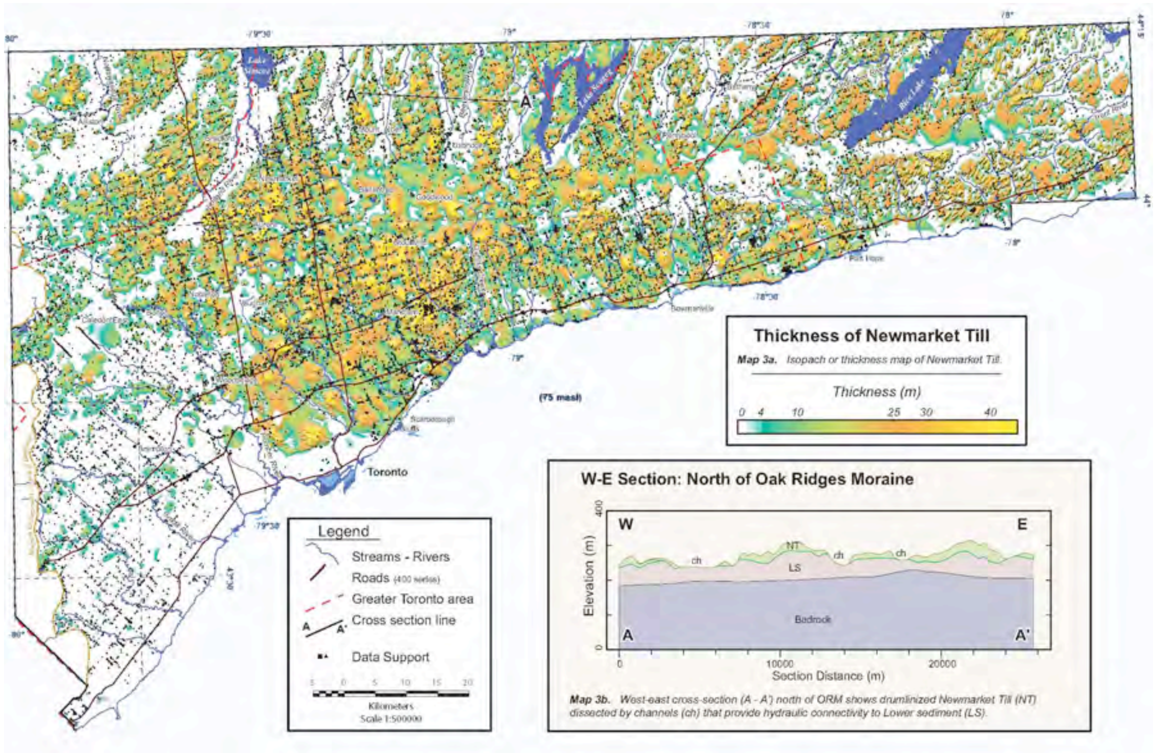


Figure 8. Sediment isopach map for NewmarketTill shows influence of channel erosion in the north part of the region, despite thicknesses up to 40 m; from Sharpe et al., 2005.

6. Halton/Kettleby sediments: Halton sediment includes several late-glacial units (Kettleby and Wentworth tills) that overlie ORM deposits (Fig. 6). This unit is < 15 m thick but locally is up to 30 m thick (Fig. 10). It is most extensive west of Toronto to Niagara Escarpment (Fig. 4). Inter-bedded diamicton, silt-clay, and sandy sediment facies indicate a glaciolacustrine and subaqueous debris-flow origin for much of this unit (Sharpe, 1988), transitional from ORM sediments (Sharpe and Russell, 2013). Basin geometry and fill processes control thickness, distribution and structure of Halton sediment (Barnett et al., 1998). It drapes hummocky, kettle-lake terrain along southern ORM flanks, thickens in local basins (Fig. 10; Russell et al., 2005a), and thins across bedrock platforms (Fig. 10, x-section). This low permeability unit partially confines ORM aquifers. Thin sandy interbeds within Halton Till allow recharge of ~200-300 mm a-1 (Gerber and Howard, 2000). The unit yields domestic supply aquifers, and provides pathways for groundwater flow (springs) of ~5-10 l/s from underlying ORM sediment.

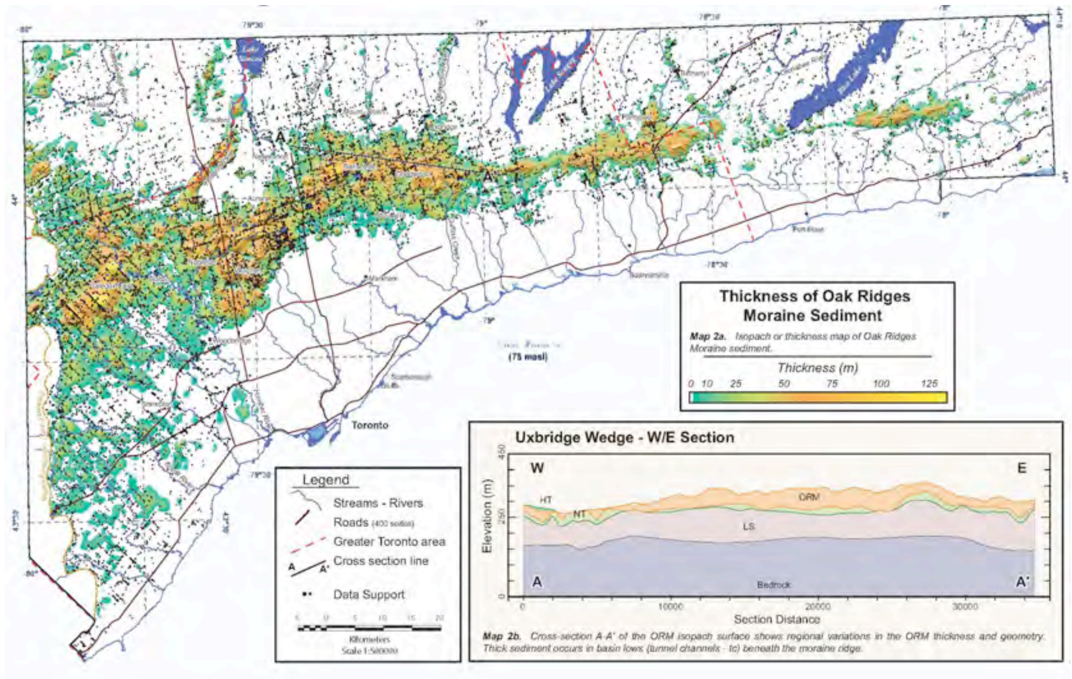


Figure 9. Sediment isopach map for Oak Ridges Moraine deposits. Note sediment area widens to the west and generally becomes thicker; from Russell et al., 2005.

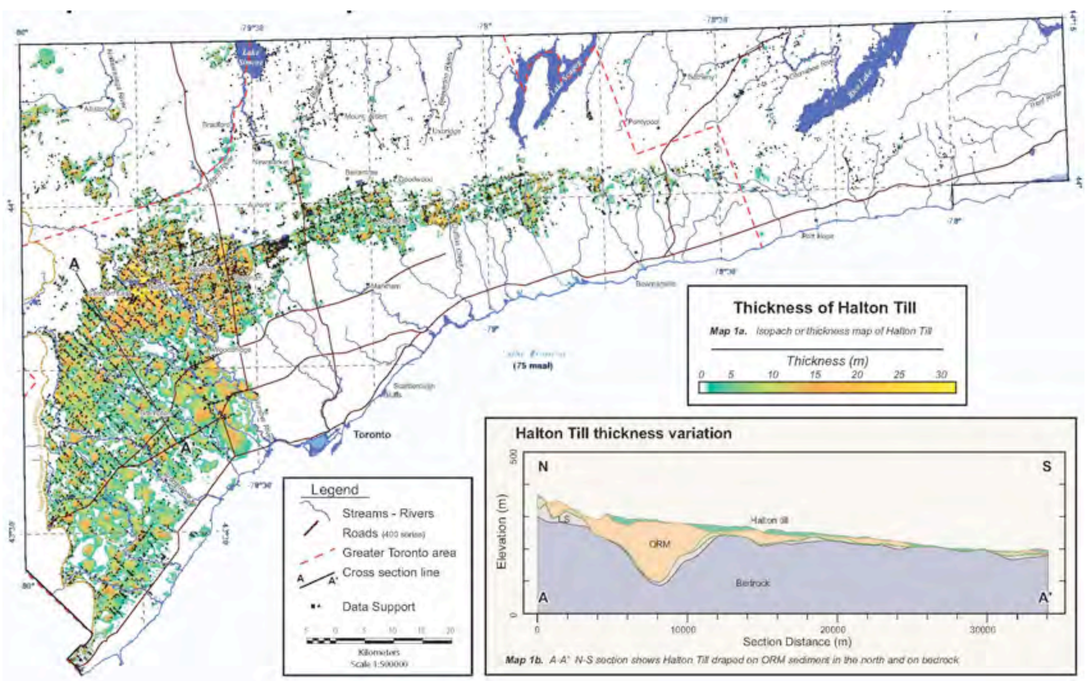


Figure 10. Sediment isopach map of the Halton Till. Note dramatic increase in thickness and extent westward; from Russell et al., 2005.

7. Glacial-lacustrine sediment: The youngest glacial sediment in the area consists of thin (~0-10m), mud and sand deposits that occur both north and south of the ORM. They are most extensive in the west and have been commonly interpreted as deposits of ice-supported and isostatic post-glacial lakes (Lake Algonquin, Lake Iroquois).

4. BURIED VALLEYS

4.1. Buried valleys across Canada

Buried valley aquifers are key hydrogeological targets in glaciated terrain (e.g., Ritzi et al., 1994; van der Kamp, 1986). However, recent reviews reveal a sketchy knowledge of their occurrence and the scale, style, and hydrogeological behaviour of this aquifer type across Canada (Russell et al., 2004) and in Ontario (Russell et al., 2007). For purposes of a national summary, Russell et al. (2004) identified two key buried valleys types: i) sediment-bedrock interface valleys and ii) Quaternary sediment valleys. Buried valleys are mapped across the subsurface of the prairie region (Fig. 11), and where current knowledge is good in some areas, it allows for a comparison with the buried valleys being review on this trip in Ontario.

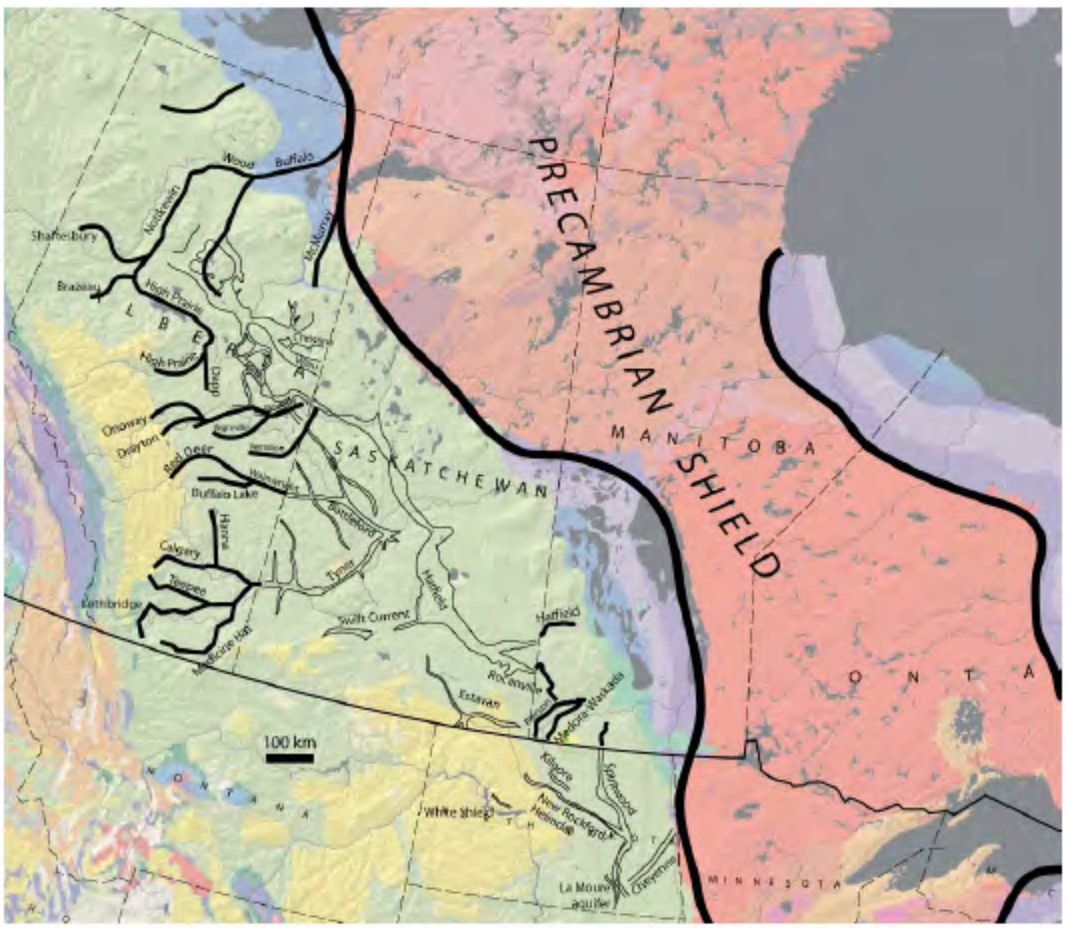


Figure 11. Bedrock buried valleys of the Canadian Prairies and North Dakota (Cummings et al., 2012). Solid lines are valley thalwegs; open polygons represent the entire valley. Red and pink colours demarcate the Precambrian Shield (igneous and metamorphic rocks), blue and purple show Paleozoic strata (most carbonate rocks), and green and yellow show Cretaceous and Tertiary strata (most shale and sandstone). Compiled from Whitaker and Christiansen (1972), Kehew and Boettger (1986), Maathuis and Thorleifson (2000), Andriashek et al. (2001), and Hinton et al. (2007).

4.2.1 Prairie buried valleys

Canadian prairie buried valleys have common elements regarding the geology of aquifer/ reservoir settings (Cummings et al., 2012) : i) they are difficult to map and new methods are needed, ii) variable fills, iii) thick mud covers, and iv) fine-grained bedrock floors (see Fig. 12). Many valleys are cut into soft, relatively impermeable Cretaceous-Tertiary shale, which is difficult to distinguish from overlying re-worked shale serving as a mud-rich cover rock.

Buried valleys and aquifers have been crudely mapped beneath the glaciated terrains of Canada and northern United States using sparse wells and outcrop data collected over 100 years (Cummings et al., 2012). Systematic mapping and resource evaluation of buried valleys is hindered by complicated network geometries, the lack of surface expression and longitudinal and cross-sectional variability. Airborne geophysics provides rapid, high-resolution data acquisition at regional scales not achievable by ground surveys alone (Jørgensen and Sandersen, 2009). Successful airborne electromagnetic (AEM) surveys have been recently completed for groundwater exploration in prairie regions due to the dependence of electrical conductivity on water content and lithology (e.g., Oldenborger et al., 2010; 2012). When tied to additional information such as high-quality boreholes, or ground geophysics, AEM surveys can be used to extrapolate knowledge to a regional scale, thereby capturing the complicated network of buried valleys as well as assessing conceptual geological models (Pugin et al., 2011).

Stratigraphic architecture can be complex and produce local hydraulic barriers (Shaver and Pusc, 1992). Fills can consist almost entirely of till (Hinton et al., 2007), mud (Huxel, 1961), sand and gravel (Huxel, 1961), or glacially-transported bedrock (Andriashek and Fenton, 1989). Most valleys have a gross fining upward succession from permeable gravel bodies along their base, to, mud-rich diamicton/ till in the upper fill (Fig. 12; e.g., Shaver and Pusc, 1992; Hinton et al., 2007). Mud-rich till, several tens of meters thick, tends to bury these valleys. Thin discontinuous sediment bodies (mud, sand or gravel) are intercalated within the till (e.g., Whitaker and Christiansen, 1972). This suggests an amalgamated till deposited over multiple events. Hence, many prairie buried valley aquifers can be bounded on all sides by low hydraulic conductivity strata (Maathuis and Thorleifson, 2000), with uncertain along-valley connectivity.

Non-glacial buried valleys are entrenched due to long-term tectonic uplift and tilting (see northeast trending valleys (Fig. 11) or incised in lowland settings close to sea-level (Posamentier, 2001). Valleys in glaciofluvial systems form by erosion related to increased water discharge (see northwest-trending valleys, Fig. 11). With ice marginal lake drainage, erosion is dominated by knickpoint erosion related to rapid, catastrophic lake drainage, as is the considered origin for southwest flowing prairie glacial valleys (Kehew and Lord, 1986). Glaciofluvial floods may also flow beyond channel banks as sheet flow events (Shoemaker, 1992) and escape to interfluve areas, thus they may not conform to the incised valley norm of floods remaining within channel banks.

4.3 Southern Ontario

Buried valleys in Southern Ontario occur in two distinct classes, bedrock interface and sediment hosted. Bedrock interface valleys can be grouped into key classes based on valley length and position in the landscape: i) escarpment troughs, and ii) escarpment re-entrants (Russell et al., 2007). Escarpment troughs such as the Laurentian Valley, parallel escarpments (Fig. 4b, c), whereas escarpment re-entrant valleys are perpendicular to escarpments (Fig. 4b). Both bedrock interface valleys have links with the inferred subglacial valleys of the area (Sharpe et al., 2005a). Sediment hosted valleys have been assigned to four classes in the Oak Ridges Moraine Area (Russell et al., 2005), as detailed in section 4.4. The complexity of buried-valley fill in southern Ontario is underestimated due to a lack of high-resolution (e.g., Pugin et al., 2011) ground-truth data and models for valley fills. Models need to consider erosional and depositional processes that were active, and have the potential for a multi-generational character in valleys fills. Most models of valley fills are based on a fluvial or proglacial glaciofluvial models (Ritzi et al., 1994; Meyer and Eyles, 2007) without adequate consideration of subglacial processes (e.g. Brennand et al., 2006; Russell et al., 2003). The lack of knowledge on buried valleys has resulted in the absence of a framework to: i) guide buried valley exploration, and ii), provide a framework for new data of the hydrogeological character of valley fills.

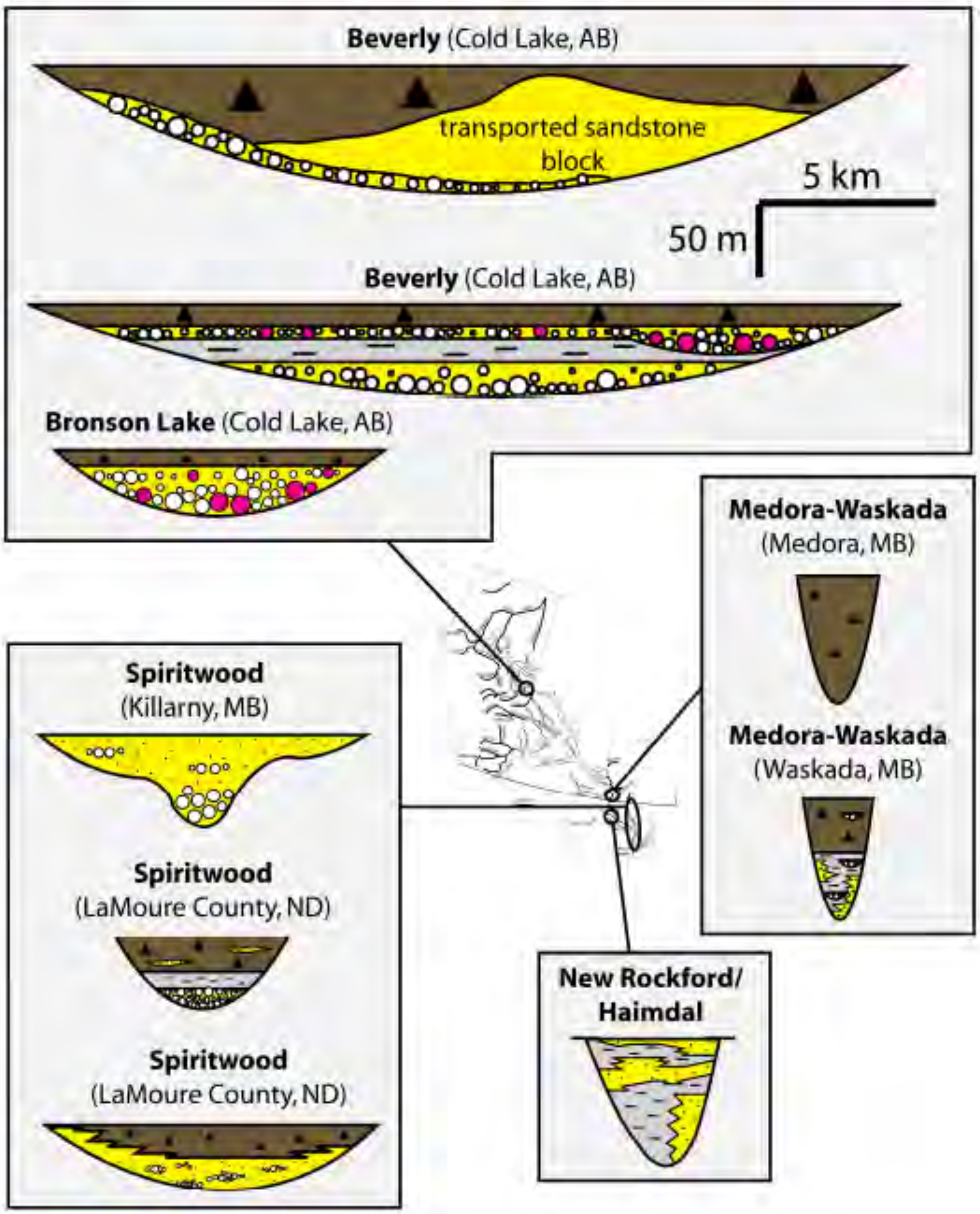


Figure 12. Simplified cross-sections of a Prairie buried-valley aquifers constrained by multiple wells and/ or seismic data. Note common presence of i) sand and/or gravel at valley base, ii) diamicton (till) in upper part of valley, and iii) a thick till cover. Pink clasts are Shield clasts; compiled by Cummings, 2010; 2012).

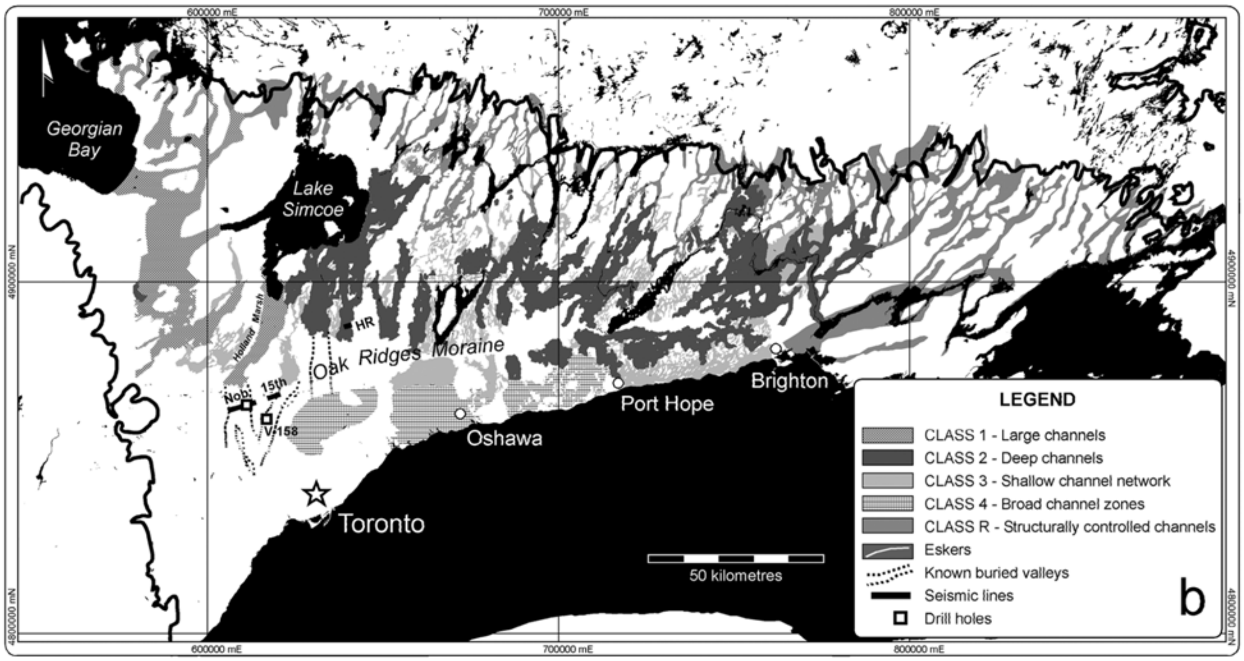


Figure 13. Tunnel channels in southern Ontario: dissected drumlinized terrain of central southern Ontario with the Oak Ridges Moraine and eskers for context. The map shows five tunnel channel classes, buried valleys, seismic lines and drill holes between the Precambrian–Palaeozoic boundary and the Niagara escarpment; from Brennand et al., 2006).

4.4 Tunnel channel character across southeastern Ontario

'Glacial' valleys in southern Ontario have a variety of forms across ~250 km of terrain, east of the Niagara Escarpment (Fig. 13). They can be assigned to five main classes based on their geomorphology, likelihood of breaching a regional till sheet, Newmarket Till), and probable depth of erosion (Fig. 13). Structurally controlled, mainly bedrock valleys (class R) are steep-sided and form an anabranching NE–SW-orientated system upflow (north and east) of sediment-walled valleys. Bedrock valley walls are ornamented by s-forms (Shaw, 1988). Sediment-walled valleys continue the anabranching network and dissect a drumlinized terrain (Fig. 14). The largest sediment-walled valleys (class 1) trend NE–SW, are up to 40 km long and <7km wide, have up to 50 m of topographic relief, and extend to bedrock at depths of >150m. Between these large valleys are two systems of smaller, shallower (<20km long, <2km wide, <100 m deep), nested valleys.

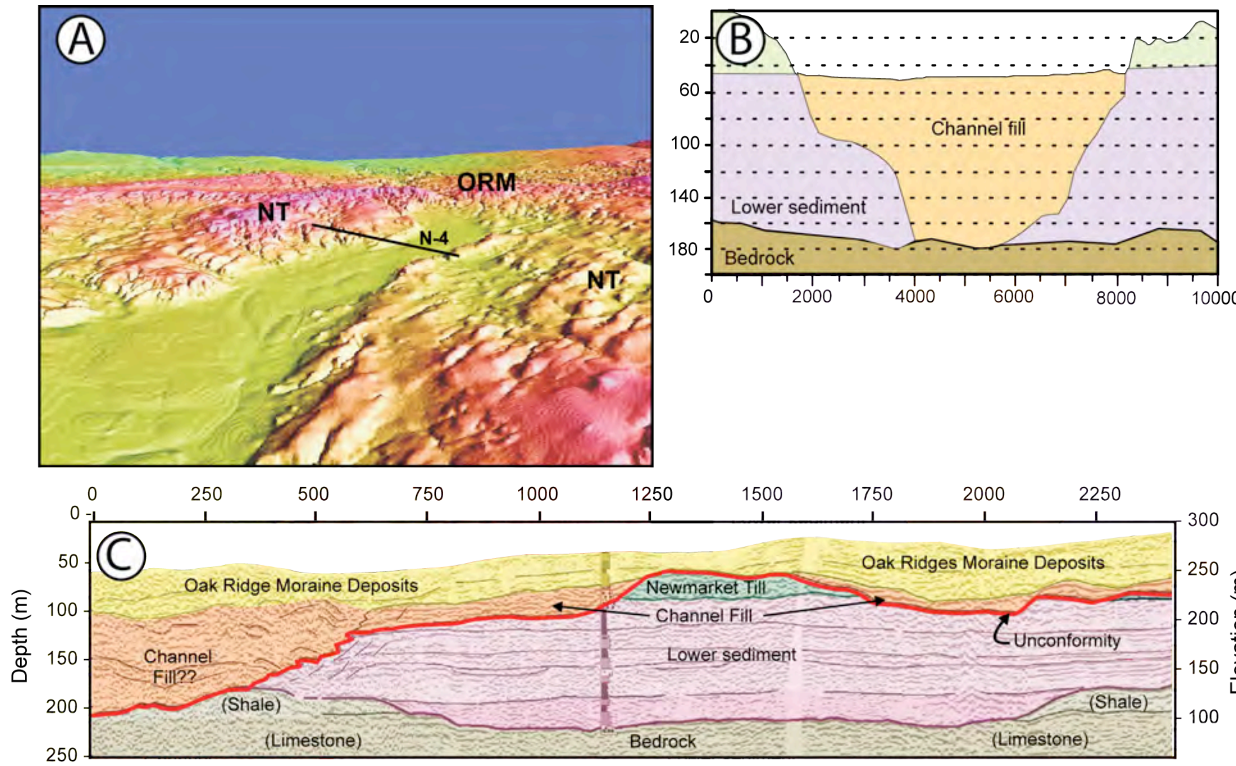


Figure 14. Class 1 tunnel channels: A) Perspective view hill-shade DEM of the Holland Marsh tunnel channel-see stop 1-2. The channel extends to the Oak Ridges Moraine in the background. Newmarket Till (NT) occurs along both sides of the channel. Colour ramp is high-red to green-low; B) Cross-section of the Holland Marsh channel and inferred subsurface stratigraphy; C) Seismic profile on the south flank of the ORM that images the subsurface southern extension of the Holland Marsh. Note stepped channel margin, 0.5 kms wide with ~40 m thick gravel unit on shoulder (west-pointing arrow). A cored borehole, Nobleton, is at eastern channel margin (see figure 18) (see Knight et al., 2008 for details).

Deep channels (class 2) completely dissect the regional Newmarket Till but are commonly floored by Lower sediment (Fig. 15), whereas shallow channels (class 3) have a regional till substrate. South of the Oak Ridges Moraine (Fig. 16), broad, shallow erosional corridors (class 4) extend into Lake Ontario (Fig. 13). Valley fills are up to ~150 m thick and include tunnel channel fills (20–60 m thick, e.g., Pugin et al., 2011), in places, overlain by ridge-building sediments of the Oak Ridges Moraine (<50 m thick), Halton Till (<30 m thick), deglacial lake sediments (<2m thick) and/or recent fluvial and wetland sediments (<2m thick). Tunnel channel fills often fine upward from gravel sheets, mesoforms (dunes) and eskers to beds of massive, graded and/or rippled sand to silt–clay rhythmites (e.g., Russell et al., 2002).

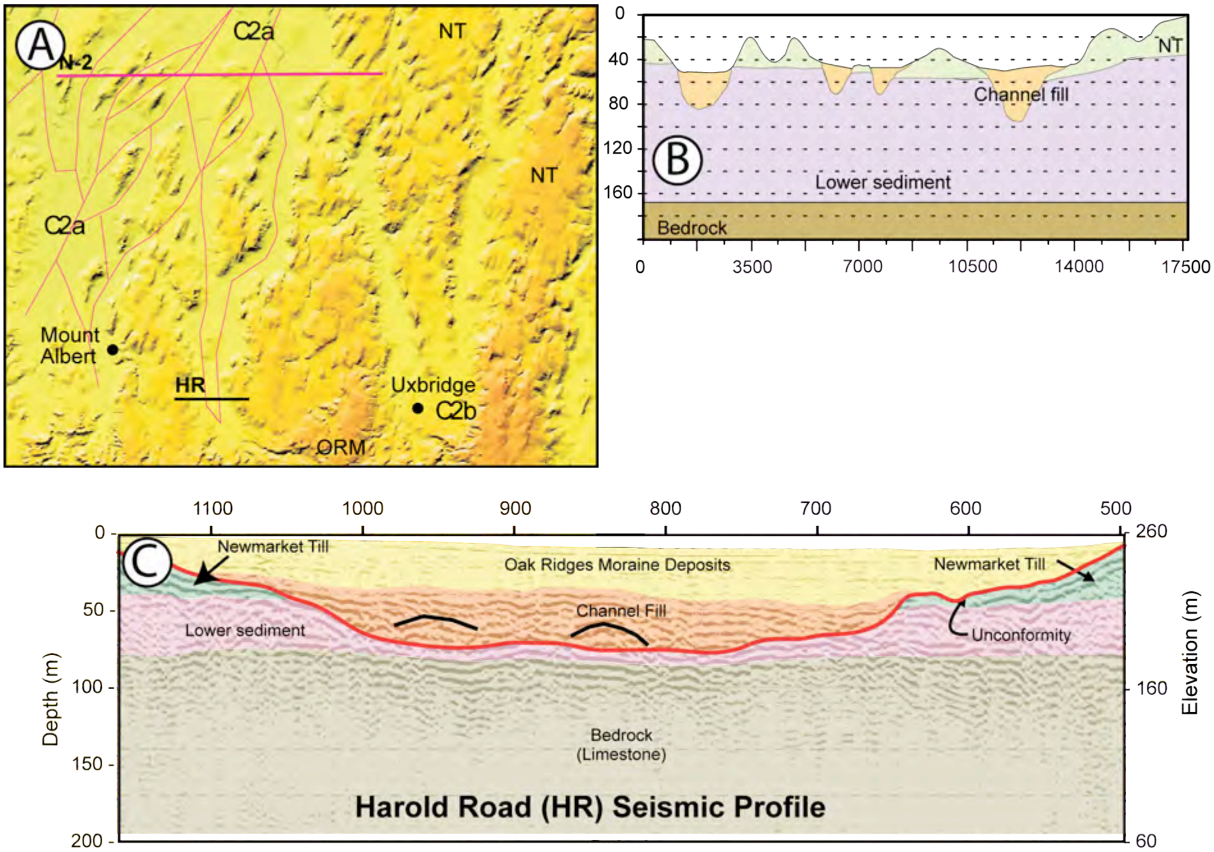
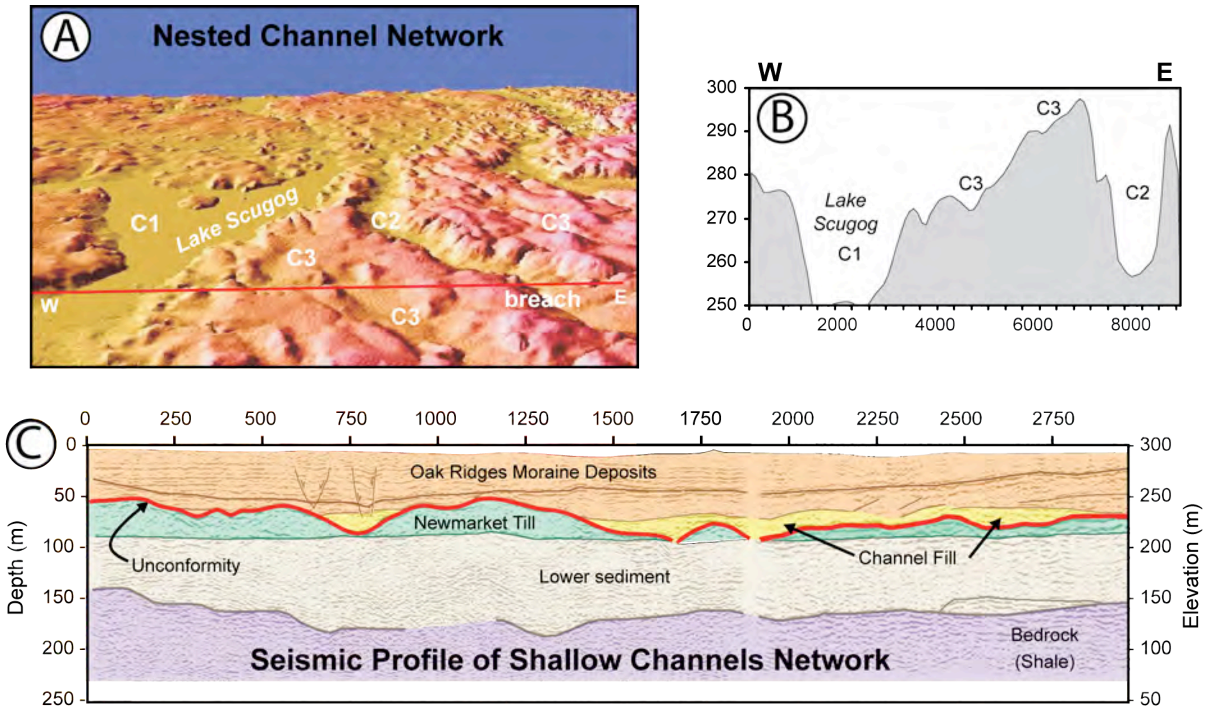


Figure 15. Class 2 channels: Hill-shade DEM of broad anabanching channels (C2a) and incised single channels (C2b). Lines highlight the channel pattern. Type C2a may evolve downflow into C2b. B) Cross-section and inferred subsurface stratigraphy of class 2 channel illustrating depth, relationship to Newmarket Till and incision into Lower sediment. C.) Seismic profile across a partially filled class 2 channel east of Mount Albert. Channel is floored by Lower sediment along the axis and Newmarket Till at the margins (50-150 m wide shoulder).

4.4.1 Tunnel channel origin

The tunnel channel system forms an integrated, anabranched valley network that was produced and/or re-occupied by turbulent, subglacial meltwater flow released during outburst floods (Shaw and Gilbert, 1991) as indicated by valleys: (i) are incised into regional last glacial, drumlinized till (Newmarket Till), are locally buried by Oak Ridges Moraine sediment and contain deglacial lake sediment; (ii) have undulating floors and upslope paths; (iii) locally contain eskers (iv) are filled by sediments indicative of rapid sedimentation (e.g., sandy hyper-concentrated flow deposits); (v) exhibit no evidence of convergent sediment deformation along their margins; (vi) are cut to elevations below Lake Ontario base level, and fail to terminate in deltas or fans at proglacial or modern shorelines; and, (vii) contain modern underfit streams up to an order of magnitude narrower than the valleys (e.g. Brennand and Shaw, 1994; Russell et al., 2003; Brennand et al., 2006).Stop 1.2 and 1.2a (Figs 1-2.3 and 1-2a.2)



4.

Figure 16. Class 3. channels: A) Perspective hillshaded DEM view of channels nested on Newmarket Till (NT) interfluves of class 1 and 2 channels. B) Topographic cross-section showing the hierarchal topographic relationship of class 1, 2, and 3 channels. C) Seismci profile across a buried Newmarket Till upland northeast of Nobleton; 15th ave profile (Pugin et al., 1999) –see figure 18. Note the shallow class 3 channels (highlighted in bright yellow) on the drumlinized Newmarket Till surface.

4.4.2 Tunnel channel evolution

Tunnel channels are interpreted to have evolved in response to the breakdown of sheet flow to progressively more channelized subglacial meltwater flow (Shoemaker, 1992). The spatial variation in valley character records the temporal evolution of a jökulhlaup (glacier flood) from a regional shallow channel network (class 3) to progressively fewer, larger channels (class 2 then 1), as flow concentrated and waned (Brennand et al., 2006). Bedrock channels (class R) were probably antecedent and re-utilized. Bedrock structure, ice-bed gap width (Brennand and Shaw, 1994) and enhanced scour at thread confluences and hydraulic jumps (Russell et al., 2003; Slattery et al., 2008) controlled tunnel channel development. Erosion of sediment-walled channels was probably enhanced by groundwater flow and piping at depth (through sandy beds of the lower sediment, Fig. 6b; Russell et al., 2003). Channel fills record rapid and voluminous sedimentation during waning jökulhlaup flow (both fluidal and hyper-concentrated) followed by subglacially-ponded sedimentation (e.g., Brennand and Shaw, 1994; Russell et al., 2003). This interpretation of central southern Ontario tunnel channels is consistent with the view that the subglacial land system (drumlins, valleys and bedrock s-forms) was eroded by a regional meltwater underburst—the Algonquin event—that unsteadily evolved from sheet to channelized flow (e.g., Shaw and Gilbert, 1990). As fan deposits are not observed at the southern ends of channels it is likely that channel formation was contemporaneous with an underburst event that eroded drumlins in Lake Ontario and swept away most sediment derived from channel erosion. Ice sheet thinning and flattening associated with underbursts facilitated deglaciation by regional downwasting and stagnation (Sharpe et al., 2004; Sharpe and Russell, 2013)

5. SUMMARY

Basin analysis studies are well developed in bedrock sedimentary basins and the petroleum industry. Such multi-disciplinary studies, with a focus on understanding the geological history of a basin as a predictive tool, are less commonly applied in groundwater studies. Regional hydrogeology studies in North America, prior ~1970, were succeeded in the last 40 years by an emphasis on contaminant hydrogeology. The contaminant focus resulted in a change to engineering style investigations. The value and necessity of geological understanding was considered secondary. The Oak Ridges Moraine hydrogeology study was one of the first regional studies in Canada to initiate a basin analysis approach with new high-resolution data collection in the mid1990s.

The Oak Ridges Moraine studies integrated terrain analysis with sediment-land mapping to refine regional geological models that could be tested by strategic subsurface data collection including; reflection seismic profiles, downhole geophysics, and continuous cores. The current geological framework is a testament to this approach as it has demonstrated the importance of a robust 3D geological model as a working hypothesis to guide data collection. Prior to this study 30 years of geological mapping had failed to identify the significance of large valleys north of the ORM. Recognition of the significance of these valleys required a new glacial meltwater paradigm and a field program to test the hypothesis (Shaw and Gilbert, 1990; Barnett 1990; Brennand and Shaw, 1994; Sharpe et al., 2002).

Regional hydrogeological studies have similar objectives to exploration scale petroleum studies: identification of reservoir location, setting, scale and spatial heterogeneity, e.g., the play concept (Russell et al., 2011). Hence, the results of the ORM study provide a good analogue for reservoirs in older glaciogenic successions. The ORM fieldtrip stops can be framed within the context of reservoir and non-reservoir sediment of channel and channel interfluves as studied using reflection seismic and continuous core (Figs. 17, 18).

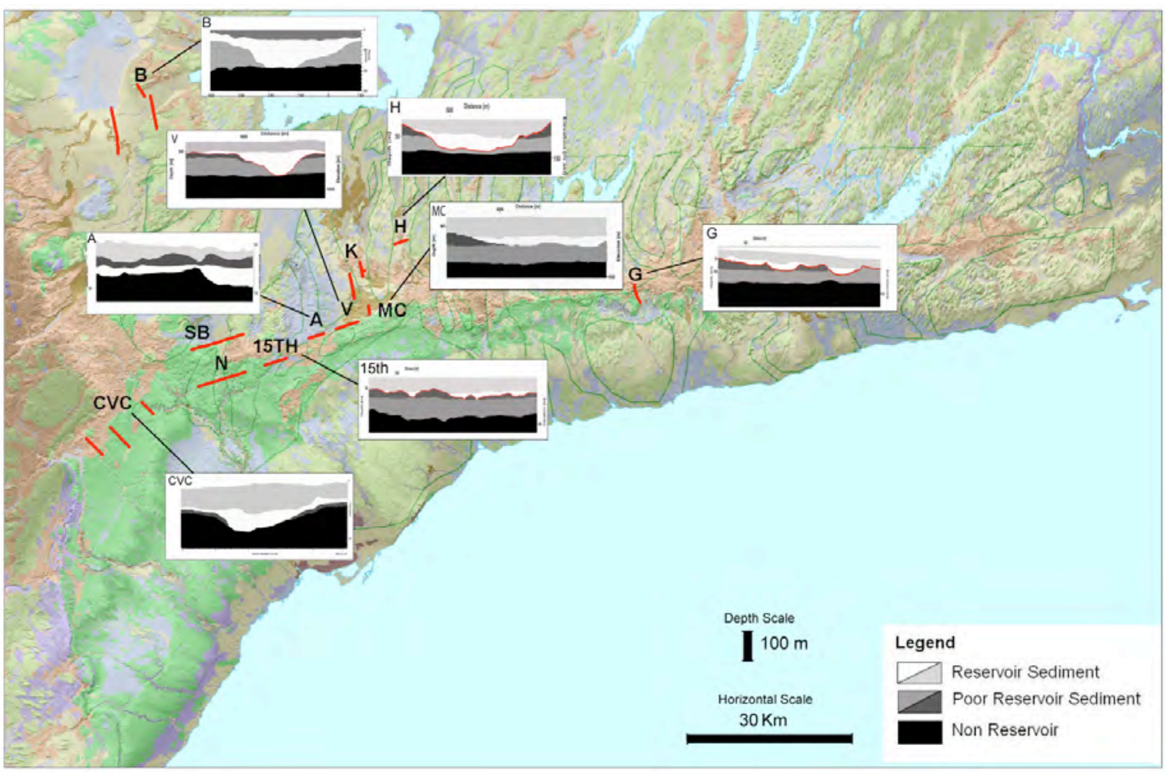


Figure 17. Reservoir sediment in a selection of youngest tunnel channels from ORM region. Note profiles are oriented as cross-sections across channels except profile G, which is oriented parallel to regional ~N-S channel orientation. The Aurora profile (A) will be highlighted as stop 1.2a (Sharpe et al., 2013b)

Reservoirs in core

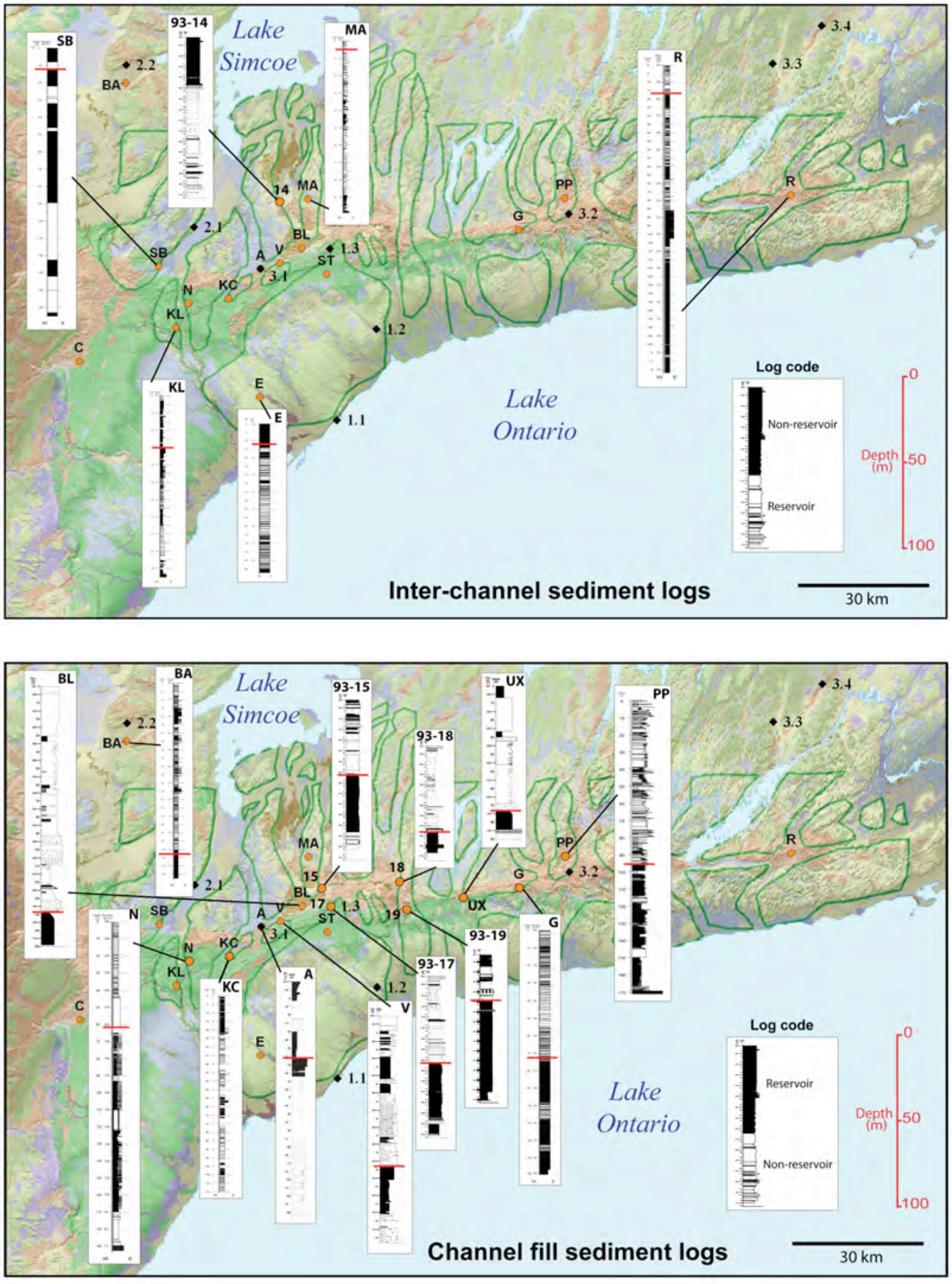


Figure 18. Reservoir successions based on continuous cores in the ORM region. Note: A) Inter-channel regions, B) ORM channels. Red line indicates regional unconformity. There are both older channel and inter-channel sediment below the regional unconformity (Sharpe et al., 2013b).

STOP 1-1 SCARBOROUGH BLUFFS

Sharpe, D.R. and Russell, H.AJ .. Geological Survey of Canada

Markham NTS 30M/14, 647650E 4840463N

Access: Bluffers Park.

Objective

1. Pre-last glacial stratigraphy beneath the last glacial maximum, Newmarket Till
2. Channels within Scarborough Formation and Lower sediment tabular strata.

Scarborough Bluffs

The well-known Scarborough Bluffs afford an opportunity to examine the stratigrahic architecture and sediment facies of widespread strata that are generally not exposed across the region. Excellent exposures occur along the Lake Ontario bluffs as well as in river valleys, and the Don Valley brickyards close to the lakeshore. Elsewhere, data on the lower sediment aquifer is derived from drilling and reflection seismic surveys. In the regional geological model the Lower sediment unit consists of all sediment older than Newmarket Till (Fig. 6). The two principal units with reservoir potential across the region, Scarborough and Thorncliffe formations, are well exposed at the Scarborough Bluffs.

Scarborough Bluffs consist of an extensive (>10km long) tabular stratigraphic architecture. Scarborough mud crops out at lake level (74 m asl) and is overlain by Scarborough sand. The contact between these two strata can be identified on the basis of moisture content and vegetation. This succession is overlain by the relatively thin, muddy Sunnybrook Till. Locally the tabular Scarborough strata are truncated by mud and Sunnybrook Till-filled channels (> 30 m deep) that extend below the level of Lake Ontario. Stratigraphically upward are Thorncliffe sand and mud. Stony sandy silt of the Newmarket Till forms the top of the succession beneath a thin cover of post-glacial lacustrine sand. Newmarket Till can be traced from drumlinized uplands north of the ORM, south to the till plain at stop 1-5, and then to Scarborough Bluffs (Fig. 1-1.1). Here, Newmarket Till feathers out against a thicker package of lower sediments forming the highest bluffs at Cathedral Bluffs (Fig. 1-1.2). Several regional unconformities are present at the bluffs, the most prominent being the high-stand, post-glacial lake level truncation associated with Lake Iroquois (Fig. 1-1.2). Several stratigraphic units observed at the bluffs can be traced northward ~75km to the Barrie area (Stop 1.5a).

(Fig. 1-1.1) Perspective elevation view of Scarborough Bluffs showing streamlined surface of Newmarket Till. Stop 1.1 is located where pier juts into Lake Ontario Bar is about 3 km.

Two specific points relate to channels at the Scarborough Bluffs. First, channels within the Bluffs occur beneath Newmarket Tilll and are older than channels exposed at surface to the north (Map 2; 1-1.1). These older channels indicate that multiple channel cutting events have occurred and should be considered when making stratigraphic interpretations of channel sediment across the area (see stop 1-2). Second, no deep channels are cut into the Newmarket Till at the lake bluffs similar to the 50-100 m depths found north of ORM (Map 2). The network of young tunnel channels cut into Newmarket Till appear to have changed to a broader and shallower form south of the ORM (Sharpe and Barnett, 1997; Map 2), as can be observed on the DEM of the area **(**Map 2).

To the east, a measured section reveals, Thorncliffe channel gravel fining up to sand, silt and clay, transitional to overlying Newmarket Till. This sequence is analogous to the lower sediments below Newmarket Till as exposed at stop 1-5. This planar contact relationship at the base of Newmarket Till is widespread (Pugin et al., 1999) and allows regional correlation of Newmarket Till, lower sediments, and a reliable means of separating 'younger' from 'older' channel systems.

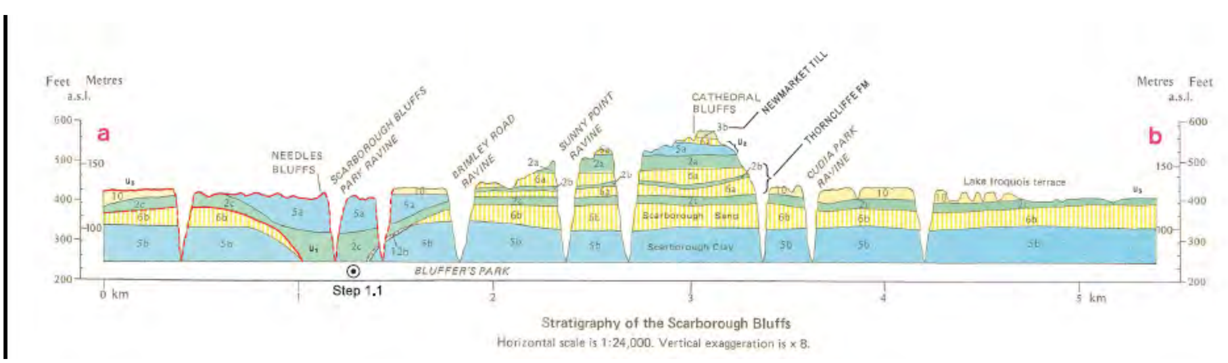


Fig. 1-1.2 Measured section of Scarborough bluffs west, near Bluffer's park (from Karrow, 1967).

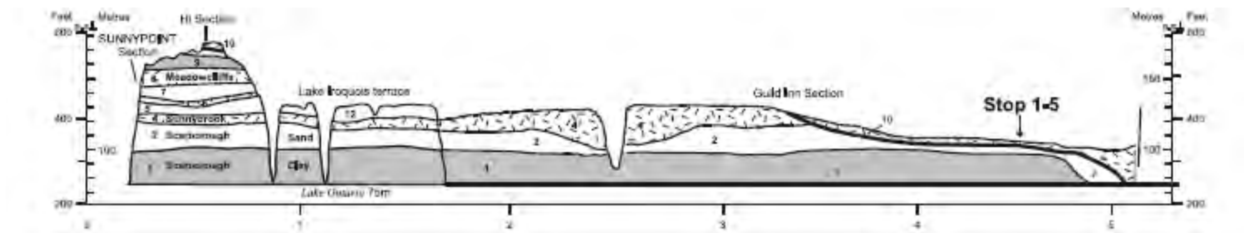


Fig. 1-1.3 Measured section of Scarborough bluffs east of Hi section at Cathedral Bluffs to stop 1.5 (Sharpe and Barnett, 1998).

5.1. Lower sediment aquifers

The thick sand and clay of the lower sediment indicate the complex aquifer-aquitard conditions that may occur beneath Newmarket Till (Fig. 6). Regionally, lower sediment aquifers are primary sources of groundwater. These aquifers can be very productive with some municipal wells capable of producing up to 6500 m^3/d (1000 Igpm). Near Lake Ontario, and in several areas south of the Moraine, the lower sediments consist of two main aquifers (Thorncliffe and Scarborough Formations) separated by Sunnybrook Till and Thorncliffe Formation muds. To the north, lower sediment aquifers may be hydraulically connected (Sibul et al., 1977), where thicker bodies of fan sediments (gravel, sand and silt) occur. At GSC Aurora borehole, stop 1-2a (Fig. 1-2a.3), Thorncliffe lower sediment consists of 75 m of sand and gravel above bedrock (Sharpe et al., 2011).

The source areas for groundwater flow in lower sediment aquifers, is a combination of recharge from the ORM and some leakage though surface Halton and Newmarket Tills (confining unit). Eyles and Howard (1988) measured modest flow in the sand aquifers to the west of this stop and attributed most of the flow to local recharge based on the chemical signature of local contaminants (road salt) in the flow system. Groundwater modeling (Smart, 1994; Gerber et al., 2004) suggests that nearly half of the recharge (~170 mm/year) to the lower aquifers originates from the ORM. Some estimate a watershed underflow component (not measured by stream gauging) from the ORM to regional groundwater flow of ~80 mm / year, some of which may be flowing through the coarser lower aquifer sediments such as those found in lower sediment channel structures to the east of this stop (Fig. 6).

STOP 1-2. HOLLAND MARSH: TUNNEL CHANNEL.

Sharpe, D.R. and Pugin. A. Geological Survey of Canada

UTM: 612281E 4880416N; NAD 83, zone 18.

Access: via Highway 89 and county roads..

OBJECTIVE

1. Recognition of tunnel channel in modern topographic surface
2. Channel network and regional landscape
3. Channel stratigraphy and setting with reflection seismic profiles

REGIONAL CONTEXT

The Holland Marsh is one of the larger valleys set within the network of valleys portrayed on Figure 6. It cuts across a regional drumlin field (see stop 1-3) but other landform relationships indicate it may have been occupied during several events (Fig. 1-2.1). It is one of a few valleys that are in alignment with re-entrant valleys in the Niagara Escarpment (Figs.4a and 6). Is up to 5km wide, extends >50km southwest to the Niagara Escarpment and is likely 100 m deep (Fig. 1-2.1).

Holland Marsh Valley

The view southeast across the deep SW-trending channel of the Holland Marsh shows the same upland surface on the south side of the channel as the one we are standing on. The channel cuts this drumlinized Newmarket Till upland as part of a regional unconformity (Fig. 6). Higher, hummocky terrain of the ORM is present in the distance. About 100 m below the Holland Marsh lies a broad bedrock low, the Laurentian valley (Fig. 1-2.2). The valley may be filled with glaciofluvial, glaciolacustrine, and organic sediments.

The broad valley fill comprises four main untis (Fig.1-2.3) including lower sediment (B1, B2), Newmartket Till (C), and an upper valley fill (D). The Holland Marsh valley fill (D) reveals reflector units of probable gravel, sand and silt across the central part of a channel. Newmarket Till is eroded and sands and gravel are observed in a few deep wells above bedrock.

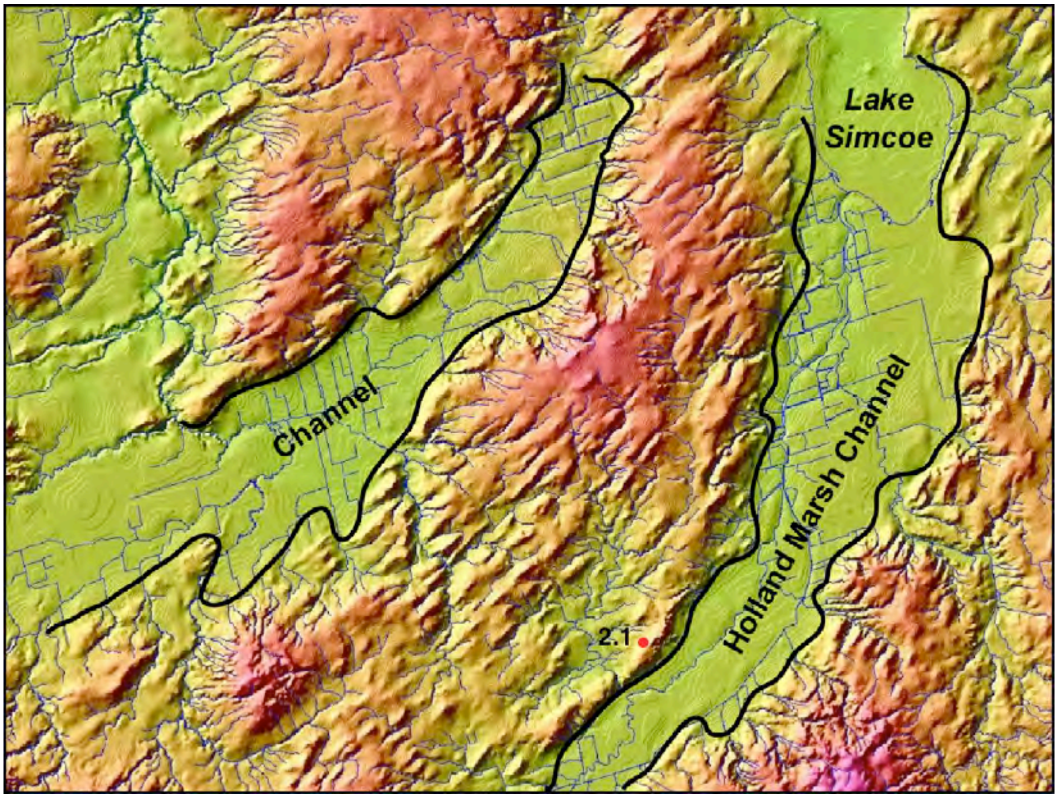


Figure 1-2.1 Digital elevation model of drumlinized terrain dissected by large channels running southwest from Lake Simcoe (see Figure 6 for channel network context). Note: East bank of the Holland Marsh channel shows truncation of the drumlin upland; while, the west bank shows drumlinization which indicates that the channel pre-existed the drumlin-forming event or that channel and drumlin formation are closely related. Stop 1-2 occurs at the red dot (2.1) on the West side of Holland Marsh Channel.

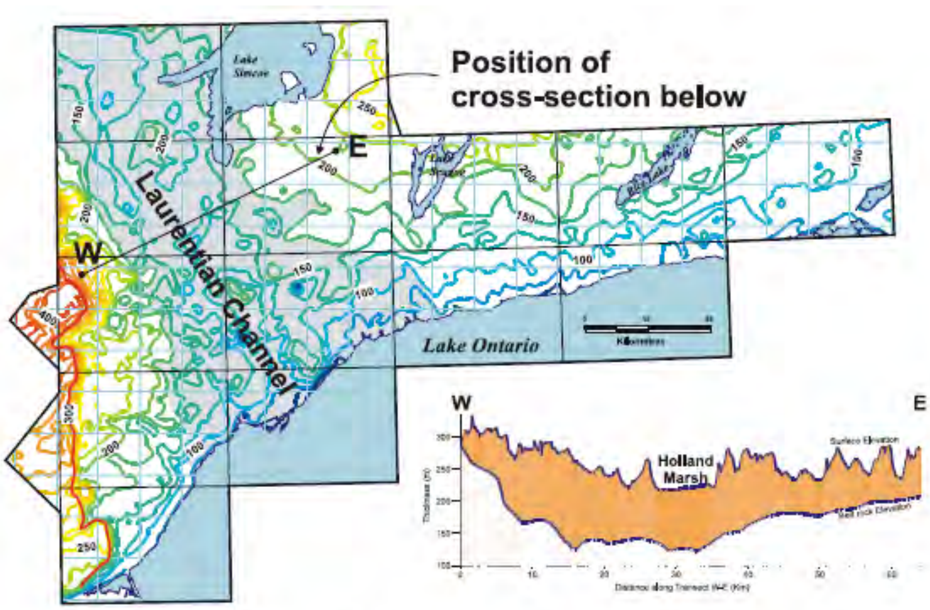


Figure 12. Bedrock topography around Holland Marsh site shows that it overlies a large bedrock valley, the Laurentian Channel. Depth scale is metres above sea level.

Figure 1-2.2 Contoured bedrock elevation depiction of Laurentian valley below the Niagara Escarpment (see figure 5b for comparison. Holland Marsh valley is inset for comparison.

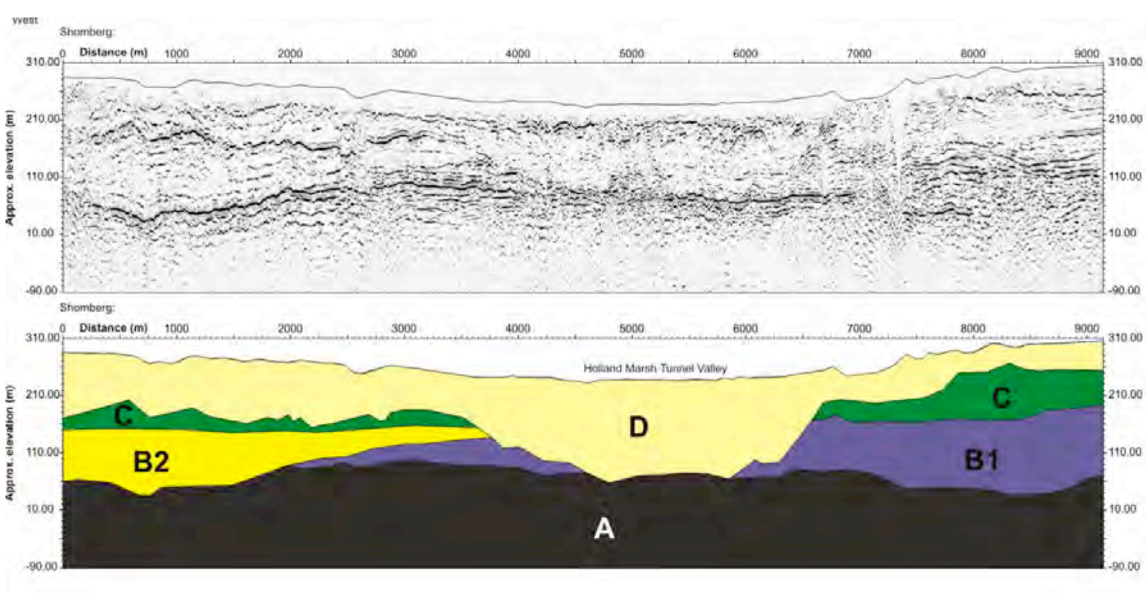
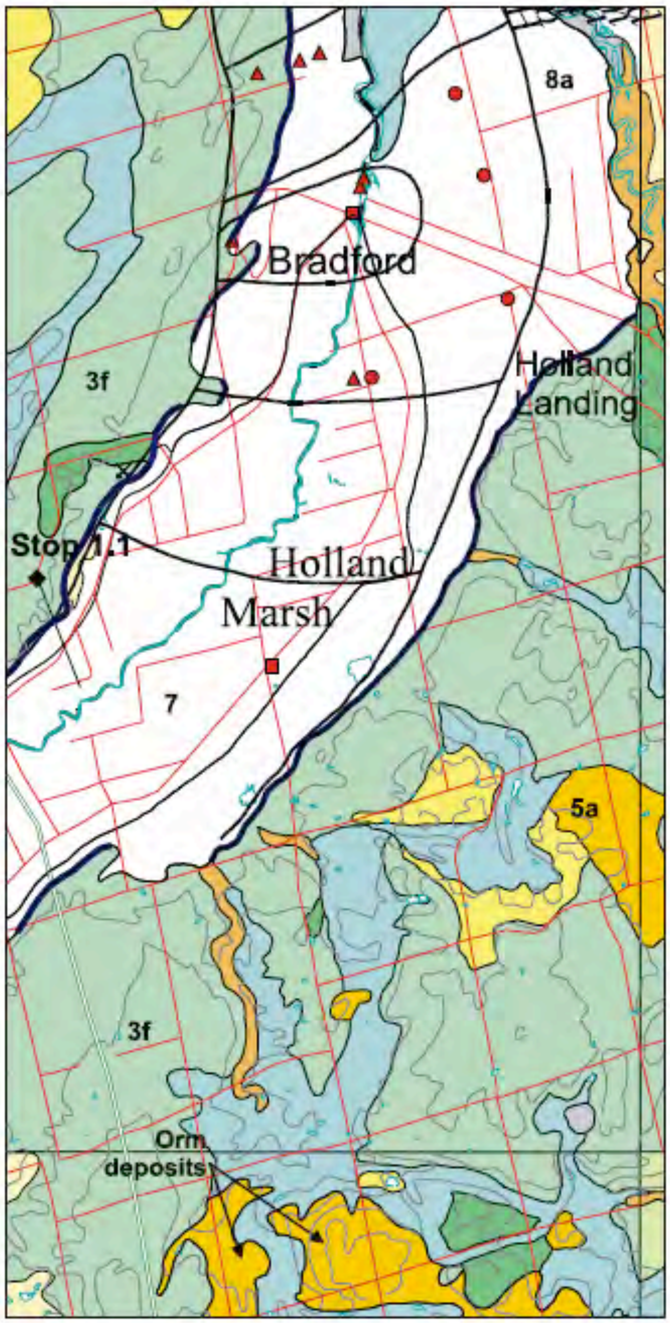


Figure 1-2.3. Reflection seismic profile of the Holland Marsh valley, southwest of stop 2.1, near Schomberg. The profile displays the subsurface expression of Holland Marsh (D), southwest of terrain with strong surface expression. There is an older valley (B2) below Newmarket Till (C) that has aquifer/ reservoir sediments that eroded older lower sediment (B1) and underlying Whitby Shale bedrock (A).

Aquifer extent and reservoir testing

In addition to the seismic-stratigraphic data, a three-month pump test was run at the north end of Holland Marsh (Jagger-Hims, 1996). It reveals a response-zone that sits beneath a portion of the north end of the Holland Marsh (Fig. 2-1.4). This long-duration pump test was conducted for two municipal wells to the southwest of Bradford and to identify potential interference from an increased pumping rate. The pumping wells are screened within a gravel zone > 10 m thick in the central portion of the confined Bradford aquifer at a depth of 90 m (130 m asl) likely within the Holland Marsh valley/ channel (Fig. 2-1.3). Area well logs suggested that the Bradford aquifer extends at least 10 km in a north-south direction and 4 km in width (Fig. 2-1.4). The pump test results confirmed the hydraulic connection over the entire north-south extend of the aquifer.



Lower Sediment

Borehole geophysical logs (gamma, conductivity, magnetic susceptibility and seismic velocity), reveal lower sediment from Holt, 10 km to the east, within a sediment log for borehole OGS 93-14 (See Fig.1-4.4). Note high seismic velocity (2500-3000 m/s) for dense Newmarket Till (diamicton). Lower sediments below Newmarket Till show as a fining upward trend from gravelly sand to silty sand. Compare the Holt sediment log with the Schomberg sediment log from the Holland Marsh (Fig. 18).

Figure1-2.4 Reservoir testing: Lines of equal drawdown form 3 month pumping-test results based on monitors (circles) and test wells (triangles and squares) defining a deep (~100 m) aquifer/ reservoir oriented parallel to the Holland Marsh channel (after Jagger-Hims, 1996)

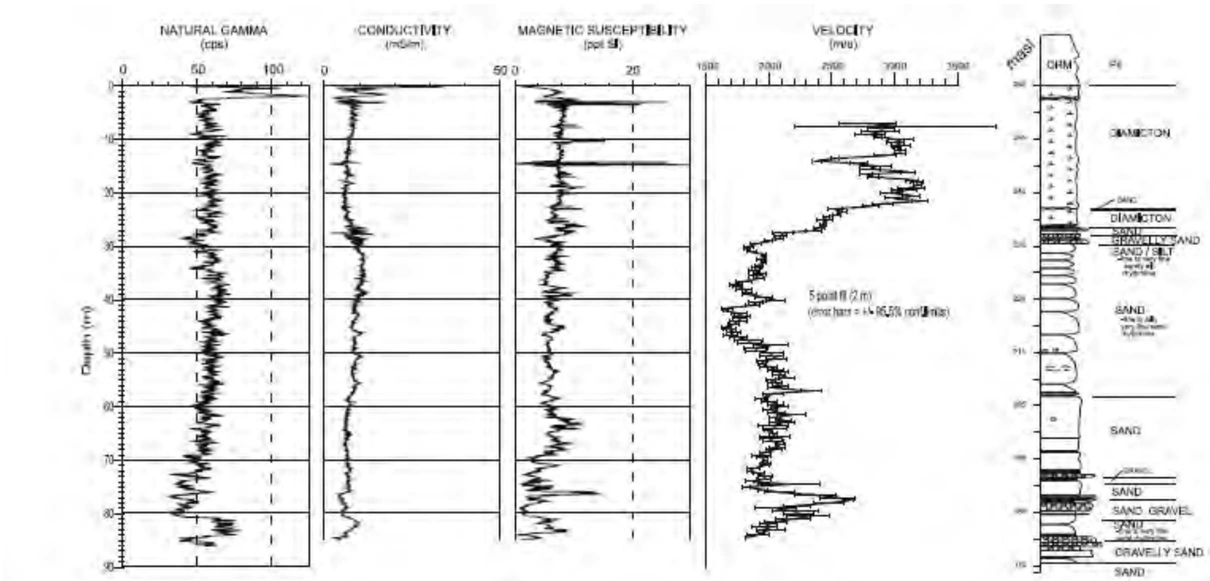


Figure 1-2.5. Borehole geophysical logs from Holt (gamma, conductivity, magnetic susceptibility and seismic velocity), 10 km to the east, and sediment log for borehole OGS 93-14. Note high seismic velocity (2500-3000 m/s) for dense Newmarket Till (diamicton, right hand log). Lower sediments below Newmarket Till show as a fining upward trend from gravelly sand to silty sand. Compare the Holt lower sediment log with the log from Schomberg (Fig. 18a.)

STOP 1-2A AURORA BURIED CHANNELS

(Optional)

Sharpe, D.R. and Russell, H.A.J. Geological Survey of Canada

UTM: 626138E 4871863N; NAD 83, zone 18.

Access: via Vandorf Sideroad west from Leslie. (Reference; Sharpe et al 2011)

Objective

1. Review the high-quality dataset that identifies nested buried tunnel channels

2. Sediment facies of Thorncliffe Formation channel sediments

Regional Context

The Aurora buried channel site (stop 1-2a) is situated ~267 m asl within the Holland watershed, a clayey glacial lake (Aurora) basin set in the ORM (Fig. 1-2a.1). The site lies on the northwest edge of hummocky, sandy ORM, Bloomington fan sediments (Stop 1-4; Fig.1-4.2; Barnett et al., 1998), partly overlain by Halton Till (Sharpe and Barnett, 1997). The Aurora basin appears to be one of a series of valleys oriented N-S and leading south towards ORM (Map 2; Fig. 1-2a.1), that are inferred to be tunnel channels (e.g. Russell et al, 2003).

The Aurora cored borehole and seismic data intersects Yonge Street aquifer (YSA), a significant aquifer within the Thorncliffe Formation (Sharpe et al, 2011), traced from stops 1-1 (Scarborough Bluffs) and 1-5. The cored borehole provides ground-truth for a 7-km long east-west seismic profile, thus providing high-quality data to interpret large tunnel channel setting observed on DEMs north of the ORM (Map 2).

Stop 1-2a occurs towards the eastern end of an E-W- oriented Aurora seismic line that is ~7 km in length and crosses the trend of the Aurora basin and probable N-S tunnel channel (Fig. 1-2.1). The seismic data provide laterally continuous stratigraphic architecture in sediments overlying bedrock (Fig. 1-2.2). Though the bedrock surface elevation varies from ~110-130 m asl along the Aurora profile, a gently-dipping bedrock slope ~4 km west of stop 1-2a may form the shallow eastern edge of a wide Laurentian valley system (Fig.4d; Brennand et al., 1998).

The Aurora GS borehole and related seismic profiles record 6 main stratigraphic packages described from the base upwards (Fig. 1-2a.3): 1) Whitby Formation shale ~127 m asl; 2) Older sediment not in borehole due to being truncated by a channel; 3)Thorncliffe Formation sand and gravel; 4) Newmarket Till (209-219 m asl); 5) a silt-clay rhythmite sequence (219-235 m asl); a base of channel unconformity (~235 m asl); and, 6) a fining-upward ORM channel fill sequence (235-267 m asl). The 80 m thick aquifer sequence (identified as Thorncliffe Formation) appears to represent a NE-SW-oriented channel, esker, subaqueous fan system that fed Thorncliffe Formation aquifer sediments to the south (Sharpe et al, 2011).

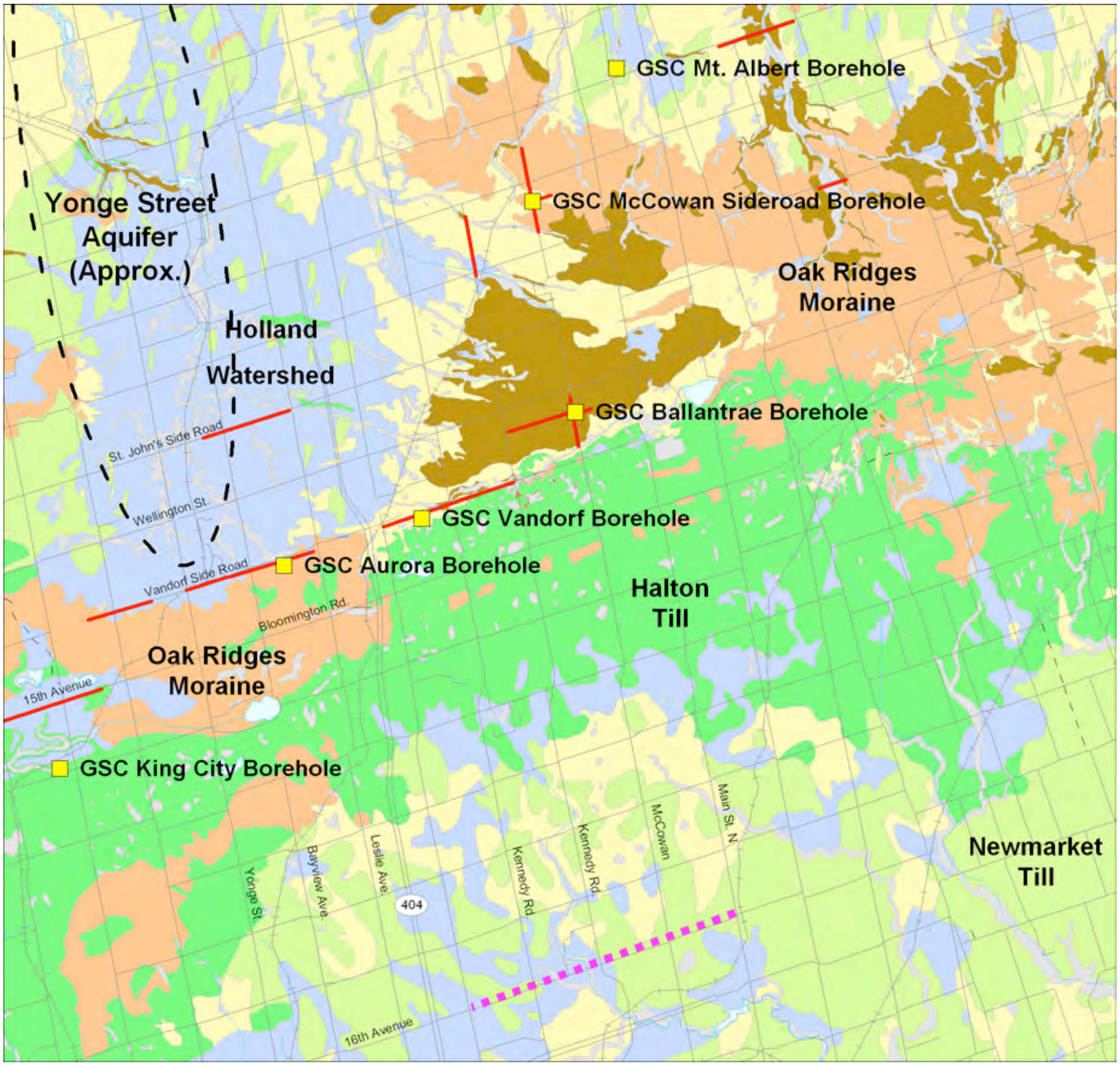


Figure 1-2a.1. Geological context for Stop 1-2a at site of GSC Aurora Borehole. Map of Aurora region shows surface geology, location of seismic profiles and related cored boreholes. Dashed line along 16th avenue shows location of figure 1-5.3 borehole section at stop 1-5 (Fig 1-5.3). See Figure 6 for stratigraphic order.

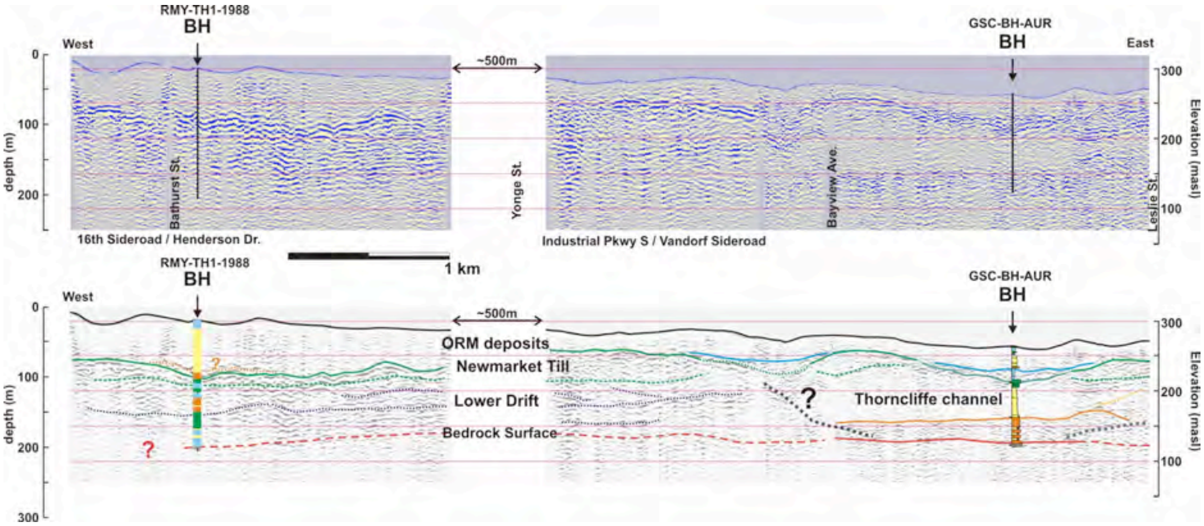


Figure 1-2a.2. Seismic section obtained along a 7-km long east-west line intersecting the location of the Aurora borehole (location Fig. 1-2a.1). The velocities determined from the surface seismic data and from downhole seismic logs in AGS have been used to convert the profile to an elevation section. At this scale, the large architectural structure is evident (main labels), and outlines a channel within the lower sediment (drift) sequence which is interpreted to be infilled with thick Thorncliffe Formation sands (upper unit) and gravels (lower unit). Note additional deep borehole control on the west end of the profile (RMY-TH1-1988).From Sharpe et al 2011; Pugin et al, 2011.

Summary

A Thorncliffe regional aquifer occurs below ~209 m asl as an 80 m thick, fining-upward, sand and gravel sequence. It appears to represent a NE-SW-oriented channel, esker, subaqueous fan system that fed Thorncliffe Formation aquifer sediments to the south (Sharpe et al, 2011). A 25m thick Newmarket Till and silt-clay rhythmite sequence confines the aquifer. This aquitard drapes into Aurora basin, a likely pre-existing sediment valley. High clay content in aquitard rhythmites may allow conductivity logs to map it as a marker horizon. The overlying ORM aquifer occurs as a 30 m deep gravel-sand-mud sequence above a regional unconformity. This channel fill sequence is thinner than nearby 100 m thick ORM channel sediments (see Fig 1-4.4). Whitby shale dips gently beneath the aquifers with no defined valleys.

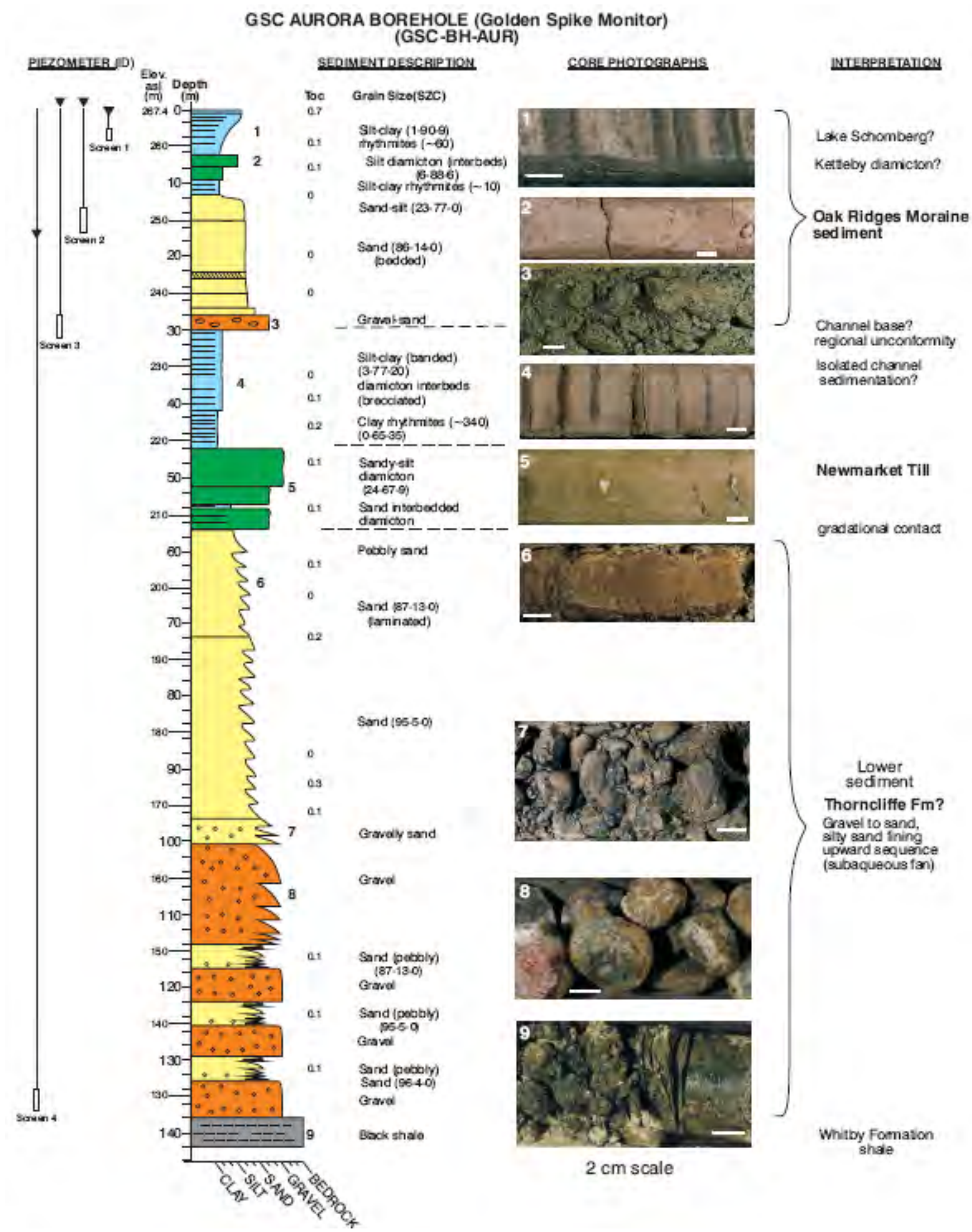


Figure 1-2a.3. Sediment log of core at Aurora borehole shows major sediment units, descriptions with rhythmite counts, TOC, grain size, photographs of prominent sediment facies in the core, and stratigraphic interpretation. Note also, four pizeometer positions for reservoir performance monitoring (From Sharpe et al, 2011).

STOP 1-3 PETERBOROUGH DRUMLIN FIELD.

Sharpe, D.R. Geological Survey of Canada

UTM: 718402E; 4908717N; NAD 83, zone 18.

Access: via highway 7.

OBJECTIVES

1. Observe a drumlinized landscape
2. Review why drumlins are part of a regional unconformity

Regional context:

Stop 1-3 is located within a large drumlin located just south of the Canadian Shield and within a carbonate sedimentary basin (Figs, 1a, 5d). The drumlin field sits on an inter-valley/channel upland, a streamlined landscape within the south-eastern Ontario tunnel channel network **(**Fig.13)**.** The drumlin field represents a regional event that is eroded and dissected by this channel network. Many channel features within the network have eskers within their valley walls (e.g. Shaw and Sharpe, 1986; Brennand and Shaw, 1996; stop 2-2) and thus are interpreted as tunnel channels (Brennand et al., 2004). Shaw (1983) interpreted this landform assemblage as the product of sheet floods, cross-cut by waning chanellized flow and return to episodic seasonal esker meltwater flow to explain similar terrain in northern Saskatchewan.

Such landscapes are also explained by the following main competing hypotheses: i) erosion during ice sheet instability and surging (Shoemaker, 1992); ii) erosion and deposition by subglacial deformation processes (Boyce and Eyles, 1991, 2000); and iii) channel erosion and fill by jökulhlaups and drumlin field formation by subglacial deformation (Mullins et al. 1996), sheet flood erosion of the drumlin field (Shaw and Sharpe, 1987).

Many researchers, including those summarized above, interpret the Peterborough drumlin field as being erosional, although other drumlins fields are interpreted as ice-marginal depositional landforms (e.g. Dyke, 2004).

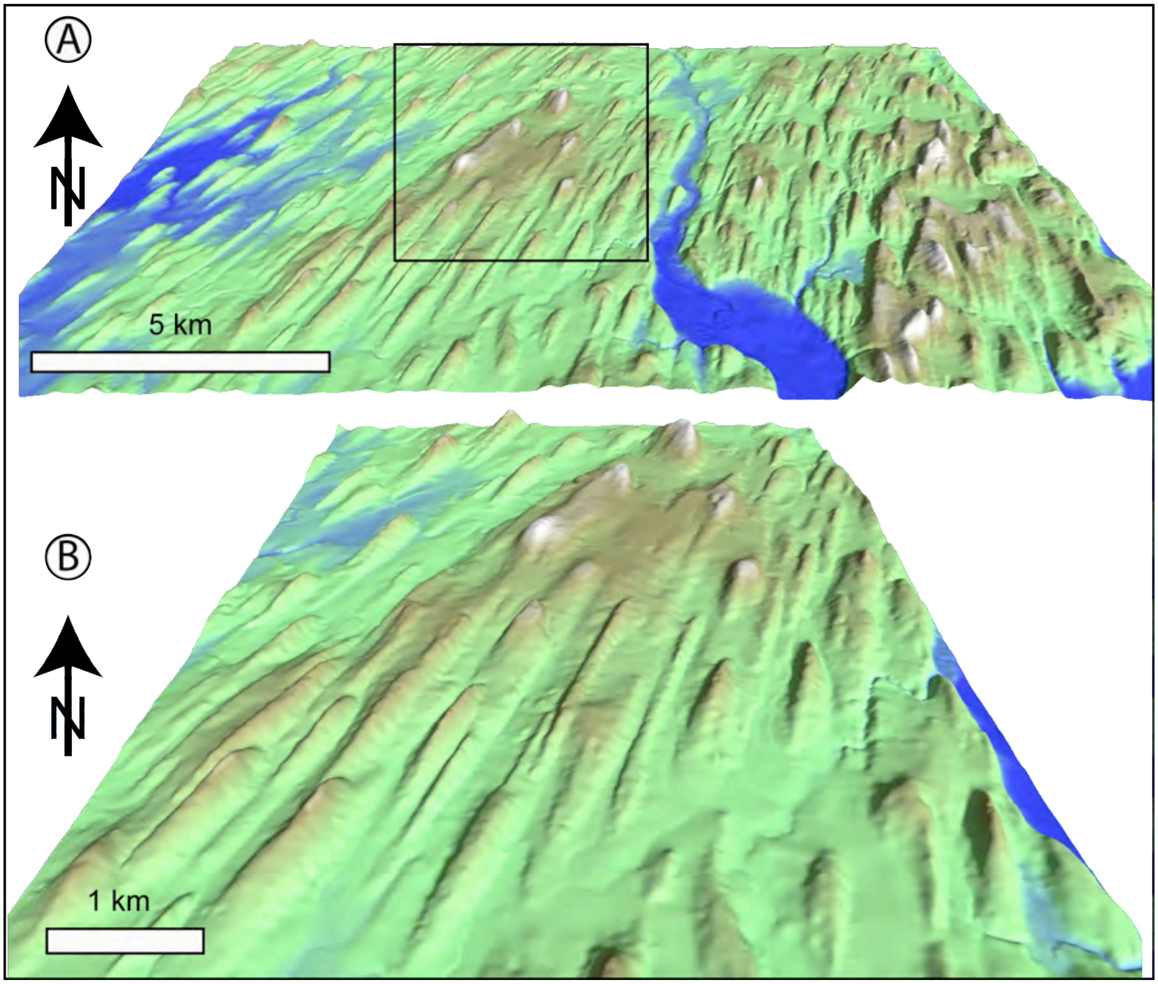


Figure 1-3.1. Perspective view of drumlins from the south. Note differences in drumlin length – width ratios, relief, and position in landscape on the scale of ~3 km across. Notice valleys oriented NE-SW bounding the northwest and southeast portion of the framed drumlin field (TC).

Peterborough Drumlin Field

Salient features of this drumlin landscape can be summarized by the following observations. Drumlins are streamlined with pointed to blunt upflow ends that taper gradually downflow (Fig. 3-3.1 a).Many forms show erosional furrows on the upflow side of forms. The surfaces on many drumlins in the area carry boulder to cobble lags (Sharpe and Shaw, 1987). Drumlins and fluting in this broad field occur in sediment and bedrock. They occur in the vicinity of tunnel channels that carry s-forms with morphological similarity to hairpin scours (Fig. 1-3.2; Shaw 1988).

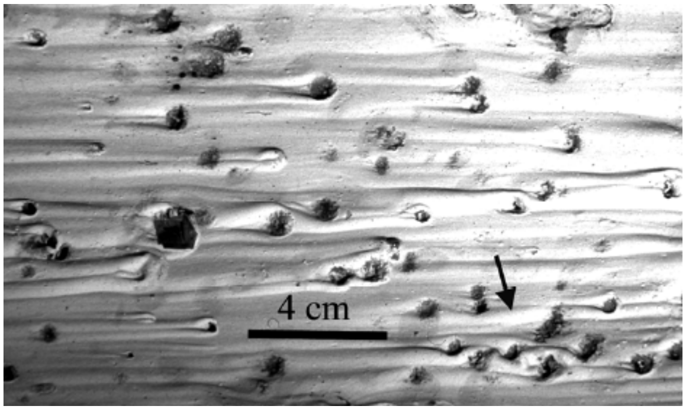


Figure 1-3.2. Streamlined forms with upflow crescentic furrows related to turbulent flow produced in a flume. (e.g. Shaw and Sharpe, 1987).

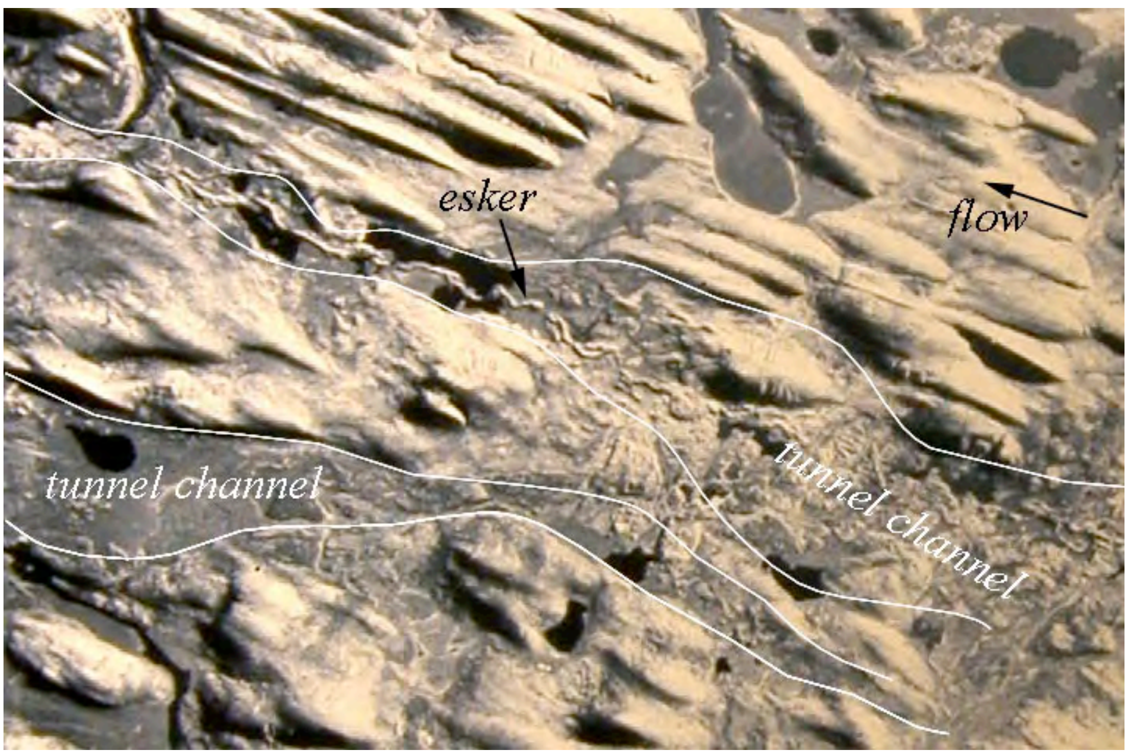
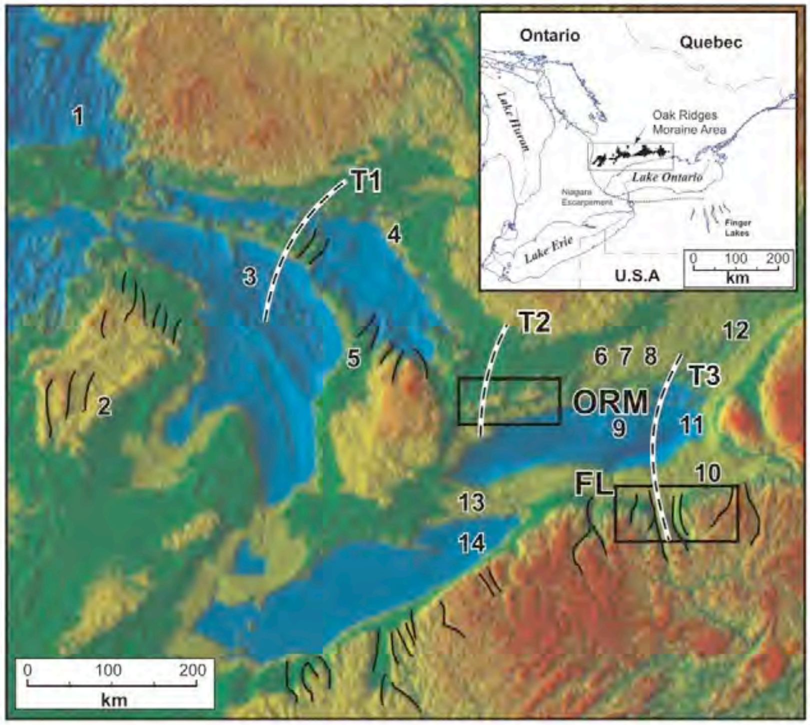


Fig. 1-3.3 Landforms assemblages drumlins, tunnel channel, and eskers in northern Saskatchewan (e.g. Shaw, 1983).

CJES-1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Oak Ridges Moraine Area
Lake Ontario
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Finger Lakes
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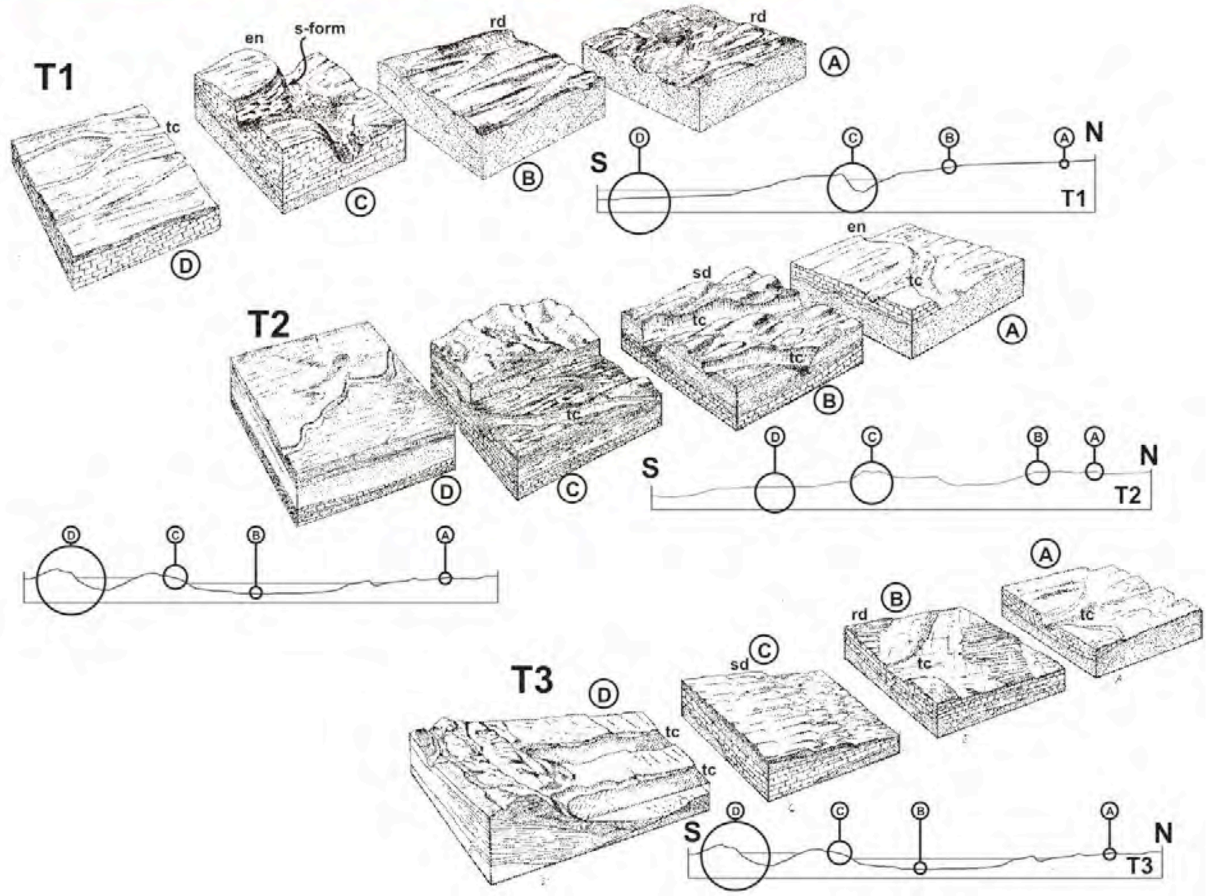
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Fig.1-3.4. Location of Oak Ridges Moraine (ORM) and Finger Lakes (FL) areas (rectangles) on digital terrain model (Gareau et al. 2005). The Great Lakes DTM highlights several erosional terrains or areas of documented regional-scale surface erosion: Troughs (channels?) in the eastern Lake Superior (1; Patterson et al. 2003) and north-central Michigan (2, Fisher and Taylor 2002); scoured terrain in eastern Lake Huron (3, Blasco 2001); sculptured bedrock, rock drumlins, and boulder lags, French River (4, Kor et al. 1991) and Bruce Peninsula (5, Kor and Cowell 1998). Erosional sediment drumlins and tunnel channels east of ORM (6, Shaw and Sharpe 1987; Brennand and Shaw 1994); sculpted bedrock in eastern Ontario (7, Gilbert 1994); Wilton Creek (8, Shaw 1988); eastern Lake Ontario (9, Gilbert 1990; Gilbert and Shaw 1992; Lewis et al. 1996, 1997); Finger Lakes (10, Mullins et al. 1989); Upper New York (11, Pair 1997); St. Lawrence River (12, Bernard 1971); Niagara Peninsula (13, Tinkler and Stenson 1992); Lake Erie (14, Lewis et al. 1999). Dashed lines locate landscape transects (T1, T2, T3). Short black lines represent inferred channels and /or re-entrants in up-flow-facing escarpments (see Great Lakes DEM figure). (from Sharpe et al., 2004)

A regional hypothesis

Shaw and Gilbert (1990) presented an explanation of regional landform distributions and associated flow events in the eastern Great Lakes by way of a then contentious hypothesis. They suggested that two closely timed, subglacial meltwater floods, the Algonquin and Ontario events, produced regional unconformities and erosional surfaces (e.g., Sharpe et al. 2004). Theoretical support for this hypothesis was provided by Shoemaker (1999) who predicted flow patterns for outburst floods in lake basins that closely match flow patterns indicated by drumlins in the Lake Ontario basin. Mapped landform relationships and analysis of event sequences using seismic data (Pugin et al., 1999; Sharpe et al., 2002) offer a comprehensive test of the outburst flood hypothesis. The concept of subglacial flooding is supported by a number of field studies from across the eastern Great Lakes region (Fig. 1-3.4). These sites have variable levels of documentation, thus key features from well-studied sites are shown on a set of schematic illustrations (Fig. 1-3.4) to re-construct expected landform trends along generalized, formative flowlines. These critical landform relationships are linked by regional geological mapping to extensive subsurface data collected in the ORM study and, correlated to the Finger Lakes region, New York.

Field evidence records a late-glacial unconformity across the eastern Great Lakes (Fig. 1-3.4). This erosional unconformity cuts into pre-existing glacial sediment and is characterized by water-scoured bedrock tracts, upland drumlin fields, extensive boulder lags, and tunnel channel networks. It underlies gravel in channel fills that fine upwards to sand and silt. This evidence poses formidable difficulties for, or directly contradicts, alternative explanations for the unconformity and the landscape as cited above.

Landscape transects (T1, T2, T3; see map above for location) oriented along the inferred flow line of Late Wisconsinan glaciation summarize terrain features related to the proposed regional unconformity. T1: Georgian Bay transect traverses Canadian Shield (A, B) southwest across the Niagara Escarpment (C) to eroded sediment on Paleozoic strata in Lake Huron (D); T2: Lake Simcoe-Oak Ridge Moraine transect traverses Shield-Paleozoic escarpment terrain (A) to thick eroded sediment (BCD, overlain by ORM sediment (C); note ORM sediment has been partially removed to reveal the Peterborough drumlin-channel surface; T3: Eastern Ontario-Finger Lakes transect traverses Shield-Paleozoic eroded terrain (A), Lake Ontario lake bed (B), rock and sediment (C), and eroded terrain in the Finger Lakes region (D). tc= tunnel channel; rd= rock drumlin; sd= sediment drumlin; en= escarpment nose; sf= s-form.

STOP 1-4 UXBRIDGE WEDGE, ORM.

Sharpe, D.R. and Russell, H.A.J. Geological Survey of Canada

UTM: 640500E 4876000N; NAD 83, zone 18.

Access: Lafarge, Stouffville pit (with permission) via York-Durham road 30.

OBJECTIVE

1. Landforms of the Oak Ridges Moraine
2. Distinction from buried tunnel valleys beneath the Oak Ridges Moraine.
3. Sediment facies and sediment architecture of Oak Ridges Moraine

REGIONAL CONTEXT

The surficial geology of the ORM has been mapped at 1:50,000 scale and locally at 1:10,000 scale (see in Sharpe et al. 1997). The dominant landform signature of the moraine is the ridge morphology that is up to 30-40 km wide and has relief of 300 m above Lake Ontairo and >100 m of relief above Newmarket Till uplands to the north (**Fig. 1-3.1**). Surficial mapping has identified a number of surface morphologies within the moraine such as hummocky terrain, fluvial incision, and groundwater piping basins.

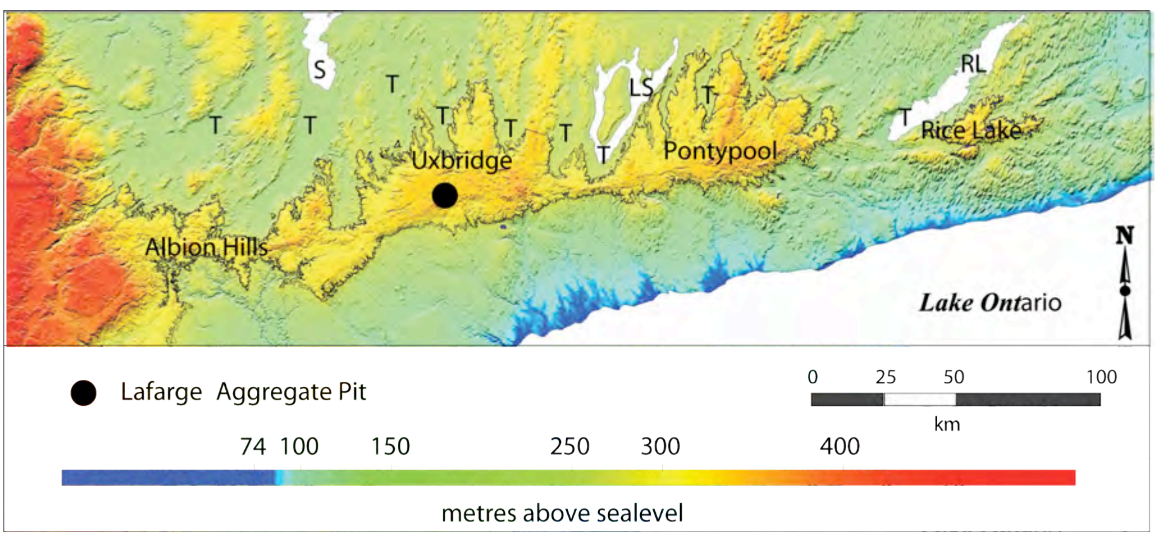


Figure 1-4.1. Stouffville Lafarge aggregate pit is located within the Uxbridge wedge of the Oak Ridges Moraine. Note the network of tunnel channels (T) north of the moraine. Letters on lakes indicate S: Lake Simcoe; LS: Lake Scugog; RL: Rice Lake.

Barnett et al. (1997) produced a detailed landform map; fans, deltas and moraine ridges for the Uxbridge wedge. These primary landforms form second and third order geomorphological terrain elements within the ORM. Two examples illustrate, at a representative scale, the depositional and erosional elements of the ORM setting **(Fig. 1-4.2**). In Uxbridge terrain, the Bloomington fan forms a pronounced feature that has > 30 m of relief and a pronounced, 1-2 km wide westward slope that extends over 5 km. This landform is interpreted as a primary depositional feature of the ORM (Barnett et al. 1997; Paterson and Cheel, 1996). The Bloomington fan has east to west paleoflow elements within its coarse sand and gravel sediment facies. Upflow to the east are subglacial feeders consist of east-west-oriented eskers and likely tunnel channel features, although they are not clearly visible at the surface except west of the ORM Rice Lake sediment wedge (Fig. 1-4.1).

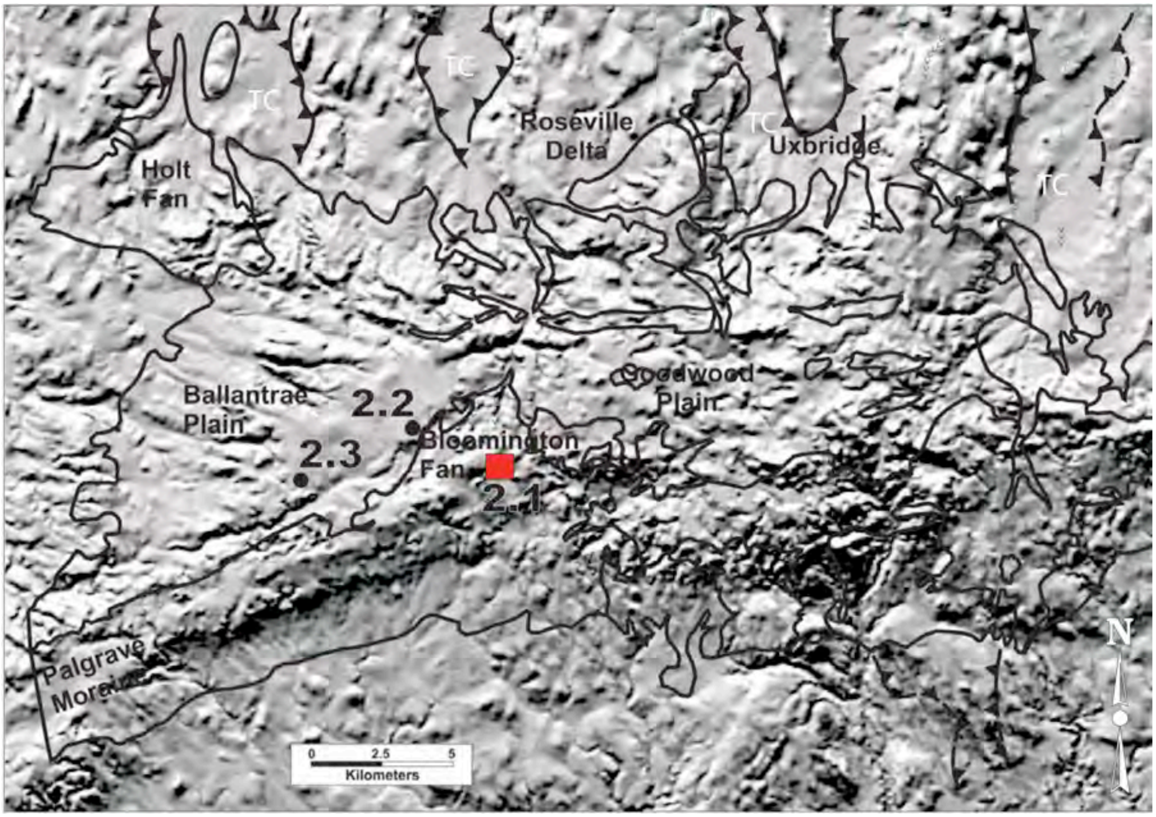


Figure 1-4.2 Landform assemblage of the Uxbridge wedge of the Oak Ridges Moraine (as mapped by P. Barnett; Figure 20, Sharpe et al 1997.) Red square is location of stop 1.3, Stouffville Lafarge pit. Note north-south trending tunnel valleys (TC) north of moraine.

Geological maps indicate that the moraine is mainly sand at the surface which overlies drumlinized Newmarket Till north of the moraine. Mud-rich diamicton of Halton Till onlaps ORM sediment to the south (Fig. 1-4.3).

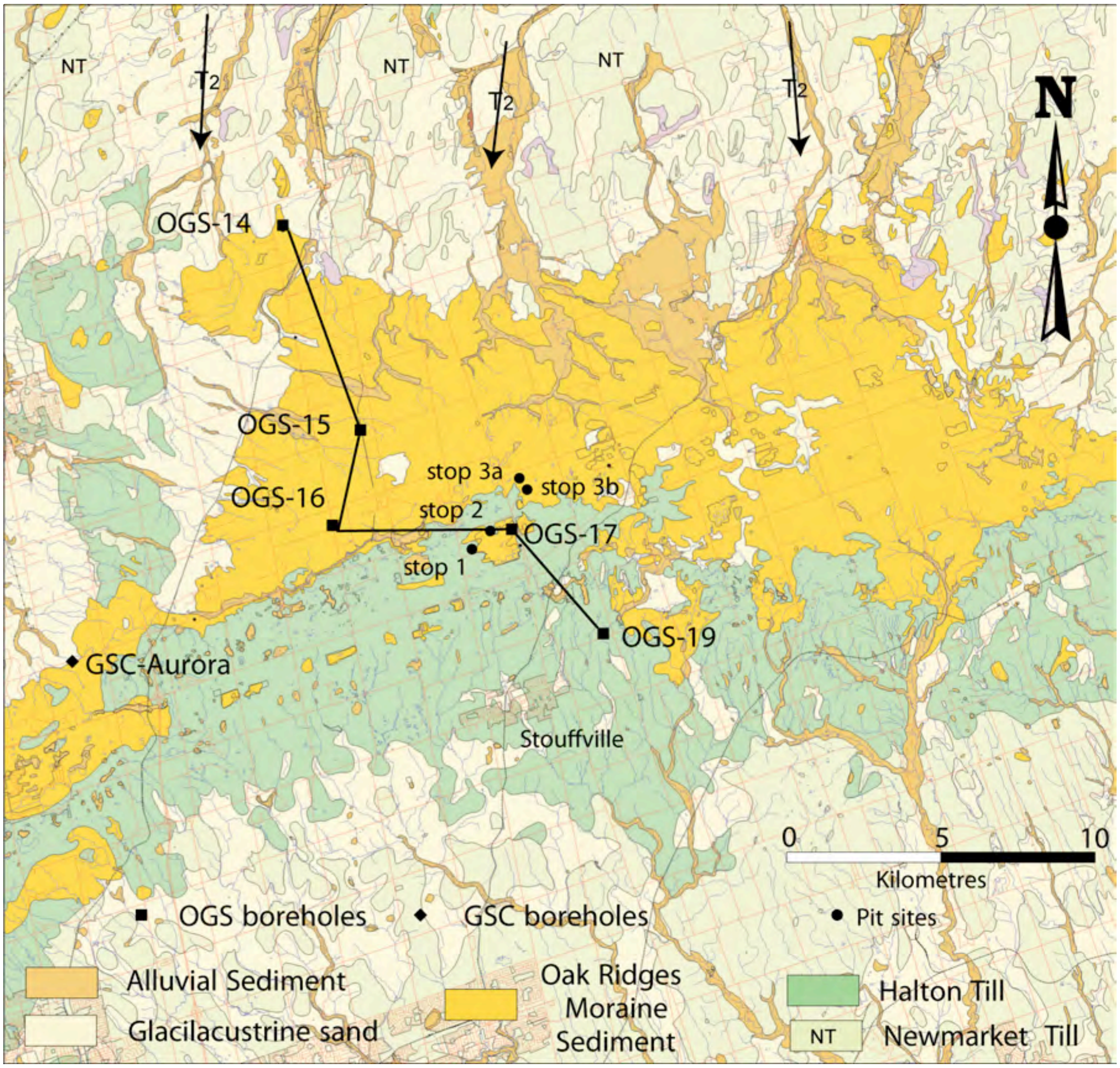


Figure 1-4.3 Surficial geology of the Uxbridge wedge and location of borehole transect relative to stop (1.4, this trip) location at OGS-17 borehole.

STRATIGRAPHY

A transect of boreholes at ~10km spacing were drilled to investigate whether tunnel channels observed north of the moraine continued southward beneath the moraine **(Fig. 1-4.3**). This transect, and the known N-S orientation of valleys north of ORM, provided ground-truth for initial E-W seismic reflection work in the area. The Uxbridge Wedge of the ORM is underlain by > 70 m of Lower sediment, 40 m of Newmarket Till, and 40 m of Oak Ridges Moraine sediment based on the borehole results around this wedge (**Figs. 1-4.3, 4).**

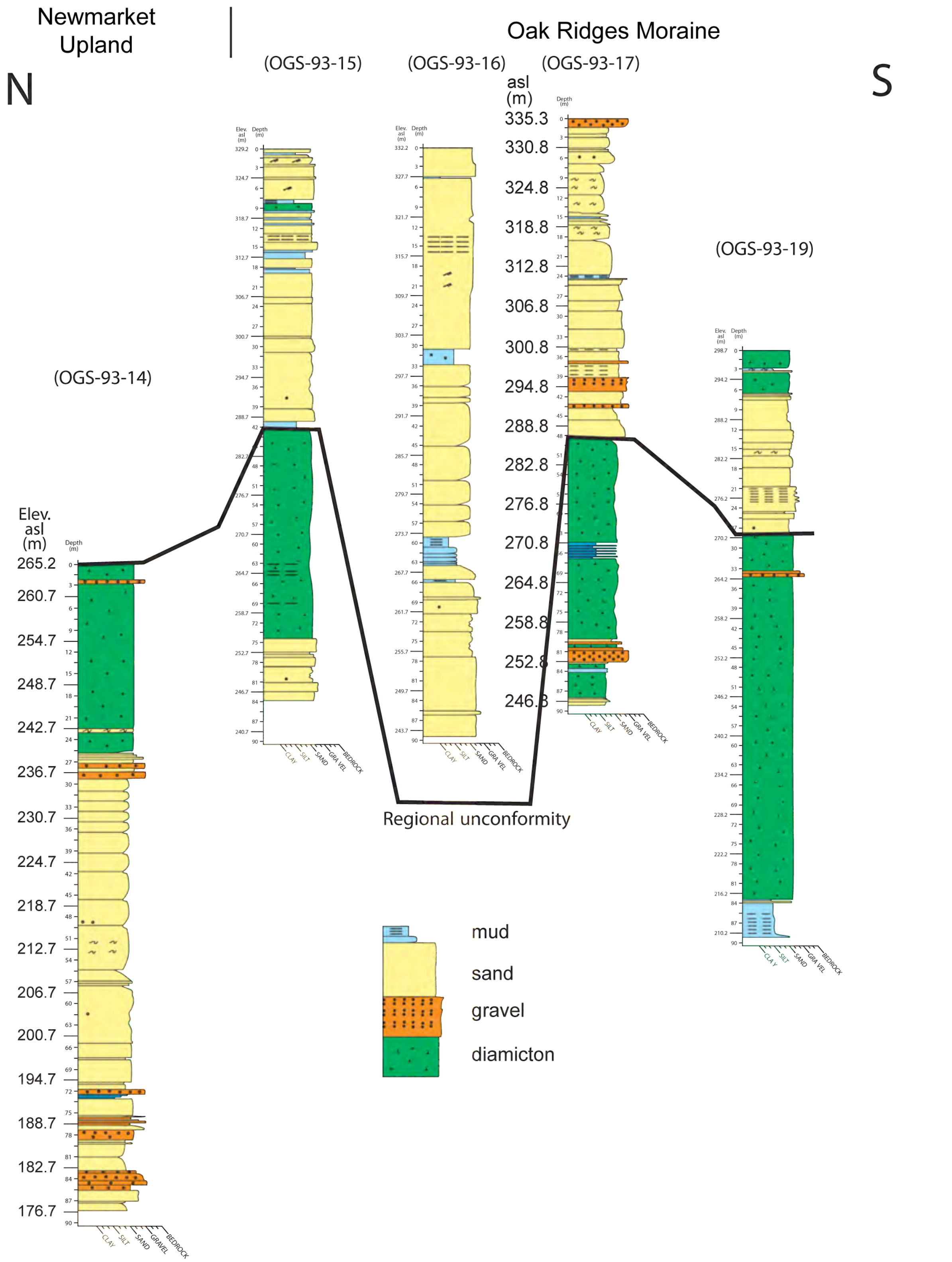


Figure 1-4.4. Graphic logs of Ontario Geological Survey continuous cored boreholes across the Uxbridge wedge of the Oak Ridges Moraine. Note inferred tunnel valley based on absence of Newmarket Till in borehole OGS-93-16. (Data from P. Barnett, Ontario Geological Survey).

SEDIMENT FACIES OAK RIDGES MORAINE

The Lafarge aggregate operation provides unique insight into the stratigraphic architecture and sediment facies of the Bloomington Fan component of the Oak Ridges Moraine. Borehole OGS 17 (Figs. 1-4.3, 4**)** provides the subsurface context for the pit face exposures. The predominant gravel exposures of the pit are underlain by ~45 m of sand. Most of this sand is not exposed in the pit, except for exposures in the southwest as sediment fines in this downflow direction (Fig. 1-4.5). A detailed sedimentological study of the pit near OGS 17 concluded that sediments could be grouped into 10 facies (sand, gravel, and diamicton) that were deposited in a glacial subaqueous fan environment (Paterson and Cheel, 1996).

Additional studies confirmed the subaqueous fan depositional model and a number of additional key sediment facies of this depositional model have been identified to the east **(**Figs 1-4.6, 7).

Recent pit exposure at Stouffville does not reveal clearly the evidence used by Russell and Arnott (2003) for the jet-efflux hydraulic model. Key sediment facies used in that study are present in the eastern Stouffville pit. At the time of the work by Patterson and Cheel, who explicitly commented on the absence of diffusely graded sand, these exposures were not present. Sedimentary evidence of super critical flow conditions and hydraulic jumps is often fragmentary. Key evidence is steep-walled scours with diffusely graded fills, climbing cross-strata, particularly ripple-scale, cross lamination and less commonly dune-scale, climbing cross strata.

The term energy-fence has been coined to illustrate the rapid and abrupt change in sediment facies from upflow to downflow of the hydraulic jump zone (Fig. 1-4.8). Commonly this facies transition is characterized by a shift from a gravel dominated system to a predominantly sand regime.

The range of sediment facies and contact relationships are clearly outlined in the diffusely graded facies in Figure 1-4.7. In 2004, this facies was exposed just above the pit floor at the western end of the eastern pit and at the far eastern part of the property at a higher level. It appears that the stratigraphic succession consists of a number of coalesced conduit – fan deposits that likely back-stepped eastward as the duration of the Oak Ridges Moraine depositional event proceeded. The depositional progression of the Oak Ridges Moraine has been outlined by Barnett et al., (1998) and further refined by Russell et al., (2004) for the western ORM. These authors identify a sequential progression of moraine sedimentation from tunnel channel erosion and subsequent fill in the sequence illustrated in figure 1-4.9.

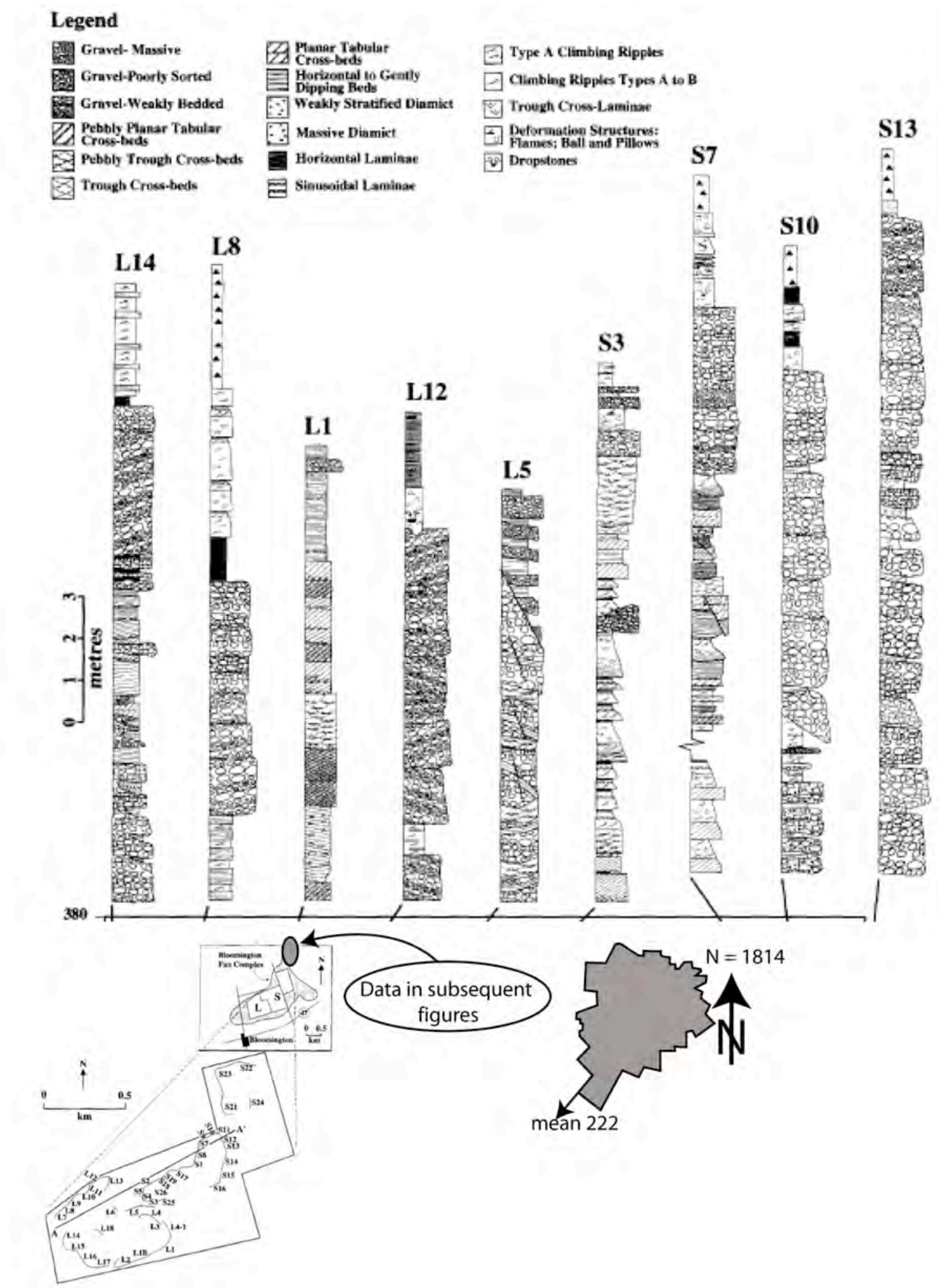


Figure 1-4.5. Sedimentological logs from Paterson and Cheel of the pit faces exposed in the early 1990's of sand and gravel synthesized in 10 sedimentary facies. No diffusely-graded facies were observed and climbing cross-strata were limited to small-scale cross-laminated fine sand. Note remainder of facies presented from this site occur to the north east of the sections logged by Paterson and Cheel (1997).

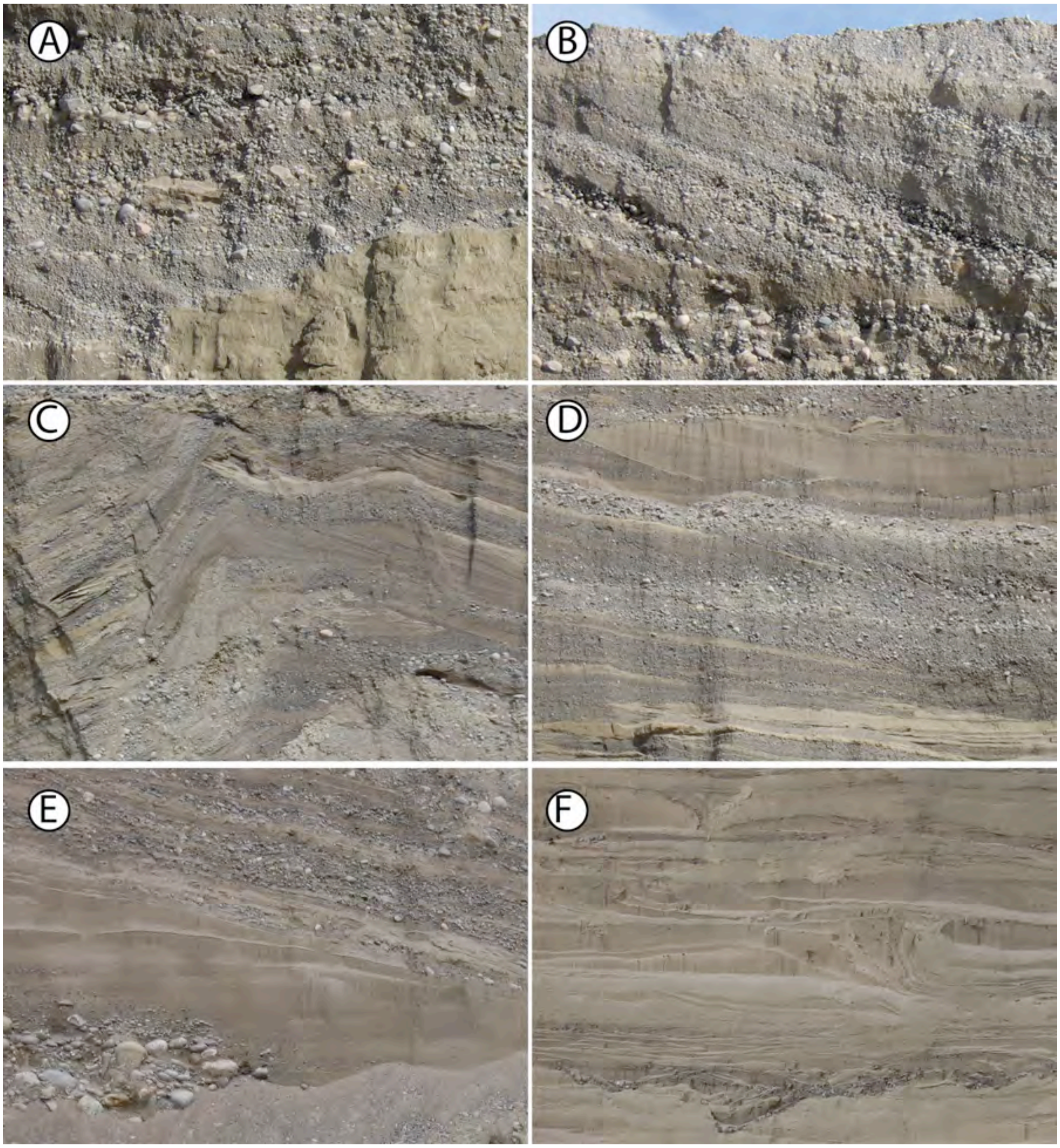


Figure 1-4.6. Sediment facies from eastern part of Lafarge pit. A) Cross-stratified gravel with intra-clasts of fine sand overlying fine sand of diffusely-graded facies. B) Gravel foresets with well developed longitudinal grading and open-work gravel toward the base of the gravel foresets. C) Local syn-sedimentary fold in coarse sand and gravel. D) Thinner bedded, cut and scour pebble gravel and sand (upper pit face). E) Sand, gravel show lateral grading from massive cobble gravel to diffusely-graded sand overlain by thin sand and gravel beds. F) Succession of diffusely-graded, cross-bedded, and small-scale, cross-laminated sand with local fluid (?) structures.

Figure 1-4.7. Diffusely-graded sand facies: A) Steep-walled scour margin and diffusely-graded scour fill. B) Close-up of scour margin with truncated diffuse-gravelly coarse sand and medium to coarse sand fill. C) Scour fill with disrupted pause-plane silt layer (at arrow). D) Diffusely-graded fine sand with minor coarse sand. E) Silt intra-clasts with diffusely-graded sand; note angularity. F) Two diffusely-graded medium sand textures with load casts in fine sand.

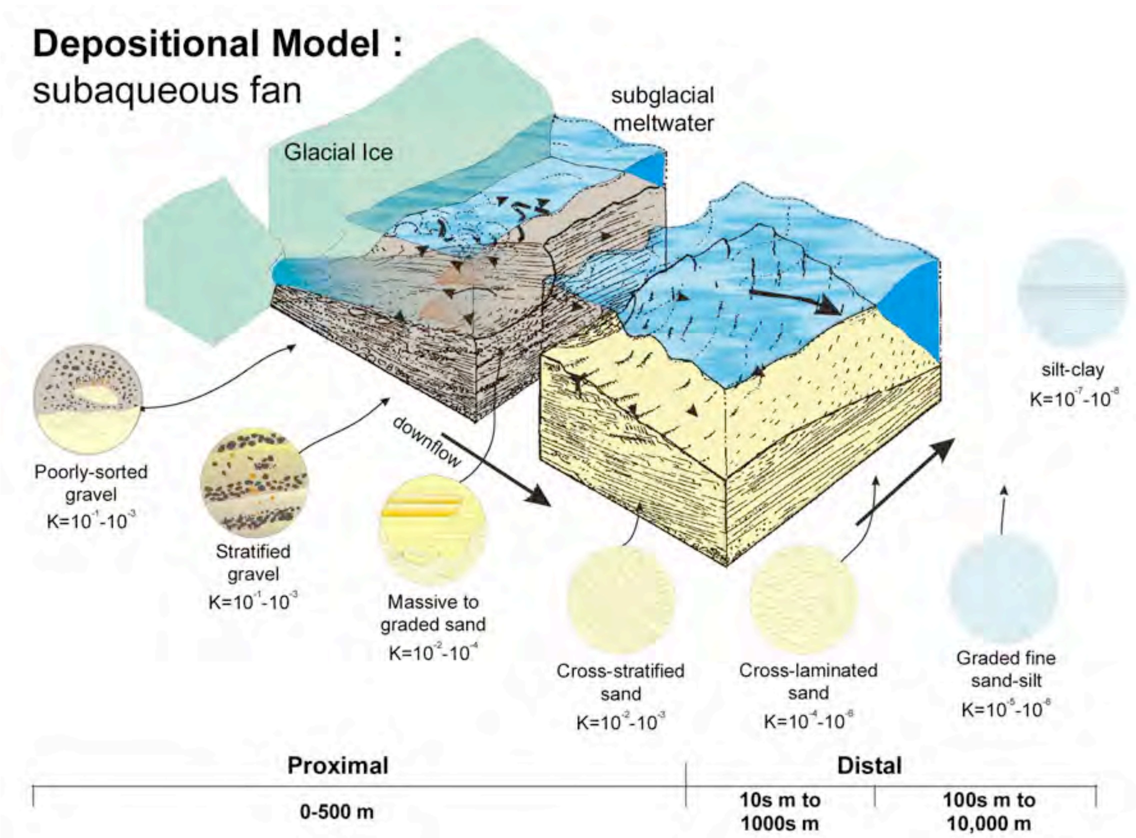
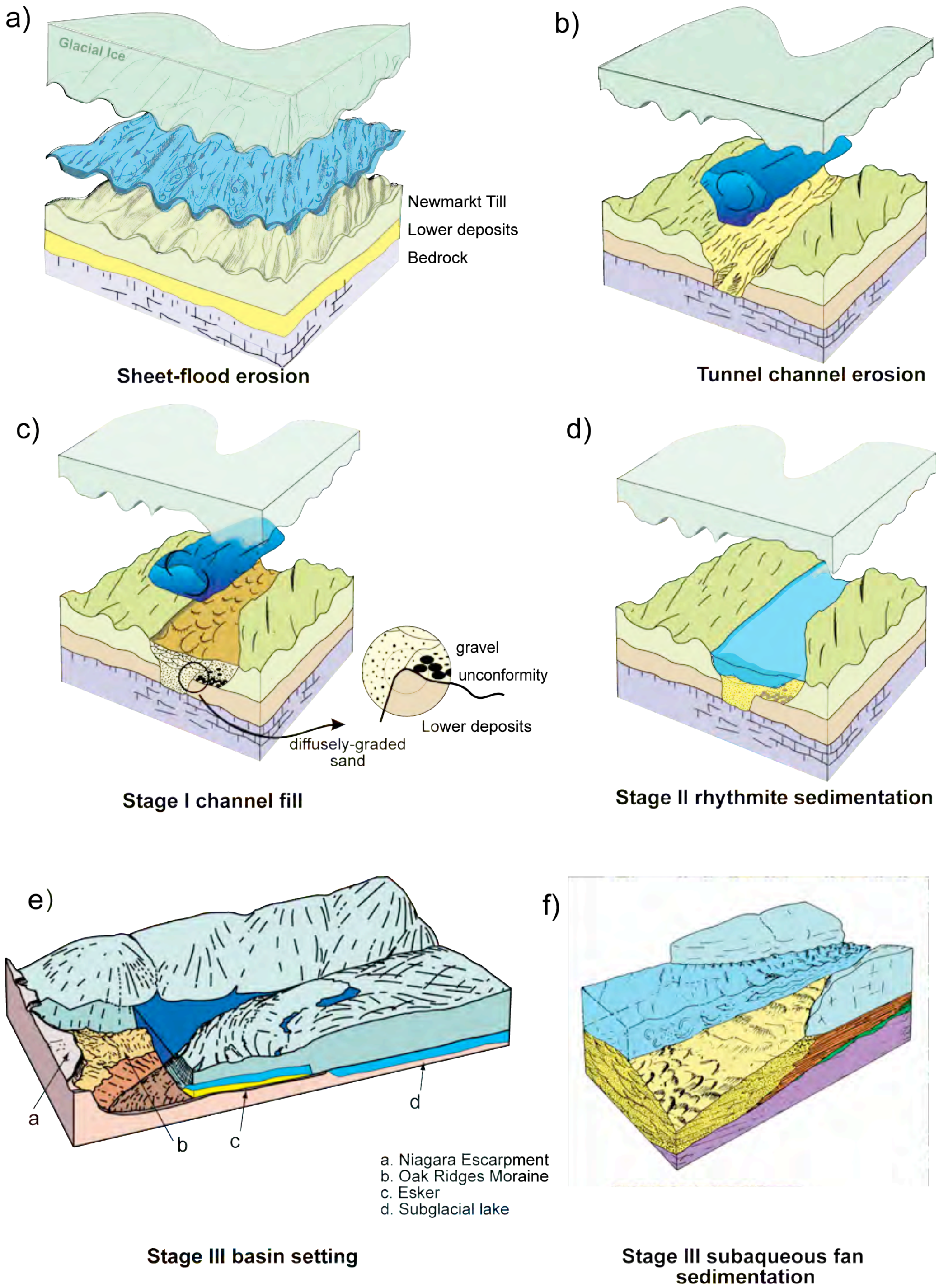


Figure 1-4.8. A jet-efflux model for glaciogenic subaqueous fan deposits in the Oak Ridges Moraine (from Russell and Arnott, 2003).

Figure 1-4.9 (next page). Graphic depiction of the sequence of erosional and depositiaonl events leading to the formation of the Oak Ridges Moraine. (A) Sculpting of Newmarket Till into drumlins by regional sheet floods. (B) Tunnel channel erosion by waning stage outbreak floods. (C) Stage I channel fill showing diffusely-graded sand along channel axis and gravel deposits along channel margin. (D) Stage II rhythmite deposition from seasonal meltwater discharge into ponded , subglacial tunnel channels. (E) Ice-contact basin model for stage III sedimentation of the ORM ridge. (F) Subaqueous fan sedimentation during stage III flood discharge from subglacial conduits. For details refer to Barnett et al. 1998, Russell et al. 2003; Sharpe et al, 2004



a)
Glacial Ice
Newmarkt Till
Lower deposits
Bedrock
Sheet-flood erosion
b)
Tunnel channel erosion
c)
gravel
unconformity
Lower deposits
diffusely-graded sand
Stage I channel fill
d)
Stage II rhythmite sedimentation
e)
a
b
c
d
a. Niagara Escarpment
b. Oak Ridges Moraine
c. Esker
d. Subglacial lake
Stage III basin setting
f)
Stage III subaqueous fan sedimentation

STOP 1-5 CLARKS HOLLOW: NEWMARKET TILL UPLAND

Sharpe, D.R... Geological Survey of Canada

Markham NTS 30M/14, 650107E, 4859297N

Access: Off White's Road, south of Taunton Road.

OBJECTIVE

1. Newmarket Till: Interfleuve cap strata and regional seismic maker horizon
2. Sediment facies of Thorncliffe Formation inter-channel sediments

REGIONAL CONTEXT

Clarke's Hollow on West Duffins Creek, a prominent stream issuing from ORM headwaters, provides a section into the regional till plain **(Fig. 1-5.1)** that extends from north of ORM to Lake Ontario (stop 1.1; **Fig. 1**). A 25 m thick succession, Thorncliffe Formation mud and sand overlain by Newmarket Till, is exposed. The succession includes: i) 5 m of rhythmically-laminated mud, ii) 8- 10 m of rippled, fine to medium sand; and iii), 10-12 m of stony sandy silt diamicton. This sand-rhythmite sequence can be traced along creek bluffs over a wide area (100km^2) and to the Scarborough Bluffs.

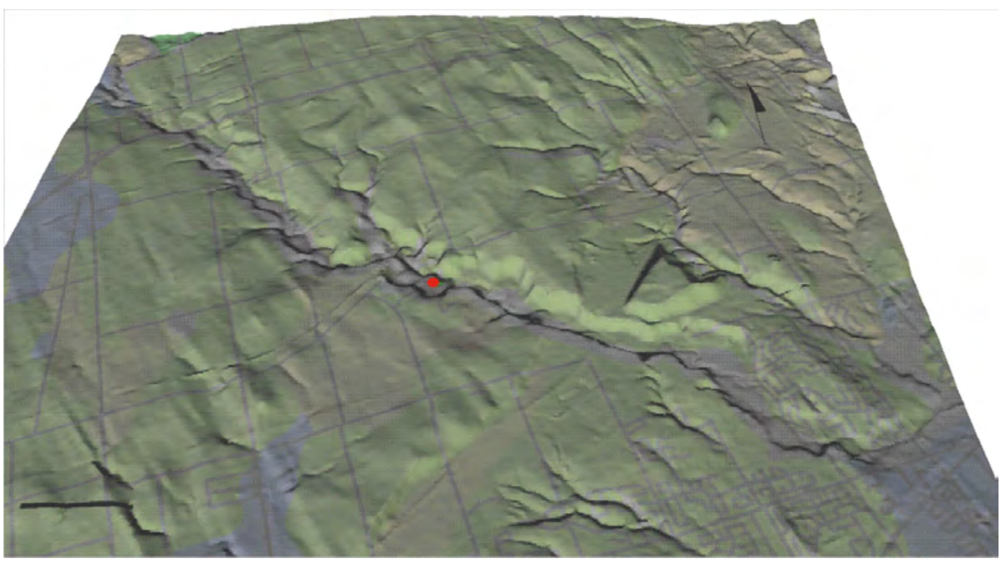


Figure 1-5.1.Perspective view of lineated (fluted) Newmarket Till plain at Clarke's Hollow, Duffins Creek. Red dot in valley mid view is stop 1.2.

The sandy Thorncliffe beds consist of climbing ripples or graded sets in fine to silty fine sand, 10-50 cm thick. A few clay laminae are present. The beds contain clay rip-up clasts, ball-and-pillow, and dewatering structures. Paleoflows indicators are variable in this area: many trend north-northeast but at this stop paleoflows are south-southeast in ripple-drift sand. They are westerly in pebbly, trough cross-beds. A wet zone at the base of the sand is groundwater seepage along the sand-mud contact. This modest groundwater seepage is well below discharge (>10L/s) connected to ORM; hence it appears to be local in origin and may represent seepage through the Newmarket Till.

Overlying, massive, stony (3-10 %), dense Newmarket Till has a planar contact, with minor structural breaks with underlying Thorncliffe sand. The till contains ~2-5 cm thick inter-beds of sand, silt and clay laminae at its base (**Fig. 1-5.2**), and near-surface jointing. Here, it also contains small injections, dykes, breccia and rafts from lower sand beds (**Fig. 1-5.2**). In nearby outcrops, discontinuous sand beds up to 1-2 m may be present. In other places, discontinuous boulder pavements are observed. Inter-beds lack continuity and suggest that diamicton beds amalgamated following episodes of local erosion/ deposition.

The regional architecture (Sharpe et al., 2005) and the internal structure (Boyce and Eyles, 2000) of Newmarket Till are both important to understanding its permeability variation. The sandy texture, thickness and high seismic velocity (~2500 m/sec) of Newmarket Till, and the erosion surface it carries, are recognized regionally (e.g. Sharpe et al., 1997; Fig. 1). South of ORM, it occurs as a subdued till upland with intermittent lacustrine cover (Sharpe and Barnett, 1997). The widespread extent and consistency in regional properties make the Newmarket Till complex a significant regional marker (Pugin et al., 1999) and hydrostratigraphic unit (e.g. Gerber and Howard 1996).

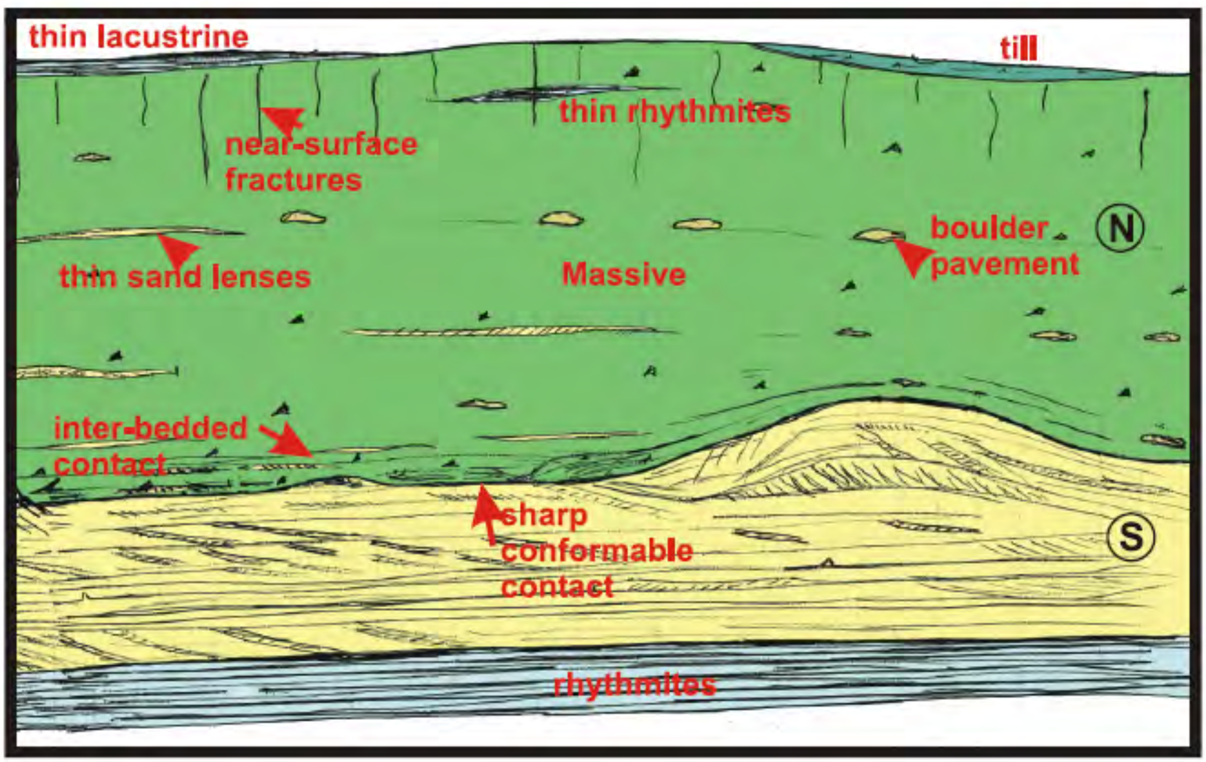


Figure 1-5.2 Architectural sketch of Newmarket Till at Clarke's Hollow illustrates planar, conformable to inter-bedded contact with Thorncliffe formation sand, and various inter-beds within the till: sand lenses, mud horizons and boulder pavements.

Higher groundwater flow zones in Thorncilffe sand and gravel to the west near Markham (Smart, 2010) appear to indicate channel and fan structure to the Thorncliffe depositional system (Fig. 1-5.3). The mound of sand and gravel at locations 0 and 3 km is transitional laterally to mud away from main flow and indicating a subaqueous fan paleo-setting. The extent of the Thorncliffe aquifer/ reservoir system along main flow is indicated in the 3 year pumping (from 2.5 km mark on

Fig 1-5.3) results shown as a drawdown pattern oriented northeast (Figure 1-5.4). This could be inferred to be the direction of a Thorncliffe channel – fan depositional complex.

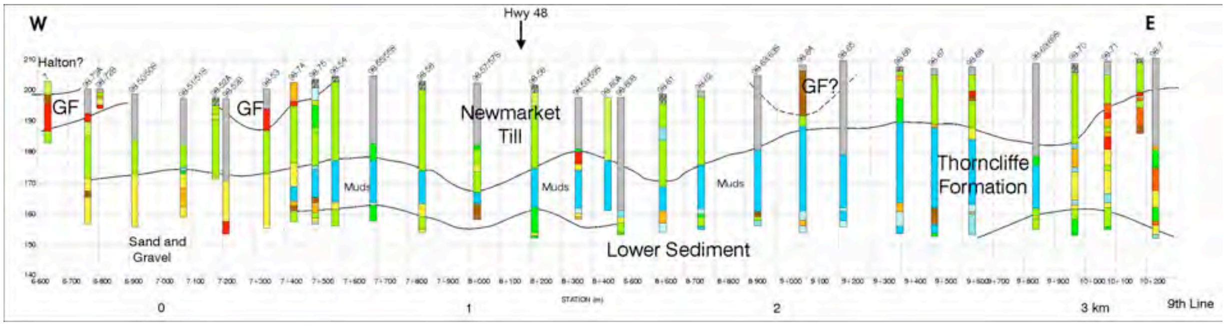


Figure 1-5.3 East-west section of boreholes drilled into the Newmarket till plain intersects channel (0 and 3 km marks) sand and gravel (yellow-orange) and 'inter'-channel fan muds (blue) of the Thorncliffe Formation. Note small channels cutting the top surface of Newmarket Till. See figure 1-5.4 (dashed line) for section location.

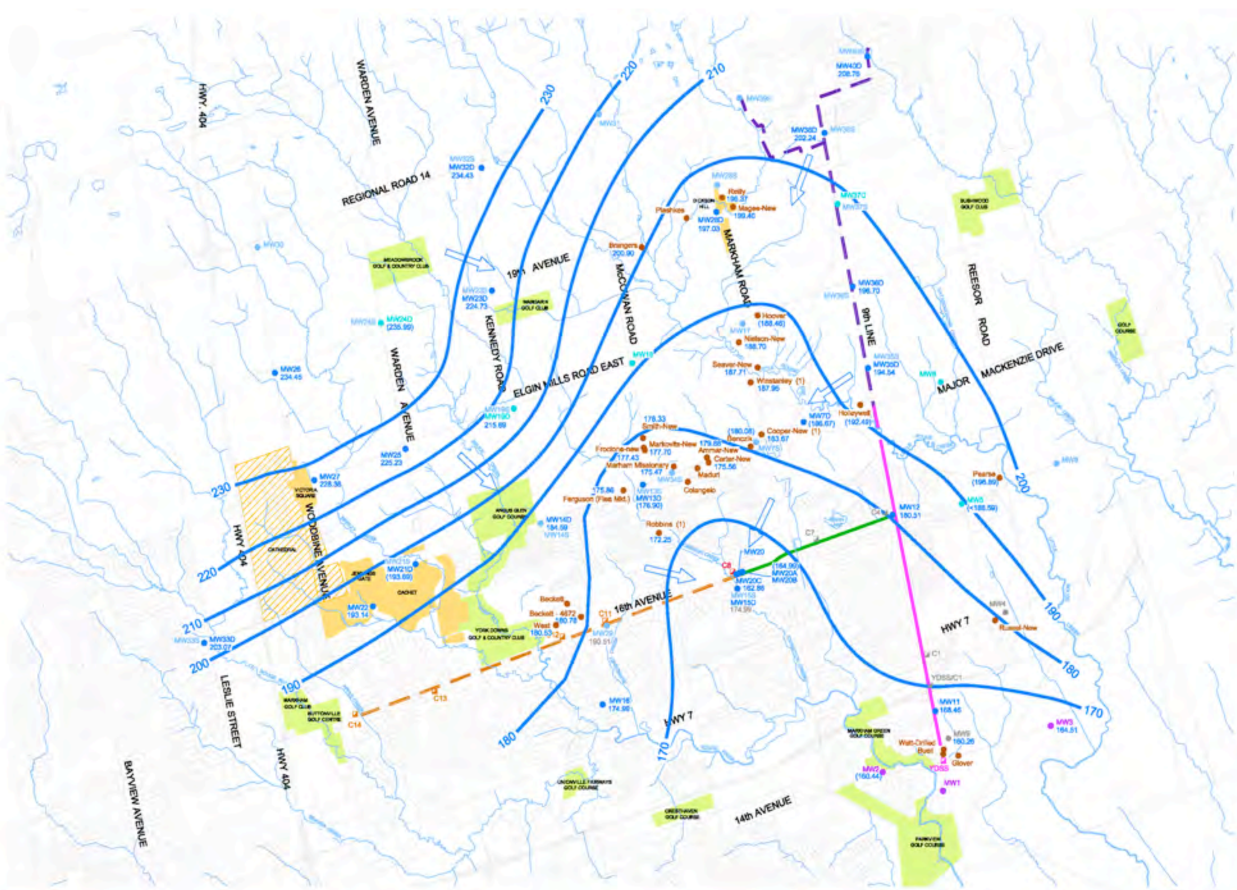


Figure 1-5.4 Pumping area of influence in the Thorncliffe Formation aquifer /reservoir August 2005. Main drawdown is oriented to the northeast from the well on 16th Avenue and extends ~10 km in terms of well response.

Stop 1-5a. Barrie:Sediment below regional unconformity

(optional)

Sharpe, D.R. Geological Survey of Canada;

Shawn Slattery, Alberta Geological Survey (now at Syncrude Canada)

UTM: 2598278E 4914019N; NAD 83, zone 18.

Objective

1. Examine coarse sediment package below the regional unconformity on Newmarket Till

2. Compare proximal sediment facies in Thorncliffe Formation with distal facies at stops 1.1 and 1.5

Regional Context

Stop 1.5a sits on the margin of a large tunnel channel trending southwest from Kempenflelt Bay, Lake Simcoe on the western margin of a network of valleys/ channels across southeastern Ontario **(**Fig.6)**.** This southwest trending valley is the next large valley north of Holland Marsh tunnel channel (Stop 1-2). Large uplands are left as 'islands' or interflueves in this network of valleys /channels. Many of the valleys have eskers and other glaciofluvial sediment within them and thus are classified as tunnel channels. The uplands have a drumlinized upper surface that ties uplands north of ORM to those south of ORM **(Figs. 6, 9).** The drumlinized upland surface is evident in the perspective view DEM showing the Kempenfelt Bay valley/ tunnel channel in the foreground (Fig. 1-5a.1).

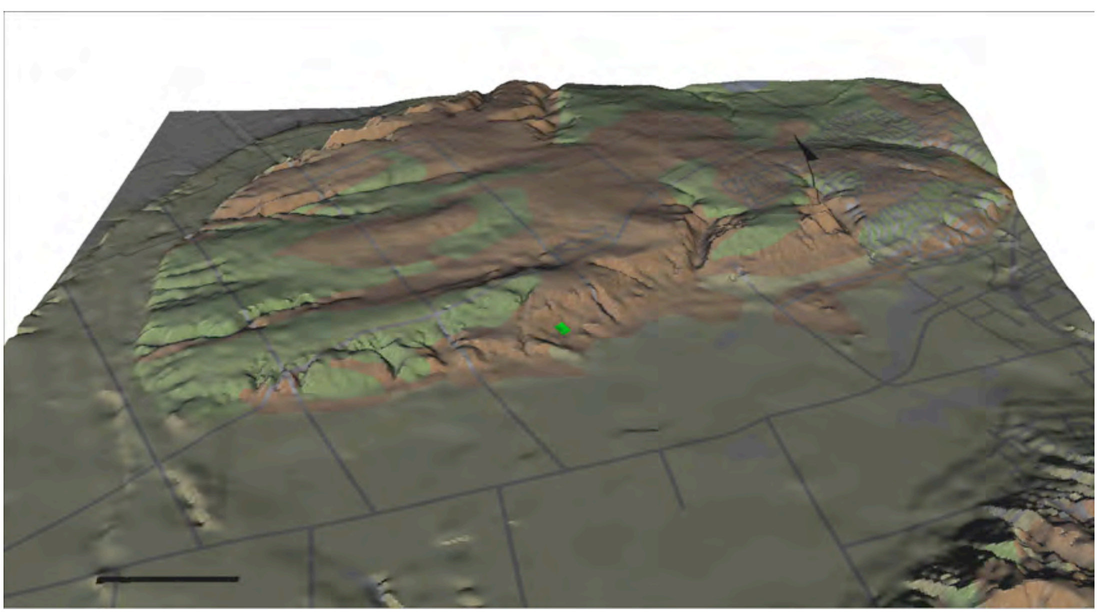


Figure 1-5a.1. Perspective view DEM showing the Kempenfelt Bay valley/ tunnel channel extending east-west in the foreground. Pit is located at green square on the north valley wall. Note northeast-southwest oriented drumlinzed upland surface. The eroded Newmarket Till (green drumlinized) surface is

discontinuous and underlying sand and gravel (orange) shows through in stream incisions. Scale bar is ~2km long.

Below the upland surface is a thin (~1-8m) remnant of Newmarket Till that covers up to 80 m of coarse glaciofluvial sediment observed in a number of uplands north of this stop (**Fig.** 1-5a.2); (Slattery and Sharpe, inputs).

Figure 1-5a.2. View to east toward Lake Simcoe of Nelson aggregate pit cut into an inter-channel upland. Pit exposes about 40 m of coarse glaciofluvial sediment with a southerly paleoflow direction.

Pit summary

The Nelson pit is defined by channel-fill (CH) and laminated sand sheet (LS) architectural elements (Fig. 1-5a.3). Element CH is characterised by an abundance of planar, cross-stratified sands (lithotype Sp) and scour-fill sequences (lithotype Ss) whereas element LS is entirely composed of horizontal- to flat-bedded sands (lithotype Sh). These elements collectively form a ~25 m thick aquifer/reservoir complex that extends laterally across paleoflow for over 100m. Locally, a silty, sandy diamicton (lithotype Dmm), Newmarket Till, overlies channel and sheet sand elements. Directional attributes obtained from elements CH and LS indicate an average southward paleoflow direction of 188^0.

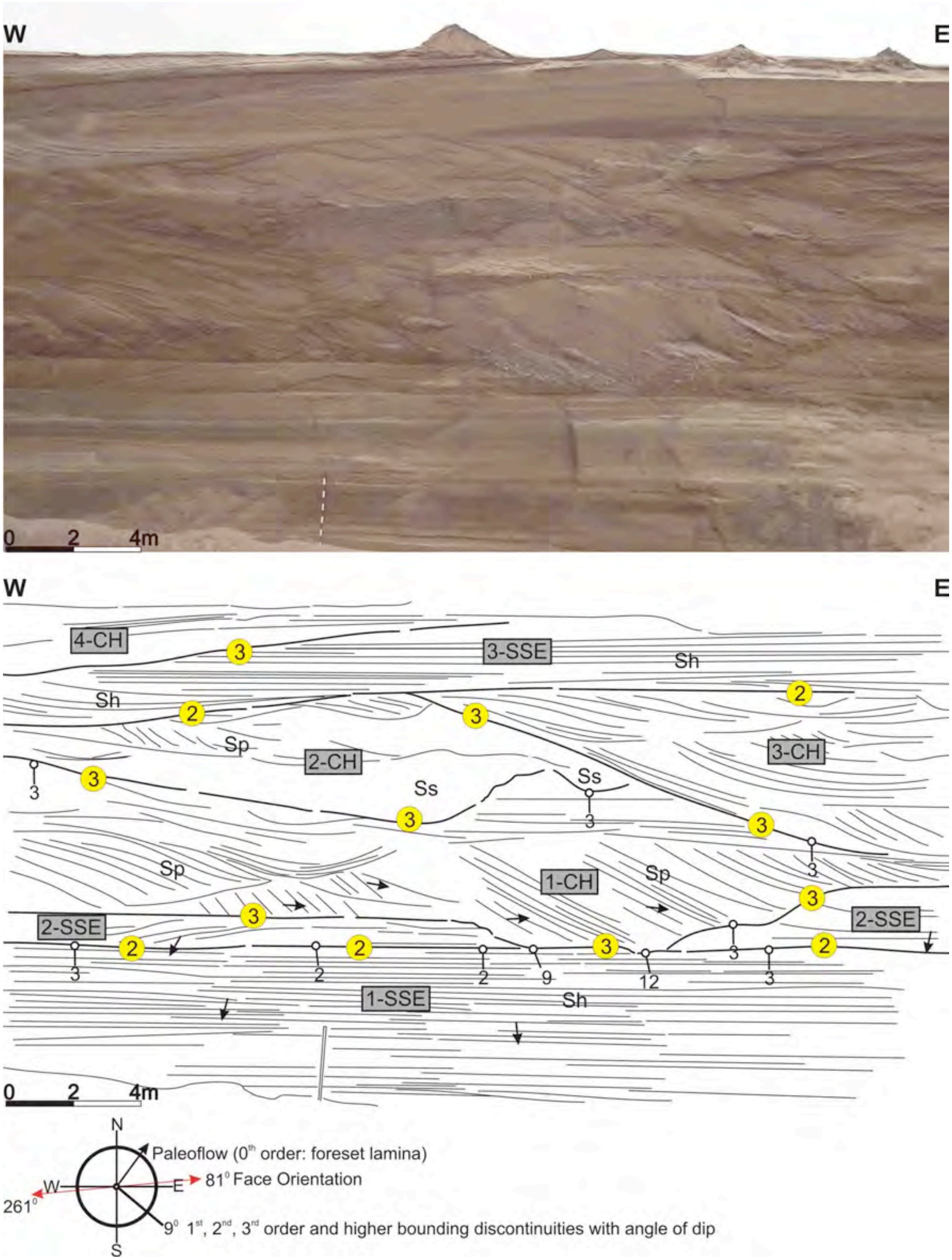


Figure 1-5a.3. Photomosaic and architectural interpretations of Neslon Pit. Measurements directed above the horizontal are away from the observer; those directed below the horizontal are toward the observer. Solitary arrows indicate the directional attributes of 0^{th} order surfaces; pins with numbers indicate direction and dip of higher order surfaces. Major boundary surfaces are numbered and circled. Architectural element codes are displayed in boxes. Lithotype codes are displayed directly on architectural elements – see text for code index.

Sandy Sheet Element (SSE)

Element SSE (Fig. 1-5a.2) forms 3-5 m thick, sheet-like bodies that extend laterally for up to ~10 m. The element is bound by lower-order, erosive surfaces that incise into underlying strata. The element is entirely composed of thin (0.3 to 0.5 m thick) uniform sheets of horizontally-bedded fine and medium grade sands (lithotype Sh). Bed boundaries within the element are accented by 0.5 to 3 cm thick accumulations of heavy minerals that can be traced laterally for several meters. Evidence of parting lineation is ubiquitous on bedding planes. In sediment-outcrop sections, the orientation of Sh units are nearly parallel to southward trending element bounding surfaces, with minimal vector variance with internal boundary surfaces.

Channel Elements (CH)

CH elements (Fig. 1-5a..2) are concave-up bodies that are defined by erosive, lower-order bounding surfaces. Elements are typically 3 to 5 m thick, ~15 m wide and commonly incise into underlying SSE elements. The medium-grained sand-dominant character and composite geometry of CH elements is demonstrated in architectural elements 1-CH through 4-CH, all of which are composed entirely of lithotypes Sp and Ss.Units of Sp dominate the element and are typically 1.5 m thick and 3m in length. Lag deposits of medium pebble grade are common at internal surfaces and typically form downstream accreting wedges. Ss units, 1 to 1.5 m thick, are erosive that incise underlying Sp units and can be traced laterally for up to 1 m. Paleoflow vectors from foreset beds of Sp units are southerly with a vector spread of 172^0, representing west and eastward trending connecting flow to the main southward trending.

Architectural Analysis

The abundance of horizontally-bedded to laminated sands within element SSE is suggestive of upper-flow regime conditions that resemble hyper-concentrated flood-flow facies (e.g Blair 1987; Smith and Lowe 1991; Best 1992 and Sohn et al. 1999). The presence of isolated, matrix-supported clasts and abundant primary current lineation on bedding planes further supports a hyper-concentrated, upper-flow regime origin (e.g. Allen1983; Bridge and Best 1988).

The abundance of planar, cross-stratified sands (lithotype Sp) that are incised by lithotype Ss is indicative of fluctuating flow regimes within the element from conditions of lower flow regimes, represented by lithotype Sp to conditions of upper flow regimes, represented by lithotype Ss. Sets of planar, cross-stratification are the remnants of migrating 3-D dunes (Levey 1978; Cant and Walker 1978), deposited under falling stage conditions. Similar lithotype assemblages have been described and interpreted as depositional facies in ice-contact subaquatic fan settings (Shaw 1985; Russell and Arnott, 2003).

STOP 2-1 PONTYPOOL CHANNEL FILL

Sharpe, D.R. and Russell, H.A.J. Geological Survey of Canada

UTM:. NTS Lake Scugog, 689966E; 4883175N

Access: via highway 7.

OBJECTIVES

1. Recognition of tunnel channel
2. Character of channel Fill
3. Sediment facies from outcrop

REGIONAL SETTING

A partially filled tunnel channel on the north side of the Pontypool Wedge of the ORM is flanked by a ridge of Newmarket Till to the west and isolated patches of Newmarket till to the east. To the north of the ORM Lower sediment is mapped in the vicinity of Bethany (Fig. 2-1.1). To the south of the partially filled tunnel channel are a number of aggregate pits along the crest of the moraine.

STRATIGRAPHY

Drilled within the ORM sediment the 170 m deep borehole intercepted a succession of mud rhythmites, and diamicton that are interpreted to be Lower sediment and overlying fine sand, interpreted to be ORM sediment (Fig. 2-1.2). The interpretation of the rhythmites and diamicton as Lower sediment is supported by the downhole geophysics. Note the contrasting signatures in the gamma and conductivity logs above and below ~96 m depth. The distinct coarsening upward signatures in the deeper sediment and higher gamma counts are characteristic of deposits within the Lower sediment. Similar signatures are seen in logs to the west in Nobleton, Holt and Schomberg boreholes along the Laurentian Valley (Fig 2-1.5). The lower counts and irregular saw tooth signature within the upper 90 metres of sediment is characteristic of the ORM sediment (Fig. 2-1.2). The sediment facies that correlate with respective geophysical signatures are highlighted in Figure 2-1.3. Note the difference in mud and fine sand content between respective facies in the two stratigraphic units.

LAFARGE PIT

The pit exposure highlights the stratigraphic architecture of the ORM in a succession of gravel overlain by sand. Gravel deposits are interpreted as conduit deposits and have a broad range of sediment facies that include: massive boulder gravel, open and closed work gravel, cross-stratified fine gravel, and plane bedded gravel. Massive gravel may contain sand intra-clasts locally. Sand deposits consist of a similar diverse range of sediment facies: massive and diffusely-graded sand, cross stratified sand, planar bedded sand. Finer sand is commonly ripple-scale cross laminated and climbing cross lamination is ubiquitous.

At this site gravel is overlain by a fining upward succession characterized by decreasing amount of gravel interbeds within medium and fine sand. The uppermost deposits are of predominantly diffusely-graded sand and climbing-cross laminated fine sand. The hummocky surface terrain reflects depositional mounds of fine sand in this mid efflux jet region of rapid sedimentation (Fig. 1-4.8) and, most probably, rapid depot centre avulsion under conditions of highly non-steady, non-uniform, flow, most probably related to hydraulic jump conditions at the efflux point (Fig.1-4.8)

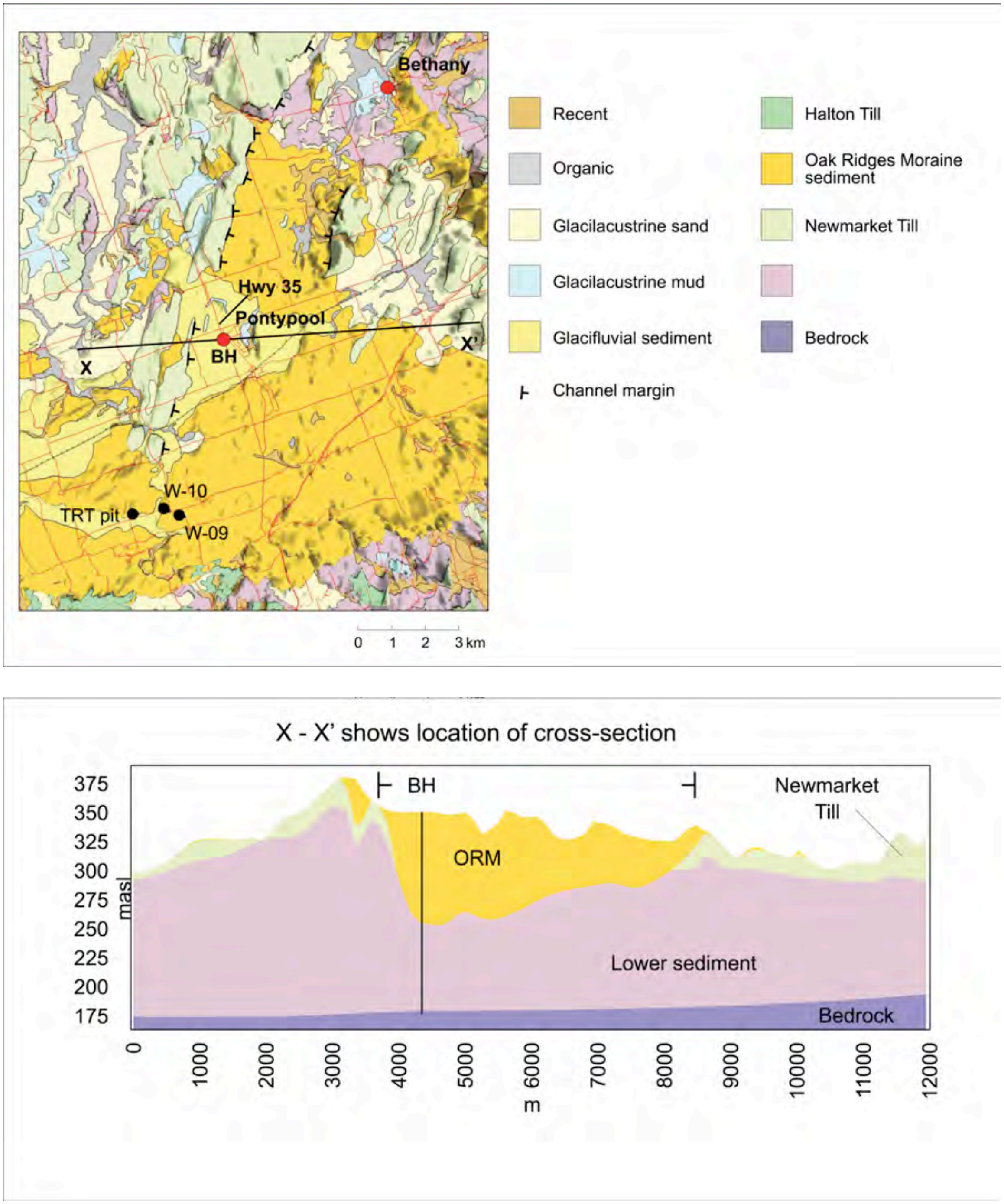


Figure 2-1.1. A) Geological setting of the Pontypool borehole north of aggregate pits. Note Newmarket Till upland to west of Pontypool borehole and fragments of Newmarket Till to east. B) Stratigraphic cross-section from geological model showing location of borehole in class 2 tunnel channel floored by Lower sediment.

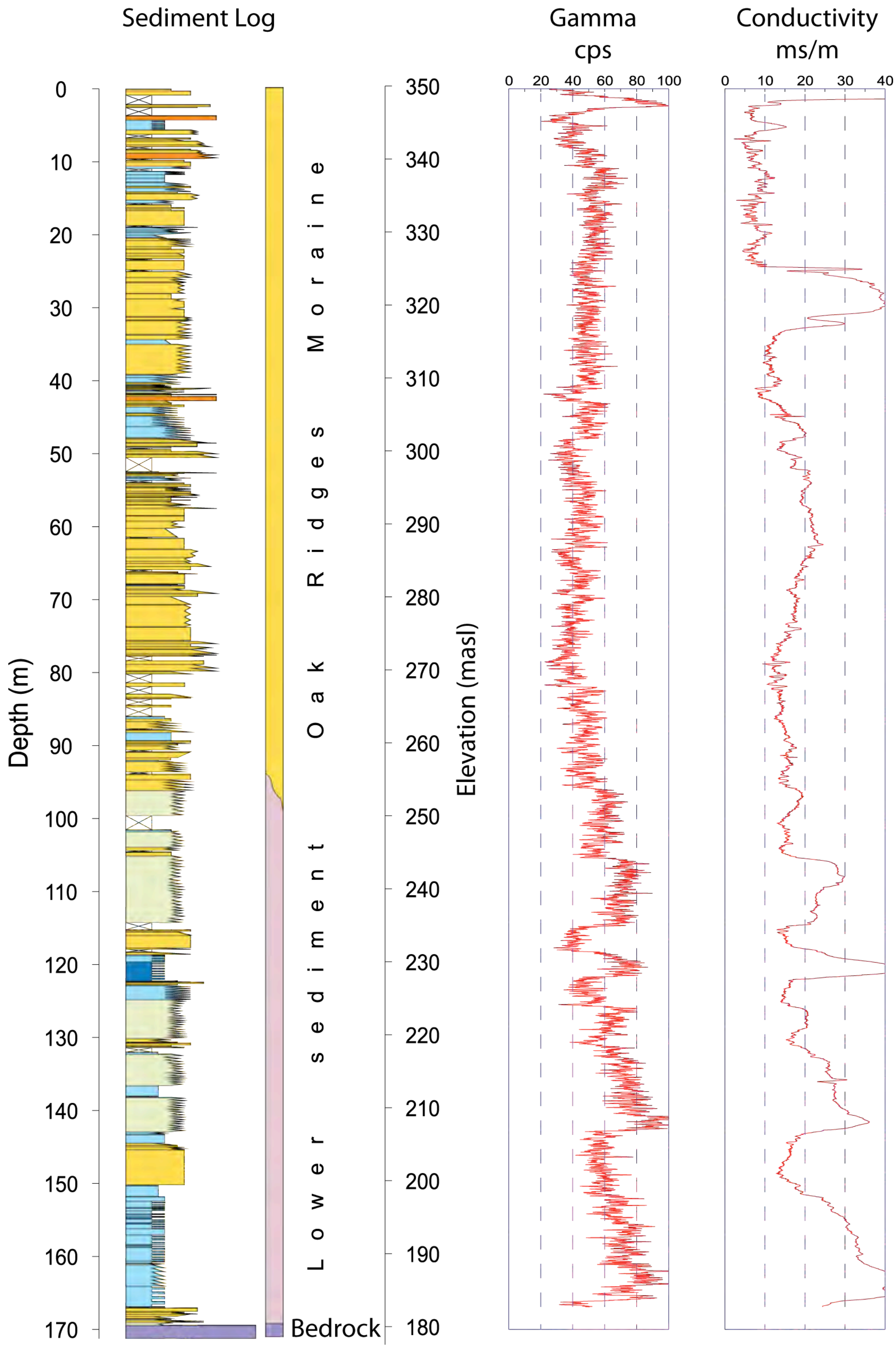

Sediment Log
Gamma
cps
Conductivity
ms/m
Depth (m)
Elevation (masl)
Oak Ridges Moraine
Lower sediment
Bedrock
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
350
340
330
320
310
300
290
280
270
260
250
240
230
220
210
200
190
180
0 20 40 60 80 100
0 10 20 30 40

Figure 2-1.2.(Previous Page) Stratigraphic log of the Pontypool borehole with down-hole gamma and conductivity logs. Note changes in the gamma log from the sediment interpreted as Lower sediment verses Oak Ridges Moraine sediment.

Figure 2-1.3. Oak Ridges moraine sediment a) microlaminated silt b) medium sand, c) gravel, d) matrix-supported, and d) clast-supported gravel. Lower sediment has, aquitard sediment, e) silt diamicton, f) silt-clay rhythmites, and aquifer sediment, g) fine sand, h) medium sand.

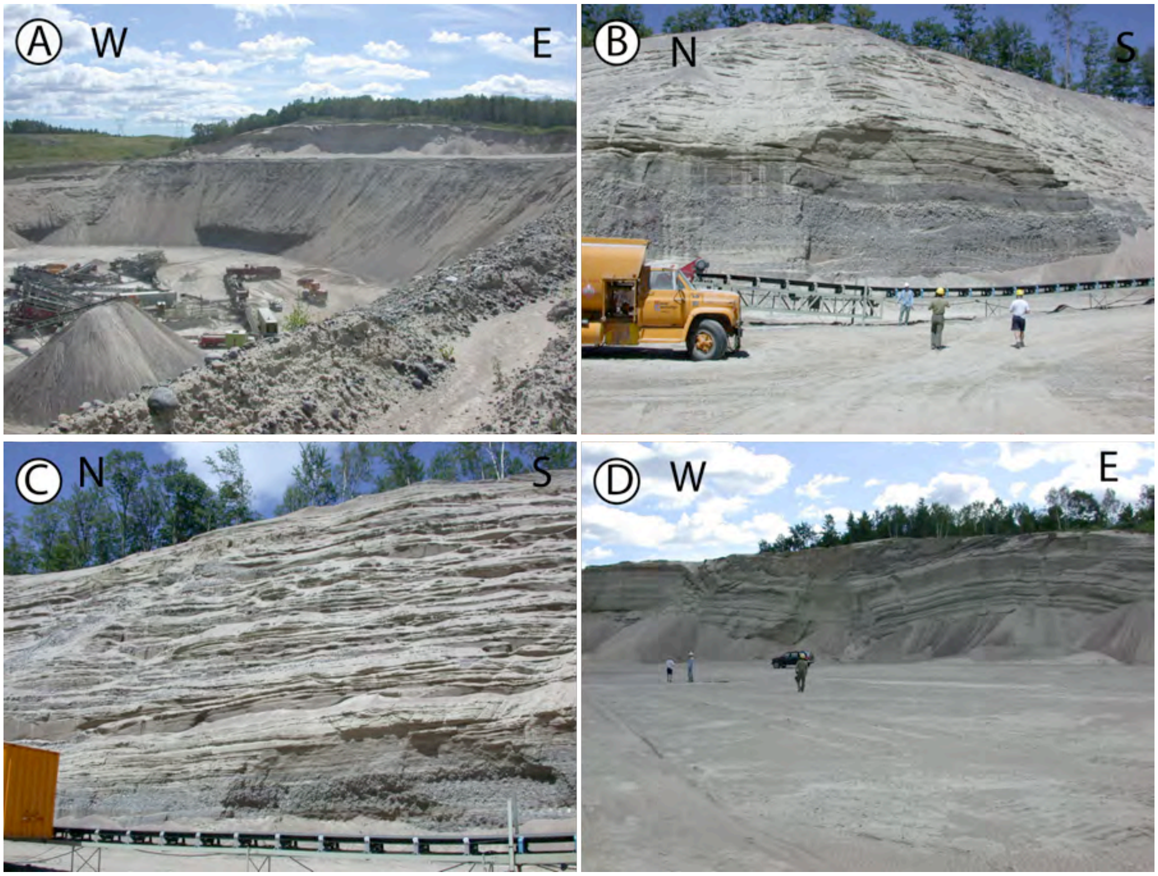


Figure 2-1.4. Sedimentary exposure in the Lafarage Pontypool aggregate pit. A) Overview of sediment stratigraphy with gravel exposed at base of face and above bench sand dominated face. B) Close-up of gravel at base of pit overlain by sand and gravel. C) Inter-stratified sand and gravel that makes up the central part of the exposed stratigraphy in A. D) Laterally continuous beds of fine sand with hummocky undulation from depositional aggradation mounds.

STOP 2-2A NORWOOD ESKER.

Sharpe, D.R. and Russell, H.A.J. Geological Survey of Canada

UTM: 742401E 4922116N; NAD 83, zone 18.

Access: via highway 7.

OBJECTIVES

3. Tunnel channel within drumlinized landscape
4. Esker ribbon deposit within tunnel channel
5. Sediment facies variability

ESKERS IN GLACIATED LANDSCAPES:

Eskers are common across glaciated landscapes, particularly the Precambrian shield areas of the Laurentide and Scandinavian ice sheets. In the Keewatin region, of northwestern Canada, eskers have been mapped with 10 – 15 km spacing and traced with semi-continuous ridge lines for 100s km. Eskers commonly occur in erosional glaciofluvial corridors that are up to 1-2 km wide and in larger tunnel valleys (**Fig. 2-2.1**).

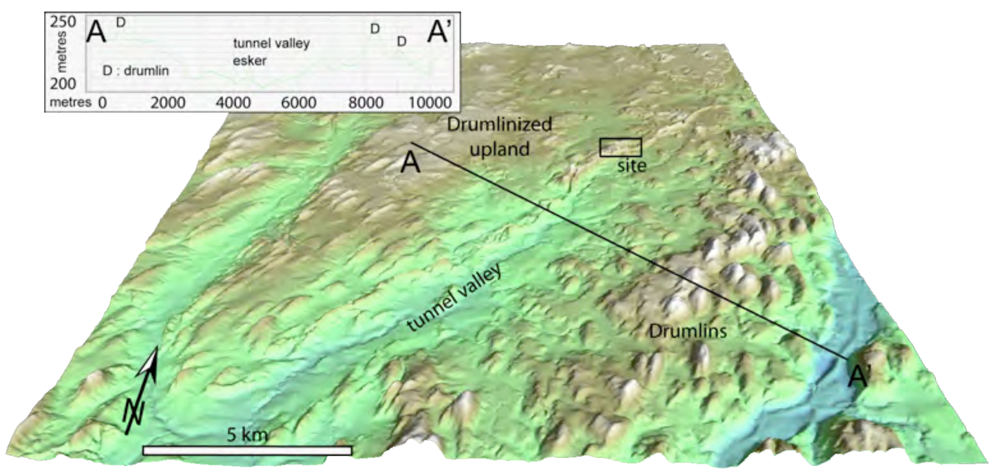


Figure 2-2.1. Perspective view of esker located in a tunnel valley flanked by drumlinized uplands. Elevation scale as per the next figure. Horizontal and vertical scale change with depth in the image.

Norwood Esker

On the Canadian Shield, only ~20 km to the north the Norwood esker is difficult to identify (Fig. 2-2.1) ; however, south of the Shield – Paleozoic bedrock contact the esker has a strong morphological form with relief of up to 30 m, is up to 1000 m wide, and extends for a length of 25-30 km.The esker is located in a broad shallow valley 6-7 km wide with ~ 50 m depth flanked by drumlinized till uplands. This broad valley is interpreted as a tunnel valley (Brennand, 1994).

The Norwood esker has four main morphologic elements (Brennand, 1994):

i) **Main Ridge:** The ridge broadens in places, but is not flat-topped. The long-profiles of the main ridges are irregularly and undulatory. The long-profiles show that crestlines trend upslope with an elevation change of 53 m from north to south.

ii) **Fans:** Two styles of fans are associated with the main ridge, major and minor fans, that extend from the main esker ridges in a downflow direction. Major fans are en-echelon, or overlapping, and occur towards the southern end of the eskers. Minor fans are connected laterally to the main esker ridges, occur on both sides of the ridge. They are developed preferentially at bends; however, they also occur along straighter portions of the ridges.

iii) **Beads:** A single bead is located - 1 km southwest of Norwood (pit N35). The bead is ~0.25 km wide and ~0.3 km long. This is joined to the main ridge by minor narrow ridges.

iv) **Hummocky Deposits:** Long (up to 8.5 m),wide (up to 0.5 km) bands of hummocky deposits, occur laterally to the main ridges towards the northern part of the Norwood eskers. These deposits are at lower elevations than the main ridges.

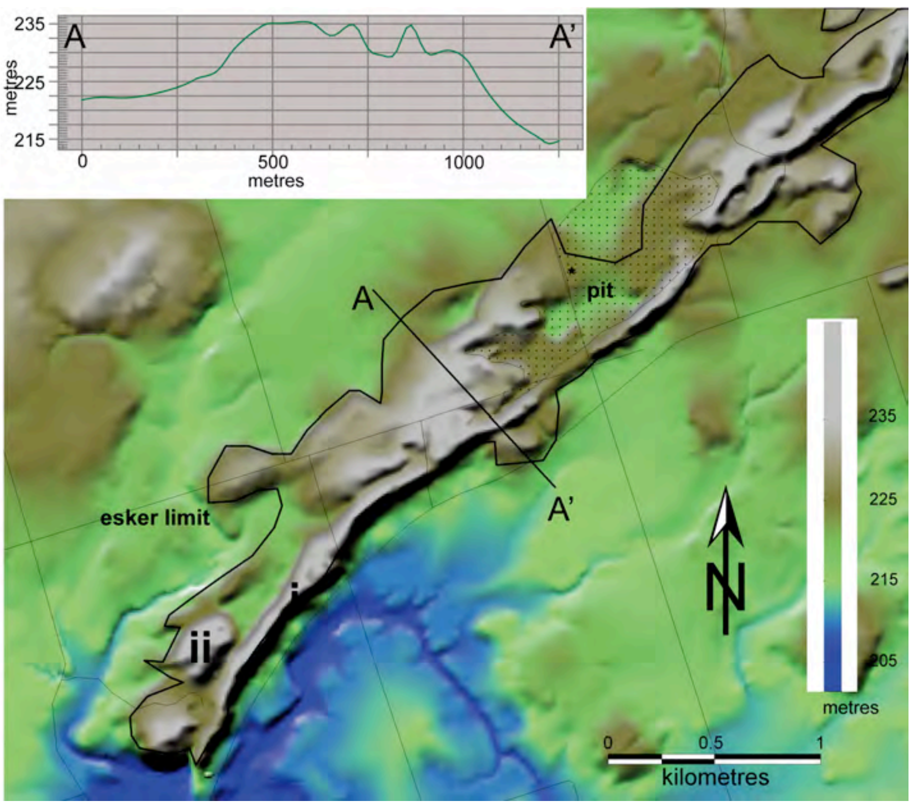


Figure. 2-2.2. Location of field visit to the Norwood esker. Stipled pattern is approximate location of aggregate pit (~0.5 km sq.) Note strongly asymmetric form of esker and landform elements.

Stop Location

This site highlights esker morphology, i) moraine ridge, ii) kettles, and iii) flanking esker fans along with the spectacular sediment facies. The esker ridge is predominately gravel with a dramatic increase in sand within fan and hummocky terrain deposits (Fig. 2-2.2). No diamicton was observed overlying the esker ridge; however, diamicton is intercalated with ridge sand and gravel (Brennand, 1994).

In the esker ridge beneath the hydro line, a spectacular boulder gravel occurs in the upper part of the stratigraphy (Fig. 2-2.3). The facies highlights the powerful meltwater discharges that are conveyed along subglacial conduits. The imbricated, sub-rounded nature of the esker indicates that even the largest clasts were entrained within the flow. The position of the boulder deposit highlights the aggradational character of eskers and the ability of subglacial conduits to maintain laterally constrained conduit dimension yet erode upward into the ice. The predominance of Paleozoic lithologies highlights the relatively short entrainment transport and rapid change in sediment provenance within esker environments.

Figure 2-2.3. A) Longitudnal section of the main esker ridge viewed fro the west. B) Boulder gravel facies in the upper part of the esker. Note clast imbrication and continuity of boulder horizon. C) Sand-gravel barform foresets in the flanking deposits of the esker. Note people for scale in all photos (nominally 1.8 h).

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