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Critical review
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Abstract: The Geological Survey of Canada (GSC) Aurora cored borehole intersects the Yonge Street aquifer (YSA), an important groundwater source in Ontario. The borehole, sited along a 7 km long seismic profile, was drilled in order to provide data to improve sustainable use and management of groundwater in Aurora well fields and the regional aquifer system. Results provide high-quality hydrostratigraphic reference data, geological context, and a prospecting model for this significant buried-valley aquifer. The improved conceptual hydrogeological model offers a plan to effectively stress and assess the YSA system.

A 130 m sedimentary succession unconformably overlies subhorizontal Whitby shale and a low-relief bedrock surface with no defined valleys. Gas seeping from the shale is trapped in Thorncliffe Formation, a regional aquifer below confining aquitards. The regional aquifer occurs below ~209 m a.s.l. and is a 80 m thick, fining-upward, sand and gravel sequence. It appears to represent a portion of a northeast-southwest-oriented channel, esker, and subaqueous fan system that fed Thorncliffe Formation aquifer sediments to the south. The newly identified aquifer system occurs above a regional unconformity within the succession. A 25 m thick Newmarket Till and silt-clay rhythmite sequence confines this aquifer. This aquitard drapes into Aurora basin, a possible pre-existing sediment valley. High clay content in aquitard rhythmites may allow conductivity logs to map it as a marker horizon. The overlying Oak Ridges Moraine (ORM) aquifer occurs as a 30 m thick gravel-sand-mud sequence above a second regional unconformity within the succession. This channel fill sequence is thinner than nearby 100 m thick ORM channel sediments.

Résumé : Le sondage GSC Aurora recoupe l’aquifère de Yonge Street, une importante source d’eau souterraine en Ontario. Ce sondage, situé le long d’un profil sismique d’une longueur de 7 km, a été réalisé afin d’obtenir des données pour améliorer l’utilisation durable et la gestion des eaux souterraines dans les champs de captage d’Aurora et le système aquifère régional. Les résultats du sondage fournissent des données hydrostratigraphiques de référence de grande qualité, un contexte géologique, ainsi qu’un modèle de prospection pour cet important aquifère de vallée enfouie. Le modèle hydrogéologique conceptuel amélioré permet de planifier efficacement des essais et une évaluation du système de l’aquifère de Yonge Street.

Une séquence sédimentaire d’une épaisseur de 130 m repose en discordance sur le shale subhorizontal de la Formation de Whitby et une surface rocheuse peu accidentée ne comportant pas de vallées bien définies. Le gaz émanant du shale est piégé dans la Formation de Thorncliffe, un aquifère régional surmonté par des aquitards de confinement. Cet aquifère régional se situe en deçà d’environ 209 m au-dessus du niveau de la mer et consiste en une séquence de sable et de gravier à granodécroissance ascendante, d’une épaisseur de 80 m. Il semble représenter une partie d’un système orienté nord-est–sud-ouest, constitué d’un chenal, d’un esker et d’un cône subaquatique, qui alimentait les sédiments de l’aquifère de la Formation de Thorncliffe plus au sud. Ce système aquifère, identifié récemment, repose sur une discordance régionale dans la succession. Une séquence de 25 m, constituée de till de Newmarket et d’une rythmite silt-argile, assure le confinement de l’aquifère. Dans le bassin d’Aurora, qui représente possiblement une vallée sédimentaire préexistante, cet aquitard moule la topographie. Une teneur élevée en argile dans les rythmites de l’aquitard pourrait faire en sorte que les diagraphies de conductivité le représentent comme un horizon repère. L’aquifère de la Moraine d’Oak Ridges sus-jacent est constitué d’une séquence de gravier-sable-boue d’une épaisseur de 30 m reposant sur une deuxième discordance régionale dans la succession. Cette séquence de remplissage de chenal est plus mince qu’une autre séquence de remplissage de chenal de la Moraine d’Oak Ridges à proximité, qui atteint une épaisseur de 100 m.

INTRODUCTION

Rationale

Regional knowledge of aquifer systems helps ensure effective groundwater-resource management. Ideally, this requires a geological understanding of the sedimentary system using a basin-analysis approach (e.g. Sharpe et al., 2002a). Recent work in the Oak Ridges Moraine (ORM) assembled, verified, and integrated basin-wide data from a variety of sources and scales of investigations to develop primary geological models of the stratigraphy, architecture, and sedimentary origin (e.g. Russell et al., 2005, 2006). This approach supports the progression from geological conceptualization and model development (Logan et al., 2006) toward hydrogeological analysis and flow modelling (Conservation Authorities Moraine Coalition, 2006). Paramount is the collection of high-quality subsurface data that aids in developing understanding of the geological framework that represents the sedimentary system of the basin.

Data from a number of continuously cored boreholes from the Oak Ridges Moraine area (Fig. 1) have been summarized in Sharpe et al. (2003a). Graphic logs of the sedimentary-stratigraphic succession and geophysical parameters were supplemented with information on location, construction, and piezometer installation (e.g. Knight et al., 2008; Logan et al., 2008). These 'Golden Spike' (GS) boreholes are essential stratigraphic references for the regional geological framework of the ORM (Fig. 2). However, only a preliminary interpretation was included in Sharpe et al. (2003a) for each of the sites, and now, additional geological analysis is required to help develop and refine current conceptual geological and hydrogeological models in the Aurora region.

New geological model in the Oak Ridges Moraine region and the Aurora basin

A brief review of recent geological models in the region traces key updates. Early geological models were based on layer-cake stratigraphy of the Scarborough Bluffs (Karrow, 1967; Eyles, et al., 1985) and inland extensions of key lower sediment units, e.g. Thorncliffe and Scarborough formations (Boyce and Eyles, 2000). Lateral continuity of organic beds within Scarborough strata and extensive thick Thorncliffe sands below Newmarket Till proved useful for correlation based on landfill cores.

These models were updated to include less extensive Halton Till, more prominent Newmarket Till, and a tunnel-channel system incised in Newmarket Till and forming the base of the Oak Ridges Moraine (ORM) (Fig. 2; Sharpe et al., 1996; 2002a, b) A meltwater-eroded regional unconformity comprising Newmarket Till drumlin uplands and tunnels channels (Sharpe et al., 2004) forms the geological framework for current groundwater modelling (e.g. Conservation Authorities Moraine Coalition, 2006).

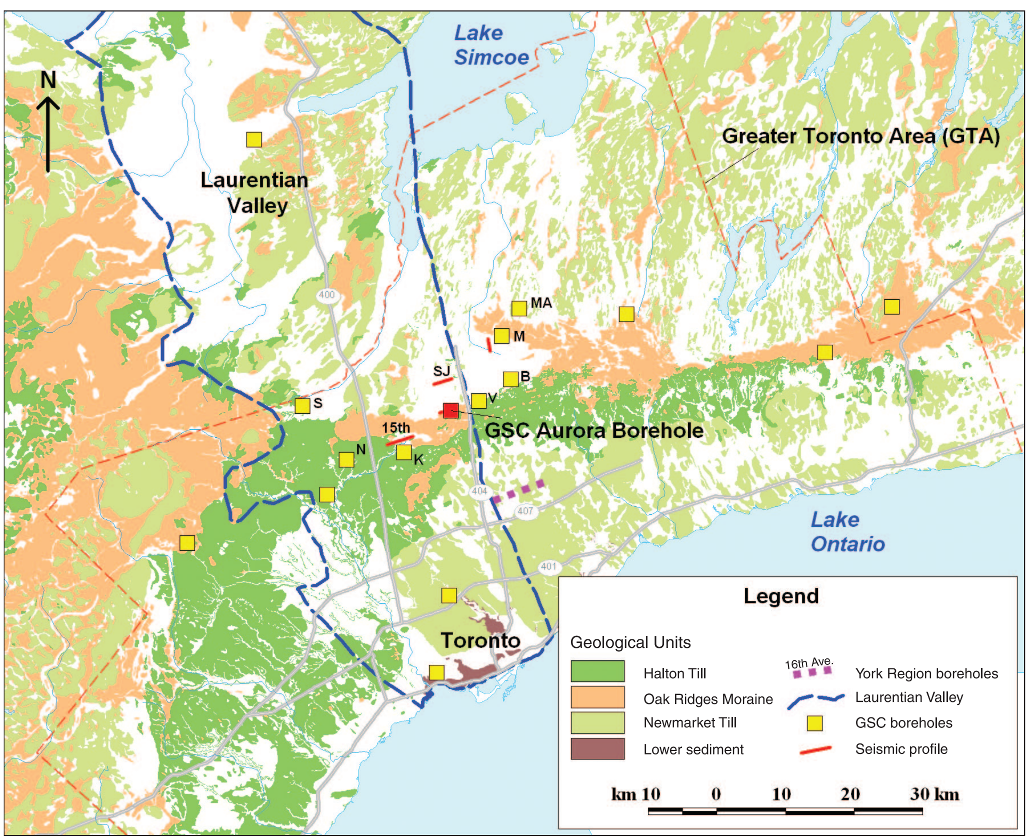


Figure 1. Location map of Golden Spike sites and selected seismic profiles in the ORM area. Note location of Aurora GS within the broad, poorly-defined outline of Laurentian valley. Other reference locations include: B = Ballantrae, K = King City, M = McGowan Ave, MA = Mount Albert, N = Nobleton, S = Schomberg, S-J = St. John's Side Road profile- V = Vandorf, 15th = 15th Ave. seismic profile.

New seismic-reflection profiling and borehole data support a revision to the regional conceptual model in the ORM region and the Aurora basin area specifically (Fig. 2, 3). The new data reveal a buried-channel aquifer system that is similar in geometry, style, and character, but older, deeper and perhaps more extensive (Pugin et al., in press), than the buried-valley (tunnel channel) aquifer system comprising the ORM sediments (Sharpe et al., 2002a, b). Existing conceptual models of the lower sediment strata consist of prominent aquifers in the Scarborough Formation, and/or, in channels eroded in bedrock and filled as part of the Laurentian valley system (e.g. Conservation Authorities Moraine Coalition, 2006); Aurora Golden Spike (Sharpe et al., 2003a) data were not used in these system models. Thorncliffe Formation aquifers may also be part of this conceptualization as subaerial delta models; however, the proposed channel/esker subaqueous-fan deposition model has not been explicitly presented with data to support its hydrogeological importance and application as is reported here.

The new hydrogeological conceptualization in the Aurora area should help improve understanding for the continued use and management of the Aurora well field and groundwater in the Yonge Street Aquifer. The presented field data and analysis comprise the first defensible, high-quality hydrostratigraphic data, which identify the geological setting and context for this significant groundwater reservoir. Field-data collection was partly funded by the Regional Municipality of York and the results are intended to inform the public, water managers, conservation authorities, scientists, and consultants alike.

Reference objectives

This report is part of a number of ORM 'Golden Spike' summaries that use continuously cored and sedimentologically logged boreholes as a starting point to provide more interpretive insight of the local geological model, supported by detailed geological mapping (Sharpe et al., 1997),

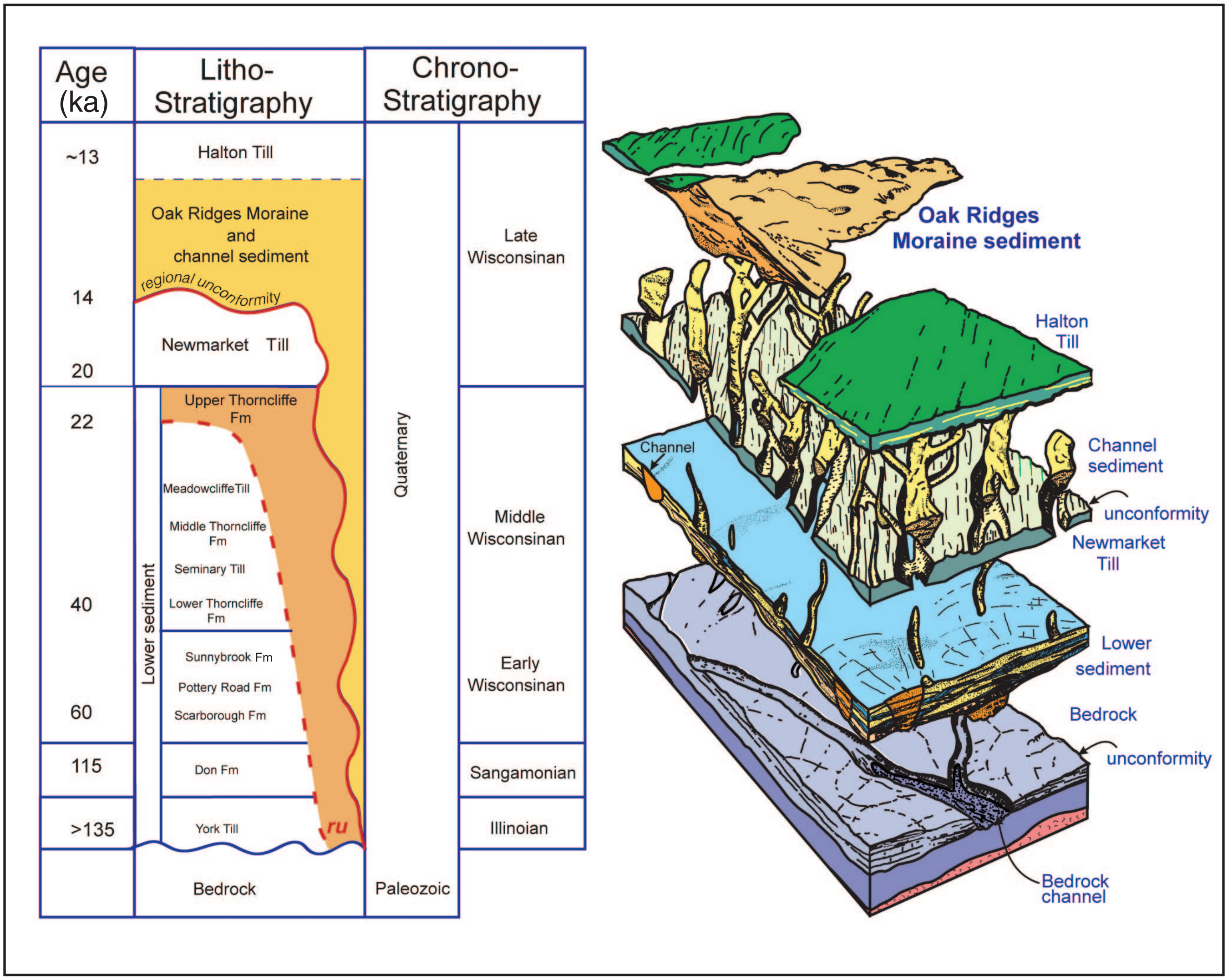


Figure 2. Geological model of the ORM. Note that the many units below Newmarket Till (Lower sediment) and defined at Scarborough Bluffs on Lake Ontario, are not readily identified 30 km to the north near Aurora.

seismic profiles (Pugin et al., 1996; Pugin et al., 1999), downhole geophysics (Pullan et al., 2002), and 3-D modelling (Logan et al., 2002; 2005). These summaries have a companion digital compilation that includes all core-logging details, analyses, and full photographic record to form a borehole database (e.g. Russell et al., 2004; 2006; Knight et al., 2008; Logan et al., 2008). The goals for the summaries of high-quality data are: a) to test and advance the local geological model with guidance from the regional geological model (Fig. 2), and, b) to provide improved hydrostratigraphic control for ongoing groundwater modelling in the region (e.g. Wexler et al., 2003; Holysh et al., 2004; Conservation Authorities Moraine Coalition, 2006) and Aurora area (e.g. Gartner Lee Ltd., unpub. groundwater rept. for York Region, 1996).

Geological setting

The Aurora GS borehole (AGS) is collared at ~267 m a.s.l. in the Holland River watershed, a clayey glacial lake basin (Fig. 1). The site lies on the northwest edge of hummocky, sandy ORM, Bloomington fan sediments (Fig. 3; Barnett et al., 1998), partly overlain by Halton Till (Sharpe and Barnett, 1997) and related mud-rich deposits. The regional geological and hydrogeological context of the Aurora site has recently been reported (Gartner Lee Ltd., unpub. rept.for York Region, No. 8670, 1999), as aquitards / aquifers with no conceptual framework for the depositional setting and sediment architecture. These simple descriptions do not aid effective correlation of hydrostratigraphic units across the area. Added stratigraphic details were presented as a lithological section with interpretations of deep- and shallow-channel aquifers. A well documented report on an adjacent property, Magna International, provides additional local hydrogeological context and parameters (Gartner Lee Ltd., unpub. rept., 1999).

The AGS borehole occurs toward the eastern end of an east-west-oriented Aurora seismic line that is ~7 km in length and crosses the trend of the Aurora basin and probable north-south tunnel channel (Fig. 3; Russell et al., 2003). A second, ~2.5 km seismic line, St. John's Side road, about 4 km to the north (Fig. 3), is also used in this analysis. These seismic data provide laterally continuous stratigraphic architecture in sediments overlying bedrock. Though the bedrock surface is not always well defined, depth estimates, calibrated with available boreholes, show bedrock elevation to vary from ~110 to 130 m a.s.l. along the 7 km of the Aurora profile. This erosion surface includes a gently dipping bedrock slope ~ 4 km west of the AGS borehole (Pugin, unpub. rept.,1997) that may form the shallow eastern edge of a wide Laurentian Valley system (e.g. Brennand et al., 1998).

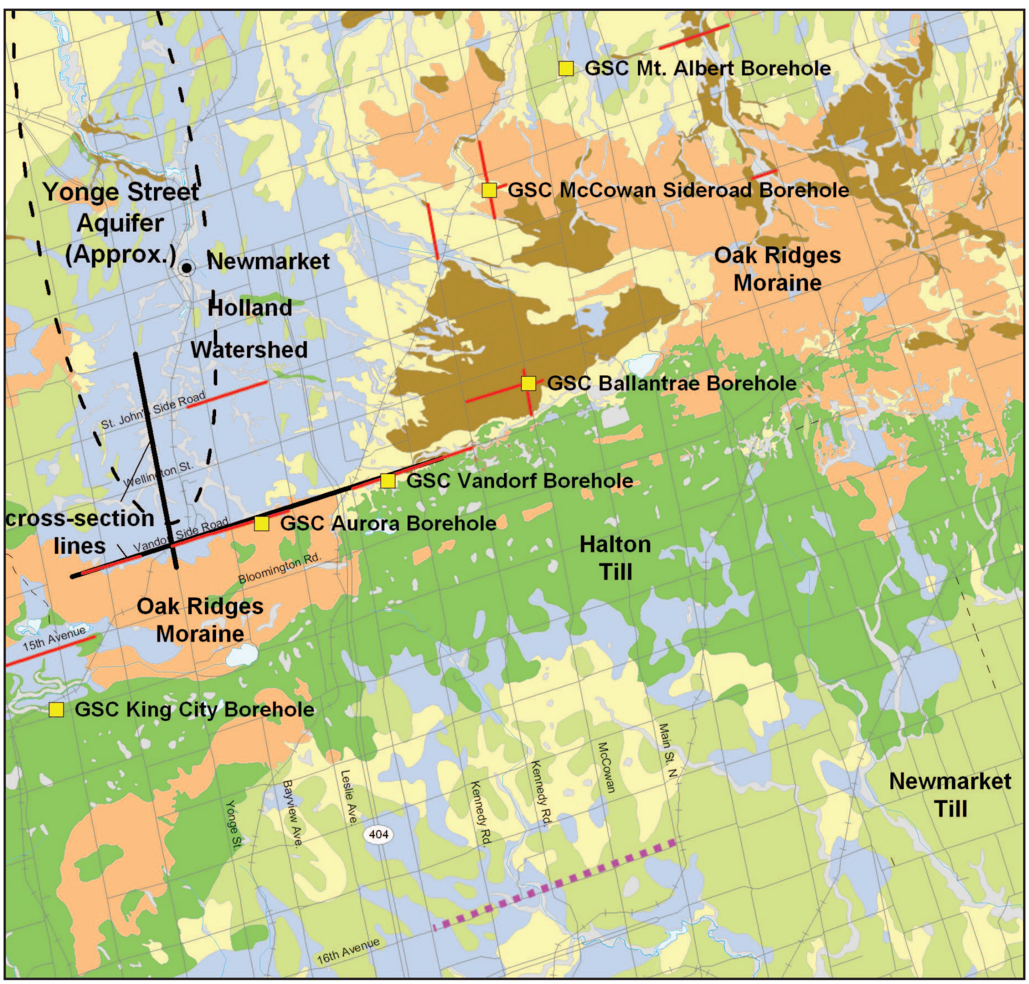


Figure 3. Geological map of the Aurora region, showing surface geology and location of seismic profile and related cored boreholes. Red dashed line on 16th Avenue shows location of Figure 8 borehole section. The brown unit with GSC Ballantrae borehole is the Ballantrae fan.

Methods

Geological mapping (Sharpe et al., 1997; 2005; 2007), geophysics, mud rotary drilling and borehole and core analysis were carried out for this study. The GSC collected ~50 line-km of shallow seismic-reflection profiles in this region using state-of-the-art 24- or 48-channel engineering seismographs, single 50 Hz vertical geophones as receivers, and a 12-gauge in-hole shotgun source. The compressional-wave data were collected with source and geophone spacing of 5 m with the source positioned 5 m off the end of the array, resulting in source-receiver separations of 5 to 120 m. A summary of this work, including data processing and interpretation can be found in Pugin et al. (1999).

A continuous core was drilled (All Terrain Drilling Ltd.), collected and documented with visual description and a complete photographic record. Sedimentological data were collected on a bed-by-bed basis. The core was sampled for grain size and total organic content. Reported depths for continuous core were adjusted using measurements from the spool counter of the downhole geophysical logger cable. The stretch in the geophysical logger cable was carefully calibrated.

A suite of geophysical logs, including natural gamma, apparent conductivity, magnetic susceptibility, P-wave velocity, relative density, spectral density ratio and temperature, were acquired (see Douma et al., 1999; Pullan et al., 2002; Hunter et al., 1998).

STRATIGRAPHIC SUMMARY OF AURORA GOLDEN SPIKE AREA

Preview

Integration of the Aurora GS (AGS) borehole and related seismic profiles define six main stratigraphic packages and three unconformities that, from the base upwards, are (Fig. 4): 1) Whitby Formation shale; bedrock surface unconformity; 2) Older sediment (not present in AGS borehole); channelized unconformity; 3) Thorncliffe Formation sand and gravel; 4) Newmarket Till; 5) a silt-clay rhythmite sequence; regional channelized and drumlinized unconformity; and, 6) a fining-upward ORM channel fill sequence. The 80 m thick aquifer sequence (identified as Thorncliffe Formation) appears to represent a northwest-southeast-oriented channel, esker, and subaqueous fan system that fed Thorncliffe Formation aquifer sediments to the south.

This report interprets a shallow (~30 m) meltwater channel (base at ~ 235 m a.s.l.) and sediment fill corresponding to the ORM stratigraphic unit. The significance of this interpretation is that the ~ 80 m thick sequence (127–209 m a.s.l.), found beneath this channel fill and below ~25 m thick Newmarket-clayey rhythmite aquitard sediments, correlates with screened intervals for several Aurora municipal wells and the 'Yonge Street Aquifer' (YSA) (Gartner Lee Ltd., unpub. rept., 1996).

Unit 1- Whitby Formation

Black shale occurs below 127 m a.s.l. in the AGS and was cored for ~4 m. It consists of ~1 m of soft silt to clay-silt shale and shale fragments over dense black shale (Fig. 4, #9). This unit emits a petroliferous odour.

<u>Geophysical signature</u>

At the AGS borehole, definitive measurements of the physical characteristics of the shale bedrock are limited because the geophysical logging tools barely penetrated the unit. However, the shale contact is defined at 138 m depth (127 m a.s.l.) by an abrupt increase in gamma counts and an increase in compressional (P-) and shear (S-) wave velocities (Fig. 5). The upper shale contact does not have a sharp, strong reflection on seismic-reflection data in this area, or in other seismic-reflection data in the ORM (Fig. 6; Pugin, unpub. rept., 1997). This is attributed to the inferred soft, indistinct bedrock surface and weak contrast in density and seismic velocity at the bedrock-sediment contact (e.g. Fig. 5).

<u>Stratigraphic context</u>

The measured shale elevation of ~127 m a.s.l. at AGS is consistent with a broad low that may be part of the Laurentian Valley (Brennand et al., 1998). Although the bedrock reflection is not always well defined along the ~7 km Aurora seismic profile (Fig. 6a), bedrock elevation is constrained at the two borehole locations toward each end of the profile, (~127 m a.s.l. at Aurora borehole and ~110 m a.s.l. at RMY-TH1–1988). There is no indication in the seismic data that bedrock elevation varies more than ~20 to 30 m along this line. It is of note, however, that ~5.5 km to the north (A5, Fig. 3) bedrock elevation was cited at ~10 m a.s.l. (Gartner Lee Ltd., unpub. rept. No. 86151, 1987) and explicitly modelled as a deep valley. Additional seismic data acquired on St. John's Side road (east-west profile parallel to the Aurora line, 4 km north of the Aurora profile and ~1.5 km south of the 10 m a.s.l. borehole; Fig. 7b), suggests bedrock may be ~ 80 m a.s.l., but gives no indication of a bedrock structure that would be consistent with the extreme bedrock depth reported just to the north (Gartner Lee Ltd., unpub. rept., 1987). Three possibilities arise: a) bedrock rises steeply from the Gartner Lee Ltd. (unpub. rept. No. 86151, 1987) borehole (~70 m in 1.5 km) to the south; b) a deep very narrow gorge occurs but was undetected in the seismic data; and c) the report of anomalously deep bedrock at the northern borehole needs to be re-assessed.

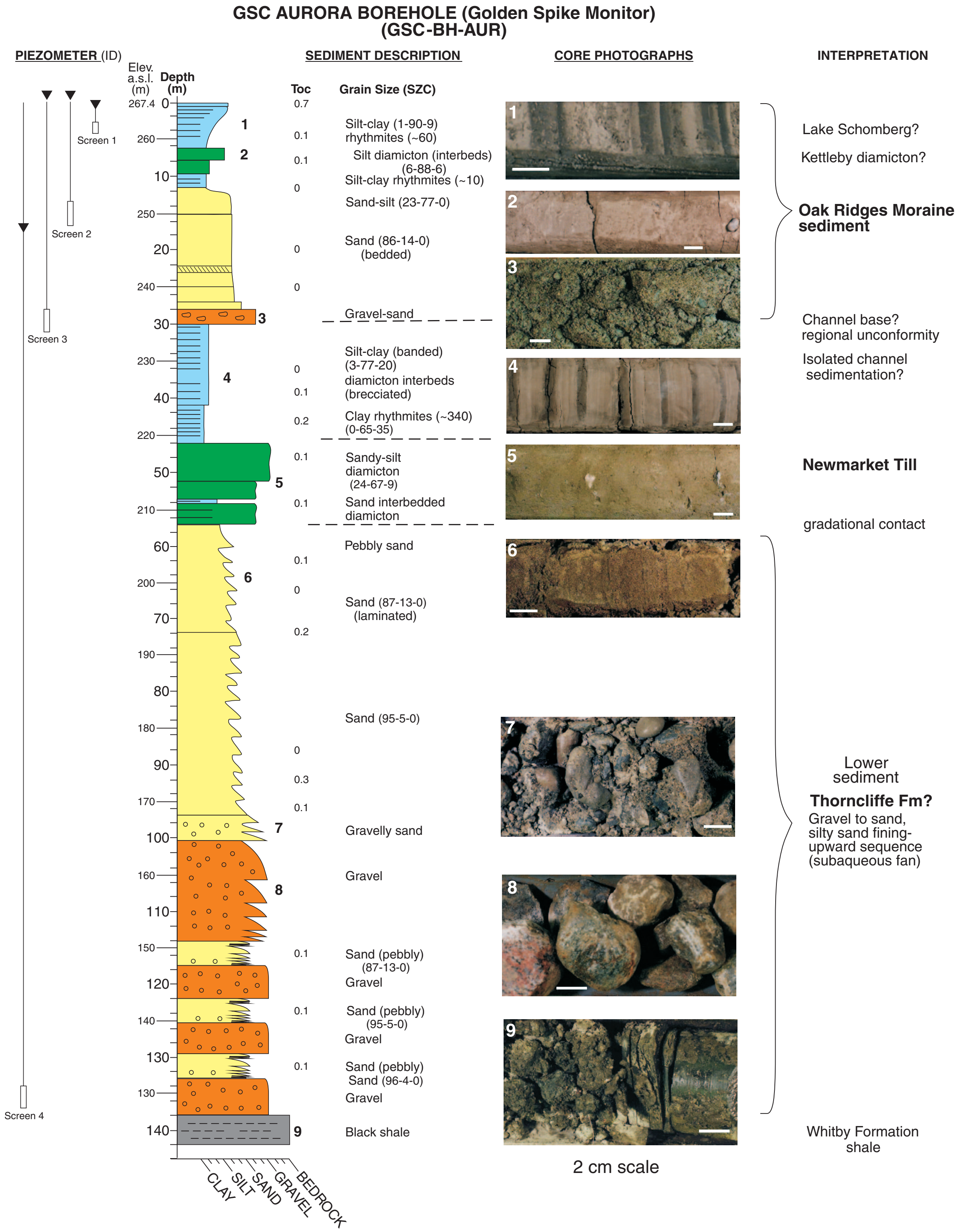


Figure 4. GSC Aurora borehole: Sediment logs of AGS core show major sediment units, descriptions with rhythmite counts, TOC, grain size, photographs of prominent sediment facies in the core, and stratigraphic interpretation. Note also, four piezometer positions.

Unit 2 – Older sediment

On the basis of seismic reflection data, ~75 m thick sediment sequence (~200–125 m a.s.l.), consisting of diamicton, gravel, sand, and mud, occurs west of the AGS borehole. Note that this unit may be expected to include a number of lower sediment units (Fig. 2), except that Thorncliffe Formation cuts into older, deeper sediments.

Geophysical signature

West of the channel (Fig. 6), the seismic-reflection profile shows a slightly irregular tabular reflector architecture in a stacked sequence ~20 to 75 m thick (~200–125 m a.s.l.) that can be traced above low-relief bedrock for ~3 km from Bayview Avenue west beyond Bathurst Street. Bed sets are ~10 to 15 m thick and some lower strata appear to thin and dip westward over this interval. In the vicinity of Bayview Avenue, these subhorizontal reflectors appear to be truncated by the channel feature that extends eastward for ~2.5 km to Leslie Street (Fig. 6).

Unconformity

The AGS seismic profile (Fig. 6) reveals a 1.5 km wide channel that straddles the position of the Aurora borehole and cuts through older sediments (unit 2). This channel is filled mainly with coarse sediment (*see* unit 3). The west channel margin cuts across >100 m of upland or inter-channel sediment to bedrock in ~1 km slope. The east channel bank is beyond the seismic profile. Recent data (Pugin et al., in press) show similar channels in the area to be ~2 to 4 km across and they eroded to depths of ~150 m.

Stratigraphic context

Older sediment strata do not occur at the AGS borehole location as they has been eroded away to bedrock at ~125 m a.s.l. by a 100 m deep channel (Fig. 6). Lithologies of the inter-channel strata are documented in borehole RMY that intercept the west end of the seismic profile (Fig. 6). From the base up, silt and muddy diamicton rest below gravel that grade upward to silt below Newmarket Till. There is insufficient high-quality data in the region to provide detailed stratigraphic assignment for these sediments. However, a key regional marker bed, Scarborough Formation organic-rich sand (Karrow, 1967), which occurs at Vandorf and Ballantrae Golden Spike boreholes a few kilometres to the east (Sharpe et al., 2003a), is not present at the AGS site in the Aurora basin, but may occur as interchannel sediment. Geophysical data however, provide clear evidence of erosion within Older sediment units below Thorncliffe Formation. Note, there is no evidence of tunnel channel breaching Newmarket Till near Yonge Street.

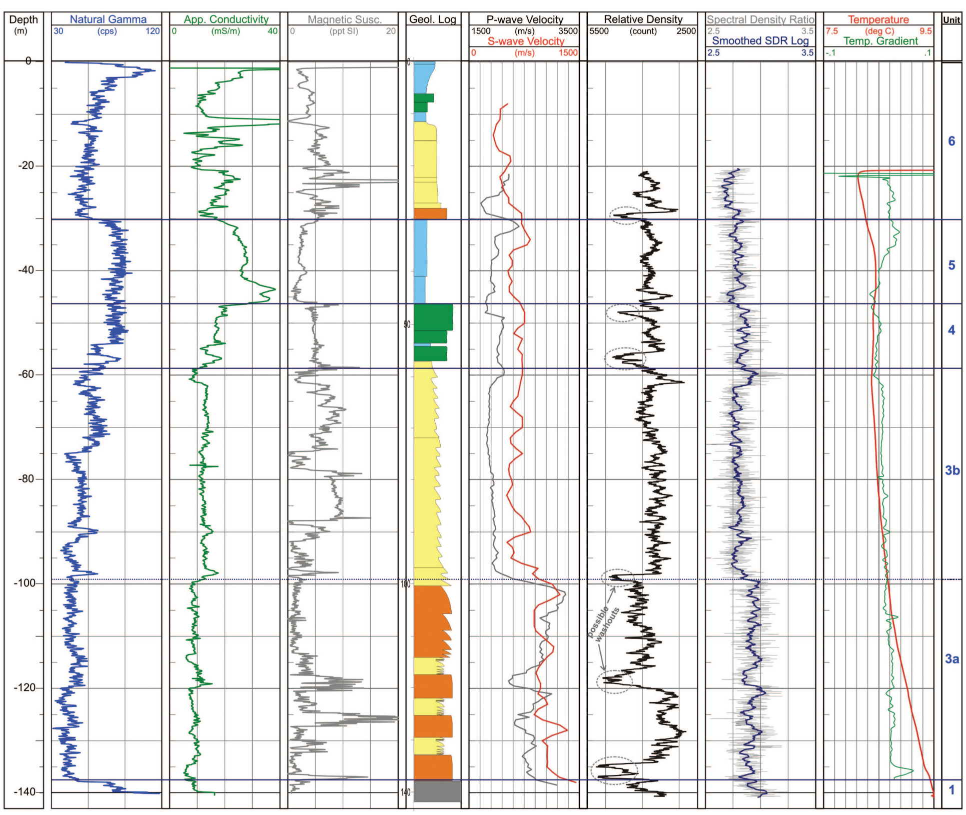
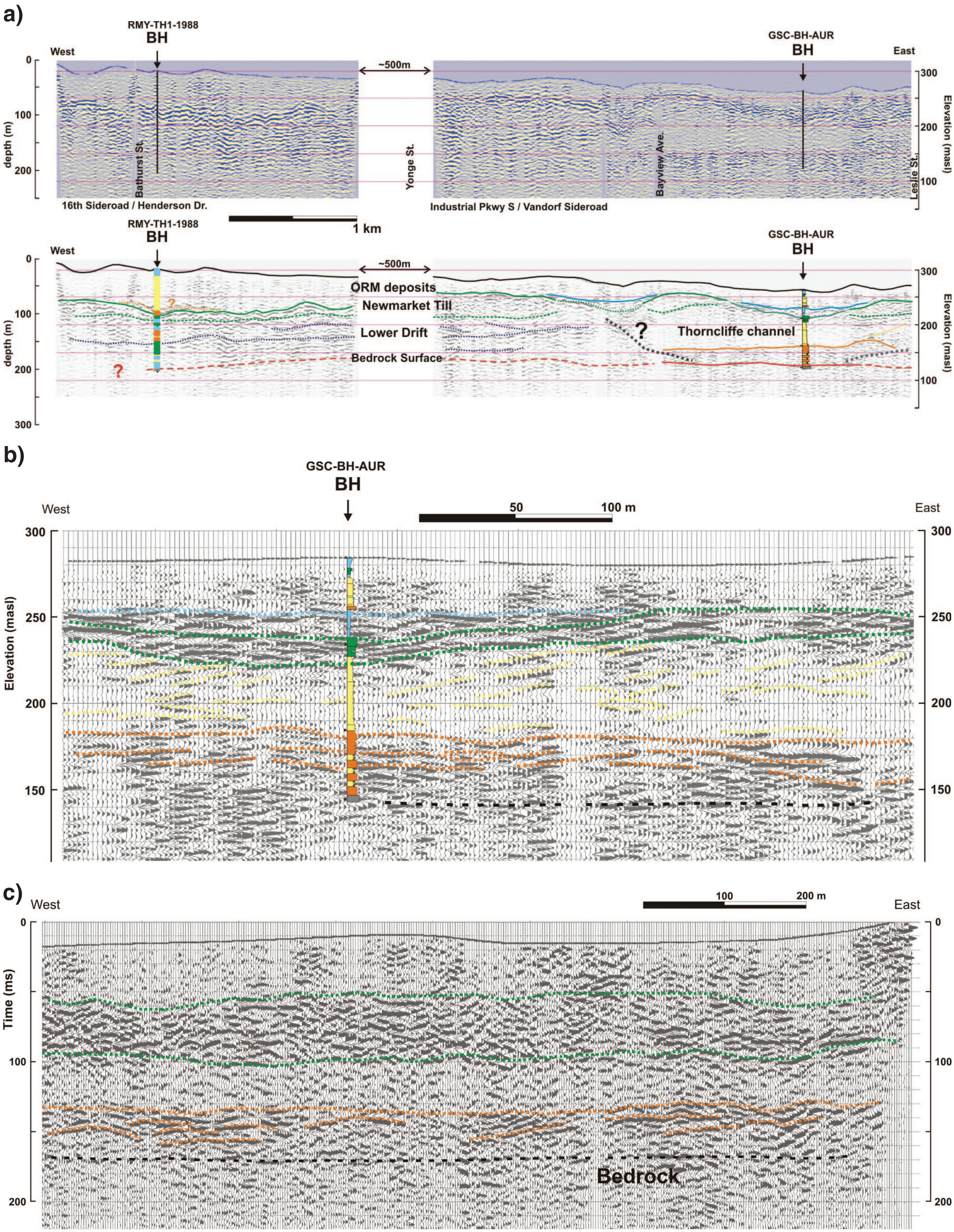


Figure 5. Geophysical and sediment logs of the Aurora golden spike. Suite of geophysical downhole logs (natural gamma, conductivity, magnetic susceptibility, relative density, spectral density, temperature, p-wave velocity, and s-wave velocity obtained in the AGS borehole. Bedrock (unit 1) is clearly defined by high natural gamma counts and seismic velocity. The lower aquifer unit (unit 3a; sands and gravels attributed to the Thorncliffe Formation) is characterized by high seismic velocities and density. The upper aquifer unit (unit 3b) exhibits variable magnetic susceptibility but is otherwise difficult to distinguish from the overlying sandy Newmarket Till (unit 4) based solely on these logs. The silt-clay rhythmite sequence (unit 5) is clearly outlined by high gamma counts and conductivity, combined with low magnetic susceptibility. The contact with the overlying ORM deposits (unit 6) is very sharp and denoted by an abrupt decrease in gamma counts.



a)
RMY-TH1-1988
BH
GSC-BH-AUR
BH
West
East
~500m
depth (m)
Elevation (masl)
Bathurst St.
Yonge St.
Bayview Ave.
Leslie St.
16th Sideroad / Henderson Dr.
Industrial Pkwy S / Vandorf Sideroad
1 km
ORM deposits
Newmarket Till
Lower Drift
Bedrock Surface
Thorncliffe channel
b)
50
100 m
Elevation (masl)
c)
100
200 m
Time (ms)
Bedrock

Figure 6. a) Seismic section obtained along a 7 km long east-west line intersecting the location of the AGS (*see* location in Fig. 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-scale architectural structure is evident (units 1–6), and outlines a channel within the lower sediment sequence which is interpreted to be infilled with thick Thorncliffe Formation sands (3b) and gravels (3a). Note additional deep borehole control on the west end of the profile (RMY-TH1–1988). **b)** Details of the seismic section obtained in the vicinity of the AGS (plotted without vertical exaggeration). At this scale, details of the structure within the Thorncliffe sands and gravels (yellow and orange) can be seen. The layers within the upper sand unit appear to have a marked component of dip to the west in the plane of this section, giving an indication of the paleoflow direction to the southwest. **c)** Eastern portion (~1 km) of the seismic section obtained along St. John Side road, approximately 4 km north of the AGS (*see* location in Fig. 1). No boreholes are available to aid in interpreting this section, but the seismic facies are very similar to those observed around the AGS (Fig. 6a, b). Thus it is suggested that these data indicate a potential sand and gravel (orange) aquifer package overlying the bedrock surface (black lines), which is level and show no deep valleys.

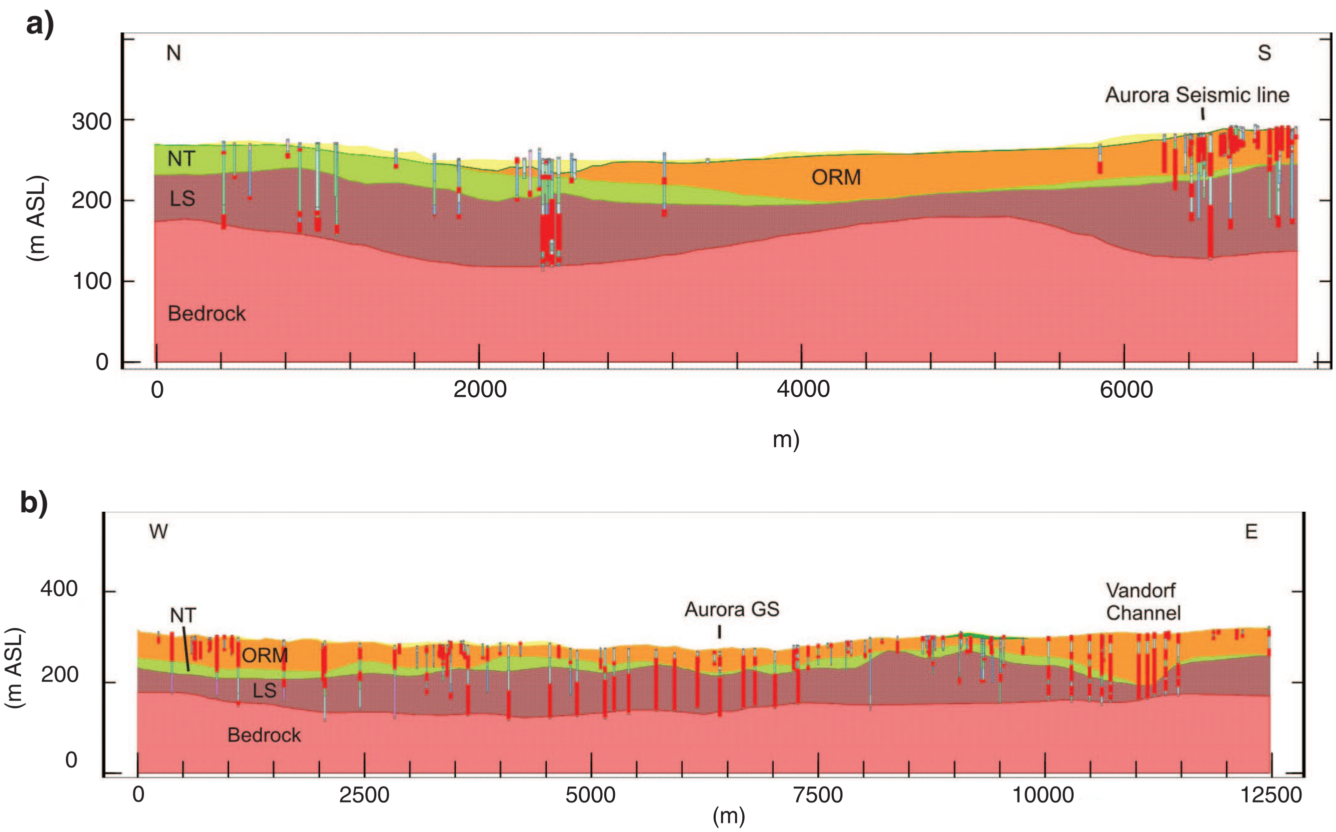


Figure 7. Geological and stratigraphic cross-sections show the AGS in context: **a**) north-south stratigraphic model section; **b)** east-west Aurora stratigraphic model section. Note vertical exaggeration is >100:1.

Unit 3 - Thorncliffe Formation

In AGS, an ~81 m thick sequence from 127–209 m a.s.l. (57–138 m depths), fines upward from gravelly to sandy sediment. The lower 40 m consists of alternating 5 to 10 m thick gravel-sand units; the 41 m upper sequence consists of ~1 to 2 m thick graded sand beds (168–209 m a.s.l.; Fig. 4).

Geophysical signature

Within the channel, distinctive strong hummocky reflectors (*see* Pugin et al., 1999) show the geometry of a lower 30 to 40 m thick gravel sequence identified in core (Fig. 4). The seismic profile also reveals a laterally extensive (~ 2.5 km east-west), ~30 to 50 m thick package of weaker reflectors to complete the channel fill. This package matches the sandy sediment in the core.

Gravel units are well defined by an increase in the spectral density and by high P- and S-wave velocities in downhole geophysical logs (Fig. 5). Thus distinct seismic facies can be used to trace this stratigraphic unit laterally, with the gravel unit characterized by a high-amplitude (strong reflector) facies. The overlying sand exhibits very little variation in density or seismic velocity and hence is characterized on the seismic profiles as a low-reflectivity facies. It has high and variable magnetic-susceptibility signals (Fig. 4) identifiable as heavy-mineral bands in core (Fig. 4, #6). The upper 12 to 14 m is characterized by higher gamma counts, interpreted as slightly finer grained sediment.

Sedimentology

At the drill site, core recovery was incomplete in gravel, but drilling-rate variation helped define trends within gravel-sand intervals. Gravel content is 20 to 25% in gravel beds with clast size ~2 to 6 cm (Fig. 4, #7, 8; Gorrell, unpub. rept., 1999). The lower 40 m consists of 5 to 10 m thick gravel-sand units (Fig. 4) with normal to reverse grading. Low-amplitude reflections within the unit suggest that there is a foreset bedding structure with a component of dip toward the west, particularly east of the Aurora borehole (AGS) (Fig. 6b). Beds thin to ~1 to 2 m thick graded sand units in the upper sequence (168–209 m a.s.l.). At the borehole, the tabular lower, sandy gravel sequence (Fig. 6), is capped by a thin (5–10 cm) clayey-silt bed at ~98 m depth (*see* natural gamma log, Fig. 5). Trends in natural gamma and conductivity indicate an overall fining-upward pattern in the ~81 m sequence, interpreted to indicate semicontinuous sedimentation.

Sand beds may also be crossbedded or crosslaminated with bed sets ~30 to 40 cm thick. A small amount (0.1–0.3%) of total organic carbon (TOC) is present in the sandy sediments (Fig. 4). A pungent odour was apparent between ~65 and 110 m below ground surface (b.g.s.) (201–166 m a.s.l.). It is interpreted as gas (methane, HS) released from underlying shale.

Stratigraphic context

The 81 m thick sand and gravel unit forms a traceable package on the seismic profile in this area (Fig. 6). It can be mapped as a contiguous unit beneath the distinctive seismic signature of Newmarket Till (Fig. 4, 5) for at least 1.5 km in an east-west direction. The erosionally based package is also identified at nearby sites (Sharpe et al., 2003a). However, the coarse sand and gravel unit at the base of the sequence (165–135 m a.s.l.) has not been readily traced (>3 km) south of the seismic line due to sparse borehole records (Fig. 3).

Coarse crossbedded seismic facies are similar to those identified, and confirmed to comprise gravel in drill core, along the Grasshopper Road seismic profile south of ORM (Sharpe et al., 2003b). Reflector patterns representing the sand and gravel sequence also occur beneath Newmarket Till, west of the channel in lower sediment (Fig. 6b). A similar sequence of cross-bedded sand and gravel has been observed in pits in the Barrie area (Slattery and Sharpe, unpub. rept., 2011).

A small amount of TOC is present in coarse to medium Thorncliffe sand (Fig. 4) that indicates possible reworking of eroded organic-rich older sediment that can contain centimetre-scale beds containing high concentrations of organic material.

Depositional interpretation

The 81 m thick gravel and sand sequence is inferred to represent a fining-upward subaqueous-fan sediment sequence. This fining-upward trend is similar to sediment trends reported for a 60 m thick gravel and sand sequence (238–174 m a.s.l.) below Newmarket Till at Holt ~ 20 km to the northeast (OGS-93–14; Sharpe and Barnett, 1997; Fig 1). The Aurora GS sequence appears to be part of a ~northeast-southwest-oriented feeder system to the extensive sheet sands that occur in the Thorncliffe Formation (Sibul et al., 1977), north and primarily to the south (Logan et al., 2005). A series of boreholes for a deep east-west trunk sewer (~10 km long) near Markham (GeoCanada, unpub. rept. prepared for the town of Markham, 1995) shows Thorncliffe Formation sheet sand (Fig. 8) below ~15 m thick, continuous surface-mapped Newmarket Till. It comprises a variable thickening (40 m) and thinning (~10 m) sand and gravel sequence. This coarse sequence is oriented ~northeast-southwest and is laterally transitional to, and overlain by, an extensive inter bedded, fine sand-mud sediment package (Fig. 8). Recent pumping test results support a northeast-southwest paleoflow pattern (Inspec-Sol/Conestoga-Rovers and Associates, unpub. rept. for Ontario Ministry of Environment, PTTW 7481-635N8A, 7850-685M75, 3061-6YVR2F, 2005). Gravel is not common in Thorncliffe Formation where it is most

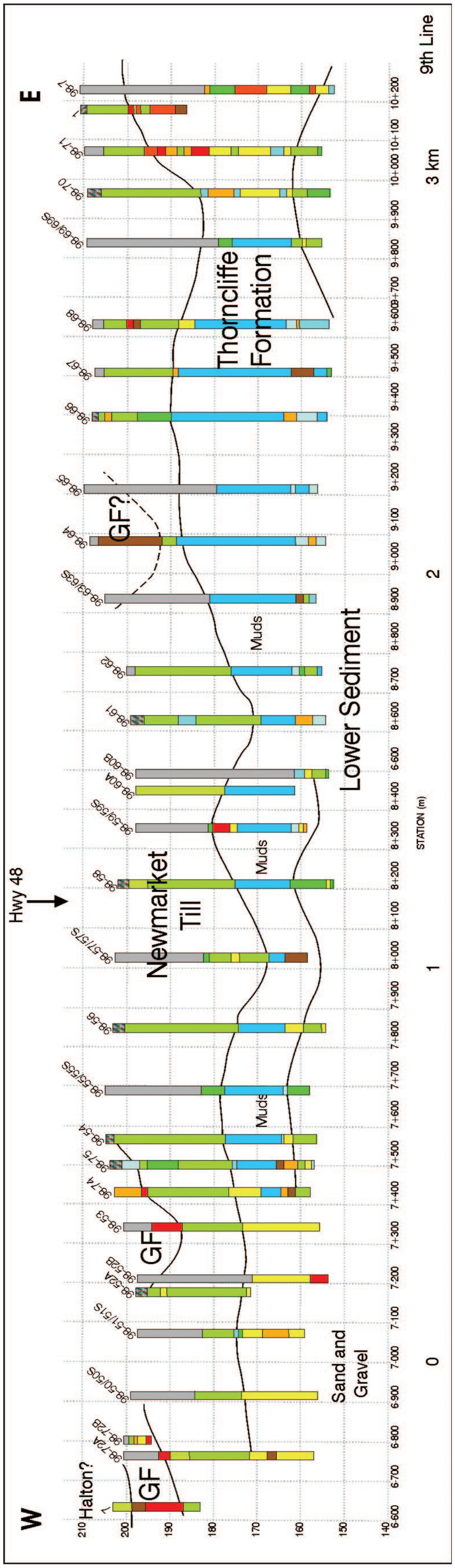


Figure 8. Thorncliffe Formation (TF) sediment facies north of Markham derived from 30 cored geotechnical boreholes summarized to major sediment and stratigraphic units. TF, a major unit of sand and gravel at 9th line (E), fines laterally and upwards to mud beneath a thick continuous Newmarket Till unit. Note that smaller, younger glaciofluvial channels (GF) are eroded into the surface of Newmarket Till.

extensively documented near the Scarborough Bluffs (Karrow, 1967; Eyles et al., 1985). These new observations and other work on Thorncliffe sediments along Duffins Creek (Walsh, 1995) indicate subaqueous-fan deposition (sediment fines upward) for this formation, rather than a deltaic setting (sediment coarsens upward) as has been proposed at Scarborough Bluffs (Karrow, 1967; Eyles et al., 1985). The lateral continuity of Thorncliffe Fm sediment from coarse to overlying fine facies, perpendicular to paleoflow, is perhaps most telling in distinguishing the inferred fan from a delta. This refined depositional model implies trends in hydraulic conductivity that can occur vertically and horizontally within Thorncliffe sediments (*see* Fig. 9a).

Unit 4 - Newmarket Till

A dense, pebbly (5–8%), sandy silt diamicton with interbedded sand-diamicton occurs at 219 to 208 m a.s.l. (depth of 46–57 m) in the AGS borehole.

Geophysical signature

The architecture of this seismic unit yields a well defined, laterally continuous, undulating, seismic-reflection pattern that defines the upper surface of the unit. Internally, unit reflectors show high-amplitude hummocky facies near the unit surface. Most reflectors show a weak seismic pattern within the unit.

The seismic (P-wave) velocity of ~2000 m/sec measured downhole is lower than the ~2500 m/sec that is typical for thick sequences of Newmarket Till observed elsewhere in the ORM (Pullan et al., 2002). However, the velocity contrast with the surrounding sediments is still high and produces a strong reflection on the seismic profile. This allows the surface of the Newmarket Till to be traced along the entire length of the Aurora profile (Fig. 6). It varies in elevation from 210 to 260 m a.s.l. over the 7 km of profile. The variable top of the Newmarket Till is interpreted as convex (drumlins?) and channel erosion forms and it is likely that thin gravel layers are associated with this surface (Pugin, unpub. rept., 1997; *see* gravel layer at ~100 m depth b.g.s.). The base of the Newmarket Till is more difficult to identify definitively, but the lower contact is typically planar at an elevation of ~220 m a.s.l.. Hence, the unit is interpreted to be substantially thicker than observed in the AGS along most of the seismic profile (Fig. 6), especially between Yonge Street and Bayview Avenue, where a thick (40–50 m) unit of Newmarket Till (?) is interpreted. The gamma counts in upper part of this unit (46–54 m depth) are higher (~80 counts per second (cps)) than usually observed in thick, high-velocity sequences of Newmarket Till elsewhere to the south (40–60 cps), implying that it has a siltier matrix texture at this site.

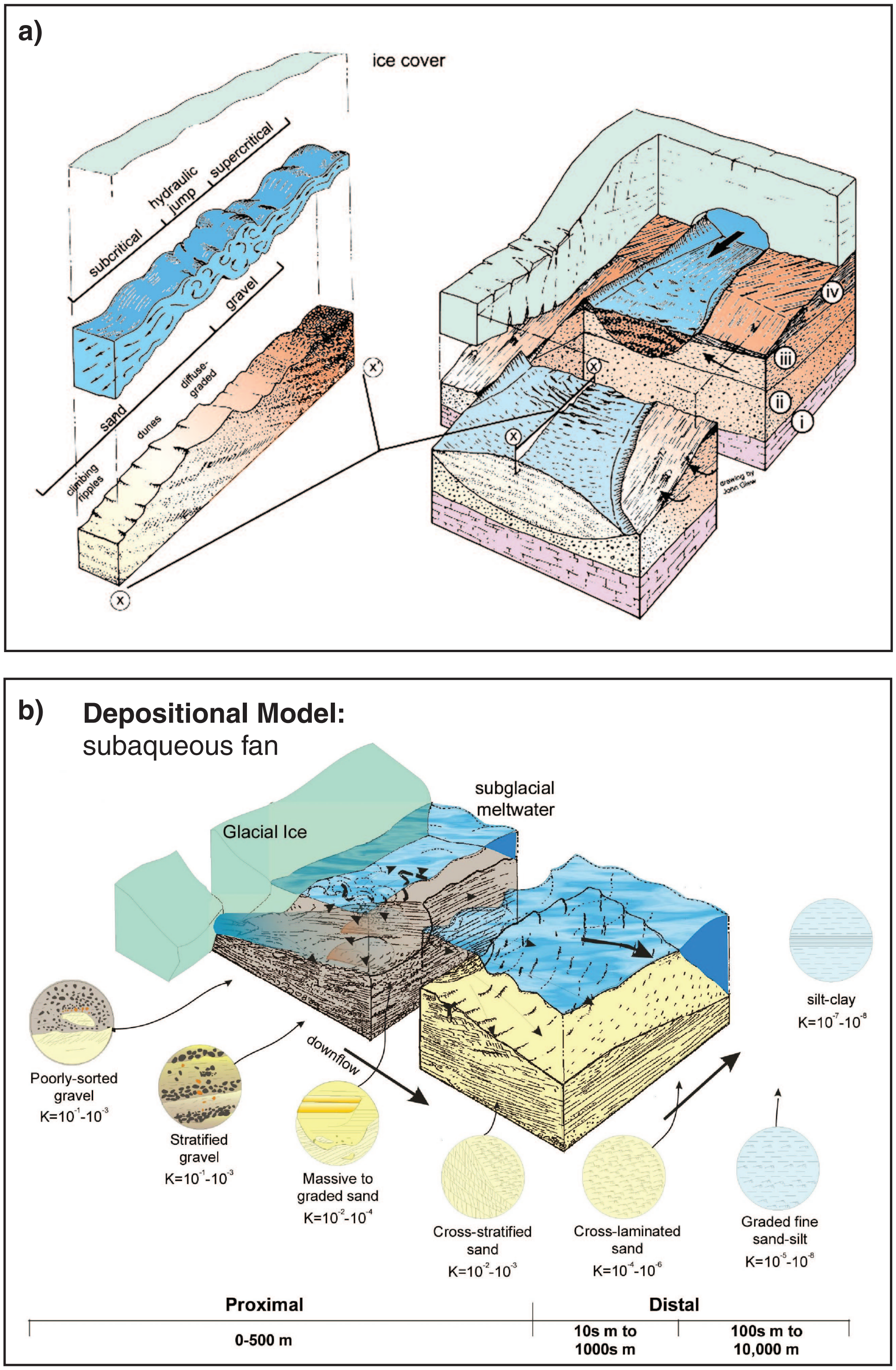


Figure 9. Subglacial (tunnel) channel environmental setting in the Greater Toronto area. **a)** Depositional setting. Note the same style of glaciofluvial sedimentation has also been inferred for the formation of channels within the ORM sequence. Sediments grade rapidly from gravel to sand with key bedforms downflow in standing water. **b)** Depositional facies model (subaqueous fan) with facies length scales and estimated K values. Note rapid facies and property change downflow and even more rapid change perpendicular to main paleoflow.

Sedimentology

The Newmarket Till consists of ~11 m of dense, pebbly (5–8%), sandy silt diamicton with interbedded sand diamicton for the bottom ~6 m. The diamicton has more silt and fewer stones (4%) in the upper 5 m. There is a brecciated interval with intraclasts of mud that imply a debris-flow origin for part of the Newmarket Till.

Stratigraphic context

The top surface of the Newmarket Till has been identified as part of a regional unconformity across the area (Barnett et al., 1998; Pugin et al., 1999; Sharpe et al., 2002a). It forms a ~20 m unit (thinner at AGS) in the region where it occurs as a series of uplands and islands, ~1 to 2 km across and 2 to 4 km long. It also appears as resedimented deposits set within a shallow eroded-channel complex. This channel system is linked from Aurora to the deeper Maple channel system to the southwest.

Interpretation

On the basis of lithology, P-wave velocity, seismic facies, eroded upper contact, detailed surface mapping, subsurface continuity and stratigraphic position below the regional unconformity, this unit is confidently interpreted as Newmarket Till that drapes into an existing valley. Some lines of evidence may nevertheless lead to questions, which are considered next.

Discussion

Interpretation of Newmarket Till above a channelized subaqueous fan succession (Thorncliffe Fm) has significant implications for existing stratigraphic models of the Oak Ridges Moraine (ORM) region. To date, channelized deposits have generally been attributed to the regional unconformity that truncates the Newmarket Till and is associated with overlying ORM sediment unit. Channelized or buried valley deposits in the older stratigraphic units are less well documented. For the Scarborough Fm, Eyles et al., (1985) interpreted channels at the Scarborough Bluff as deltaic in origin. Martini and Brookfield (1995) inferred a sub-aerial origin for channel features at the Bowmanville Bluffs.

The top of the Newmarket Till occurs at 208 m a.s.l. at the AGS, at least 40 m lower in elevation than the Newmarket Till surface beneath Bayview Avenue, (Fig. 6). Newmarket Till seismic facies can also be linked to surface upland outcrop east of Leslie Street (Fig. 1, 6). The Newmarket Till uplands adjacent to Aurora basin (Fig. 3) have surface elevations of ~300 m a.s.l., and maximum observed Newmarket Till thicknesses are ~50 m (Sharpe et al., 2002b). Regionally, the Newmarket Till slopes southward, but this factor does not account for an added elevation differential of ~50 m and total thicknesses up 90 m (Logan et al., 2002; Logan et al., 2006).

In the Aurora area, variation in elevation of the Newmarket Till suggests draping on existing topography. Regional study of this till sheet reveals places where it appears to have been deposited into pre-existing landscape depressions as sediment gravity flows. The tendency for Newmarket Till to occupy topographic lows can be observed along some Lake Ontario bluff sections (e.g. Brennand, 1997). A debris flow interpretation of the Newmarket Till deposition at the borehole site is also consistent with the relatively low seismic velocity of the unit in this borehole (2000 m/s instead of 2500 m). This process may also have concentrated finer grained portions of the Newmarket Till, linked to the observed relatively high gamma counts.

A draping configuration suggests that Newmarket Till dips slightly into Aurora basin as part of a pre-existing low to the north (perhaps older Thorncliffe channel noted above). However, the base of the Newmarket Till on seismic profiles (Fig. 6) south of Aurora shows modest elevation ranges (~10–30 m) and an undulating pre-existing surface.

Across a very wide area, the top surface of this unit forms a regional unconformity (e.g. Sharpe et al., 2004). At AGS, a regional unconformity could be considered to occur at ~30 m depth based on gravel at the base of the ORM sediments. The drumlinized-channelized eroded top of the Newmarket Till (Fig. 6a, 7b), however, supports the inference of a regional unconformity on its surface (Barnett et al., 1998). Nevertheless, the sediment sequence of mud (rhythmite unit 4), not gravel, overlying the Newmarket Till has not been observed elsewhere in the GTA. This is discussed next.

Unit 5 - Silt-clay rhythmites

This unit occurs at a depth of 30 to 46 m (219–235 m a.s.l.), and consists of a lower ~4 m sequence of 340 silt-clay rhythmites and an upper 12 m unit of banded silt clay with brecciated intervals.

Geophysical signature

There is no apparent seismic architecture for this unit as it is too thin to detect. This unit is clearly defined as a higher conductivity and lower magnetic susceptibility unit in borehole geophysical logs. The lower rhythmite unit (42–46 m depth) is delineated by conductivities of 30 to 35 mS/m. This reflects higher amounts of clay (~13–36%) determined by grain size measurements in this unit compared to <10% at most in all other units. Such conductivity values are still relatively low for clays suggesting that the measured clay size fraction is not related to clay mineralogy. The conductivity signature could prove to be an important means for mapping the lateral continuity of this aquitard across and beyond the Aurora basin. Natural gamma logs cannot readily distinguish this unit from the underlying Newmarket Till. The uppermost part of this unit is characterized by higher P- and S-wave velocities, and high temperature gradients.

This suggests that the sediments here may be overconsolidated and possibly fractured (brecciated character). The seismic profile indicates that this finer grained unit fills a depression in the Newmarket Till surface that extends at least 100 to 150 m on either side of the borehole in the east-west direction.

Sedimentology

The banded silt clay sequence contains brecciated silt-clay diamicton. The silt-clay rhythmites contain ~13 to 35% clay fraction (grain-size), while the banded silt clay is <20% clay. Rhythmite sediment layers were not observed in the diamictic interval, but they may have been present before the sediment was deformed, redeposited, and brecciated.

Stratigraphic context and spatial distribution

The presence of this unit in the AGS is unique, not having been identified in any other GS core or outcrop observation. Thin sequences of this unit may overlie a more extensive area of Newmarket Till (*see also* interpreted channel fill unit ~250 m west of Bayview Avenue, Fig. 6), but it has not been identified in other high-quality cores or measured sections beyond Aurora basin. Mapping its extent would require new borehole geophysical data.

On the basis of the seismic reflectors and core data, this silt-clay unit is interpreted to only exist in the lowermost depressions of the Newmarket Till surface in the Aurora basin, where it is interpreted as part of low-energy suspension sedimentation within an existing channel. This valley-fill environment is very evident along the seismic line at the borehole (Fig. 6). However, if it is found in other locations, it could form an important marker horizon and aquitard (including possible Newmarket Till) capping the Yonge Street aquifer. There is a high incidence of reported clay in water-well records in the Aurora basin, but it may be difficult to separate this clayey unit from the Newmarket Till in well records alone. In fact, stratigraphic modelling extends the Newmarket Till (some may be this silt-clay unit) as being present in this basin (Logan et al., 2005), a likelihood that would only change if high-quality core data shows evidence to the contrary.

Depositional interpretation

Brecciation and lower clay contents indicate a likely debris-flow origin for the silt-clay diamicton unit. The silt-clay rhythmites can be inferred to represent annual sedimentation in this freshwater setting. Assuming that clay caps deposited in fresh water represent winter suspension sedimentation (Banerjee, 1973; Gilbert, 1997), the rhythmite sequence represents ~340 years of uninterrupted low-energy, glaciolacustrine sedimentation. The amount of deposited clay and the duration of sedimentation are uncharacteristic of an ORM depositional setting (e.g. Gilbert, 1997) because other cores reveal sequences of ~100 rhythmites in ORM sediments (Sharpe and Russell, 2005). This rhythmite unit likely indicates that an isolated subglacial basin was sealed by glacial ice for a short interval on the undulating upper surface of the Newmarket Till. The rhythmites may record renewal of reservoir storage following meltwater floods, related to the regional unconformity (Sharpe et al., 2004) as ice re-attached to the Newmarket Till bed. In this scenario, the rhythmites were protected from subsequent removal because only a shallow ORM channel was eroded at this location.

Unconformity

An unconformity erosionally truncates unit 5, silt-clay or unit 4 (Newmarket Till) along most of the seismic profile (Fig. 6 a, b). In places, a deeper channel (~30 m deep) on the eroded Newmarket Till surface occurs ~4 km west of the AGS borehole. These features are part of an extensive unconformity that extends across the ORM area and well beyond (Fig. 2; Sharpe et al., 2004).

Unit 6 - Oak Ridges Moraine sediment

This unit consists of a ~30 m thick fining-upward sequence of gravel-sand-silt-clay that rests on unit 5 and a suspected regional unconformity, at the borehole location.

Geophysical signature

Only the lowermost portion of this unit can be observed on the seismic sections, as reflections from within 15 to 20 m of the ground surface cannot easily be resolved. In general, the ORM unit is a low-amplitude, relatively transparent seismic facies. Little internal structure can be observed on these seismic sections. The ORM package at the AGS has a distinct coarse to fine character based on increasing gamma counts. The unit is clearly delineated from the underlying unit 5 by sharp, distinct changes in gamma counts, conductivity and magnetic susceptibility.

Sedimentology

The 2 m thick gravel unit at the base of this sequence grades from ~20% stone (4–8 cm) to coarse-medium sand. High magnetic susceptibility identifies an influx of coarser sediment in this package. Sand ranges from coarse to medium to fine, and comprises 2 to 8 cm thick graded units within 0.6 to 1.5 m thick sets. Overlying ripple crosslaminated sand becomes silty upward. At 12 m depth there is a transition to silt-clay sediments with diamicton interbeds. Near the top of the sequence, silt-clay deposits are rhythmically laminated in two packages, in total ~70 rhythmites (Fig. 4). The rhythmites are conformably interbedded with a silt diamicton at 6 to 8 m depth.

Stratigraphic context

The ORM sits above the regional unconformity (on unit 5 mud). This package likely represents ORM channel-fill sediments (or ORM ridge-building east-west sedimentation). The package is, however, thinner here than it is in nearby areas to the south, and to the east, where ORM north-south channel-fill sediments are 86 and 110 m thick respectively at the Vandorf and Ballantrae Golden Spike borehole reference sites (Sharpe et al., 2003a). To the southwest, along Aurora-King City projected channel path (Russell et al., 2000), the ORM sediments are 50 m thick resting on moderately-breached Newmarket Till where they comprise two prominent seismic facies along the 15th Avenue seismic profile (Pugin et al., 1999). ORM sediments are ~130 m thick further south along the same channel path at the IWA landfill site south of King City (Russell et al., 2000), where they also comprise two fining upward sediment packages.

Depositional interpretation

As regional erosion gave way to ORM deposition (Sharpe et al., 2004), the gravel to mud sequence reported at AGS represents high-energy meltwater flow followed by transitional deposition into waning-flow sand and silt-clay suspension sedimentation. Gravel at the base of the ORM sequence represents inferred subglacial meltwater flow events; that is, a) rapid NS channel sedimentation, or, b) construction of the ridge of ORM sediment related to east-west sediment discharge (Barnett et al., 1998; Russell and Sharpe, 2002; Sharpe and Russell, 2005). The base of channel interpretation indicates a shallow channel depth compared to nearby tunnel channel depths of >100 m as discussed. The channel-fill interpretation also suggests that the 12 to 30 m sand-gravel package is an equivalent of other cored channel fill sequences: a ~70 m thick sand to silt-clay rhythmite package 5 km to the east at Vandorf, and a ~60 m thick sand package 10 km to the east at Ballantrae (Sharpe et al., 2003a). The ridge-building scenario requires that the Aurora basin received insufficient sediment, other than some mud, to fill the basin.

The upper interbedded mud, fine sand, and silt diamicton likely represents debris-flow activity in a glaciolacustrine basin during waning flow to ridge building or channel filling. This interbedded, transitional sediment may correlate with Kettleby Till, which is similar in character and stratigraphic significance to late-stage deposition of interbedded glaciolacustrine silt, sand and Halton diamicton, south of the Oak Ridges Moraine (Russell et al., 2003).

If the clay caps represent winter sedimentation (Gilbert, 1997), this indicates 70 years of ORM varve deposition. This estimate compares well with estimates of <100 years for ORM low-energy sediment correlatives to the southwest at Vaughan (Russell et al., 2003) and ~100 years for ORM deposition at Vandorf (Gilbert, 1997). Gilbert inferred that ORM sedimentation at Vandorf was into a ~100 m deep lake that was stable for at least 100 years. This is interpreted to represent a low-energy, reservoir-filling phase of moraine sedimentation (Barnett et al., 1998; Russell et al., 2003). It appears that the underlying sand and gravel beds were likely deposited with high energy and in less than one season, during rapid channel sedimentation (Russell et al., 2003).

This correlation implies that prominent approximately east to west paleoflows (Duckworth, 1979), found in subaqueous fan sediments in the Ballantrae wedge of the ORM (Peterson and Cheel, 1997) and further east near Bloomington, were confined to higher ORM ridges a few kilometres south of the Aurora basin. Hence, ridge-building sediments are not present at the AGS borehole except possible low-energy, distal mud. This presumably required overlying ice to sag into the basin and preclude thicker, sandy ORM sediments to fill the Aurora basin.

STRATIGRAPHIC SIGNIFICANCE OF THE AURORA STRATIGRAPHIC REFERENCE AND GOLDEN SPIKE (AGS) SITE

Five key stratigraphic relationships from the Aurora high-quality data are critical to regional geological and hydrostratigraphic understanding and require elaboration to identify progress from previous stratigraphic reconstructions (e.g. Gartner Lee Ltd., unpub. rept., 1996, 1999). The five key relationships are: a) multiple unconformities; b) coarse-grained Thorncliffe sediments; c) Newmarket Till variability; d) shallow ORM sequence; e) lack of bedrock valleys.

Multiple unconformity and channelized surfaces within the regional stratigraphy

Existing stratigraphic models of the area recognize two regional unconformities: a) on the bedrock surface, and b) a channelized and drumlinized surface that truncates the Newmarket Till and Lower Sediment (Fig. 2). Data from this study support the interpretation of a third event surface within the Lower Sediment unit (Fig. 2; Sharpe et al., 1996). This new regional unconformity occurs at the base of the Thorncliffe Formation tunnel-channel-cutting events, similar to the regional unconformity cut on Newmarket Till and at the base of the ORM sequence (Fig. 2). Channel features are similar in dimension to ORM channels, 2 to 4 km wide and up to 100 m deep with an apparent northeast-southwest orientation. This erosional history is being extended across much of the region with new high-quality seismic (Pugin et al., in press) and borehole data (Fig. 8). Where a channel system occurs, older formations considered to be present across the region are missing and replaced with channel and related high-energy sediments.

Character of Thorncliffe Formation (Unit 3)

A key finding at AGS is that the Lower Sediment unit of the regional stratigraphic model consists of one thick stratigraphic unit (Fig. 2). The Thorncliffe Fm is more prominent at AGS, and the older classical formations which are found at Scarborough Bluffs (Karrow, 1967), as well as at Vandorf and Ballantrae and west at Nobleton (Sharpe et al., 2003a), are not present as they were eroded away by high-energy channels. In addition, the sedimentological character of the Thorncliffe formation at AGS is much different that the generally accepted and described from Scarborough Bluffs. Thorncliffe Formation typically consists of glaciolacustrine sediments, fine sand, silt, and clay, in places constituting a thick sequence of rhythmically bedded sediments (e.g. in the Nobleton borehole core; Sharpe et al., 2003a). The ~80 m thick coarse sediments found at AGS likely represent the depositional phase of a high-energy meltwater system that eroded all older formations. The coarse sediment is also part of the feeder system for extensive sandy sediments to the south (Fig. 9). Upflow (Holt), down flow (Markham), and lateral to the thick Aurora sand and gravel are fine sand, silt and clay found in thick sequences. Regional data indicate northeast-southwest paleoflow indicators for these coarse to fine sediment bodies. The formative depositional model is inferred to include tunnel-channel and subaqueous-fan sedimentation, analogous perhaps to the events that constructed many portions of the ORM (Russell et al., 2003; *see* model event sequence in Fig. 9a). Hence, channel and fan sediments lie on a regional unconformity at the base of Thorncliffe channel-cutting events, similar to where ORM sediments rest on the regional unconformity cut on the Newmarket Till (Fig. 2). And, the subaqueous-fan model applied to the ORM equally applies to Thorncliffe sediments (Fig. 9b).

The new subaqueous-fan interpretation for Thorncliffe sediments is very significant in terms of new stratigraphic and sedimentological models and new depositional setting. These new models aid in assessing, testing, and evaluating the occurrence, extent and properties of the Yonge Street Aquifer system. Whereas south of Aurora, the Thorncliffe Formation comprises subaqueous-fan fine sand, silt, and clay, it is likely that from Aurora north, the formation comprises a tunnel valley or esker system that fed fan sediments to the south. In this scenario, an inferred topographic low below Aurora basin is an expected position for channel or esker sediments. Eskers commonly occur in topographic lows (Brennand, 2000; Brennand et al., 2006), where low, subglacial pressure attracted meltwater flow. The channel/esker-fan hypothesis presents a predictive model for hydrogeological evaluation of the Yonge Street aquifer system (*see* model configuration and event sequence, Fig. 9a; depositional facies model 9b).

Newmarket Till (Unit 4) presence and variability

The presence and variability of the Newmarket Till in the Aurora basin is significant. Newmarket Till is interpreted based on texture, seismic velocity, facies and character, stratigraphic position, continuity of seismic reflectors, and relationship to nearby mapped surface outcrops. It is noted that the unit is more silt-rich and characterized by a lower seismic velocity than the typical thick sequences of Newmarket Till observed at higher elevations in the ORM. The elevation of Newmarket Till at the AGS is ~218 m a.s.l.. Adjacent uplands with Newmarket Till at surface are up to ~300 m a.s.l.. If the bottom contact of Newmarket Till is planar, as observed in seismic profiles across the till (Pugin et al., 1999), the elevation range would require a unit thickness of ~80 m. Such a unit thickness has not been observed anywhere in the area (Sharpe et al., 2006). Based on these data, the depositional model for Newmarket Till in some settings includes a draped geometry such as is apparent in the Aurora basin. This finding implies that the Aurora basin was, in part, a pre-existing low or valley, at least to the north. Thus, the conceptual model of valleys in the region may include valleys that existed prior to Newmarket Till deposition and subsequent major ORM channel erosion. Such pre-existing valleys may relate to incompletely filled Thorncliffe tunnel valleys (previous section). These pre-existing valleys perhaps preferentially funneled later flow. The occurrence of existing valleys can also be observed at Cook's Bay on western shorelines of Lake Simcoe where drumlins cut into the Newmarket Till preferentially sculpted the west side of the valley within existing topographic lows (Russell et al., 2003). Pre-existing valleys are evident in new seismic data east of Aurora along Kennedy road (Pugin et al., in press), as well as at AGS (Fig. 6).

The occurrence of a silt-clay rhythmite sequence (Unit 5) above Newmarket Till

Silt-clay rhythmites are common in the area within the ORM sediments and within Lower Sediment packages (Sharpe et al., 2003a). The seismic section seems to indicate that this unit is only found in depressions on the Newmarket Till surface, and perhaps is an important feature of the Aurora basin area. If present, the high clay content may allow the unit to be readily mapped with borehole conductivity logs. Hence, the unit may be a key marker horizon that has importance, along with the Newmarket Till, as a protective aquitard to the Yonge Street Aquifer (YSA).

Shallow meltwater channel – only 30 m of ORM sediments (Unit 6)

The interpretation of a shallow tunnel channel at AGS (rather than ORM ridge building) helps confirm the above stratigraphic changes. The shallow-channel concept appears to be at odds with the size of the Aurora clay basin and surface valley because a deep channel with thick coarse ORM sediments may be expected as occurs elsewhere in the region (Russell et al., 2003). Based on the seismic data, a similar shallow channel occurs on the west side of the basin (west of Yonge Street). Key support for the shallow channel inference includes: a) fining-upward sediment package, b) correlation of rhythmites, c) identification of underlying Newmarket Till, and, d) contrast with Golden Spike borehole sediment data in nearby deep channels at Vandorf and Ballantrae.

Fining-upward sediments

AGS shows ~30 m of channel fill that fine from gravel, sand to silt-clay. The trend is similar in deeper channels, but this sequence is thinner than other channel-fill sediments found in cored boreholes and in seismic profiles in the region (Barnett et al., 1998; Russell et al., 2003). Thick ORM ridge sediments occur to the southeast and they are present at AGS as the upper few metres of silt-clay rhythmites, which may represent distal equivalents of Bloomington fan (Fig. 3; Sharpe and Barnett, 1997).

Correlation of rhythmites

Rhythmite correlation indicates that low-energy ORM deposition occurred in about 100 years, based on the occurrence of ~100 rhythmites that comprise a persistent mud interval. AGS shows ~70 rhythmites which is roughly similar in number to other ORM cored sites.

Newmarket Till and Thorncliffe unit aquifers

Interpretation of unit 4 as Newmarket Till and unit 3 as Thorncliffe Formation is consistent with the shallow-channel interpretation; that is, there is not a deep ORM channel. Seismic data clearly show the underlying unit 3 (interpreted as Thorncliffe sand and gravel strata) to extend beneath high-amplitude reflectors, inferred Newmarket Till, that extend with continuity westward beyond the channel.

Nearby Golden Spike cores in deep channels

There are clearly defined deep channels at Vandorf and Ballantrae (Sharpe et al., 2003a); however, downhole seismic velocity and seismic profiles show no Newmarket Till in these deep channels. Continuous cores confirm the absence of Newmarket Till, and channel fills consist of coarse to fine sequences ~80–100 m thick.

Lack of bedrock valleys

Based on a single data point, a borehole to 10 m a.s.l. (Gartner Lee Ltd., unpub. rept., 1987), recent hydrogeological modelling has inferred a north-south bedrock valley subparallel to the Laurentian Valley. The current study, with kilometres of seismic data transverse to the inferred valley, and intersecting the modelled position, has no evidence for the existence of such a feature. Bedrock elevations along the seismic transect are in the range of ~110 to 127 m a.s.l.; possibly as low as 80 m a.s.l., but no valley feature.

Apparent north-south-trending ‘bedrock valleys’ are modelled as part of Laurentian Valley; one a pronounced and deep ‘channel’ has been inferred to exist beneath Newmarket, Aurora, and Richmond Hill. Granular deposits within sections of these inferred channels are suggested to be one component of the Yonge Street Aquifer complex.

Such valleys are believed to have provided a major regional drainage course/network from ancestral Georgian Bay to ancestral Lake Ontario, prior to the start of the relatively recent glacial periods (Eyles et al., 1985; Conservation Authorities Moraine Coalition, 2006). Deep channels in the bedrock are typically inferred to have left a lag on a regional unconformity, and, be preferentially filled with coarse granular sediment generated during early stages of drainage associated with deposition of glacial sediments. The lowest sediments in the bedrock channels are assumed to correlate with sediments deposited in an equivalent time to Scarborough Formation (KMK, unpub. environmental rept. commisioned for King City, York Region 2006).

The data presented in this study however, show no distinct bedrock valleys in this study area. The seismic data show no clear bedrock valley where they have been inferred previously (Gartner Lee Ltd., unpub. rept., 1987). Furthermore, the 80 m thick coarse sequence is inferred to be the Thorncliffe Fm and may have been deposited as part of early meltwater channel-forming events, cut into older sediment, which created the Aurora topographic basin.

HYDROGEOLOGICAL SIGNIFICANCE OF THE AURORA STRATIGRAPHIC REFERENCE AND ‘GOLDEN SPIKE’ SITE

The hydrogeological significance of the AGS seismic data includes a discussion of a) the absence of a deep tunnel-channel aquifer system filled with ORM sediments, b) the presence of an extensive confining unit for the Yonge Street aquifer system (Newmarket Till and rhythmically-laminated silt clay), and c) the Yonge Street aquifer is most likely a valley-constrained channel-esker-fan complex of the Thorncliffe Formation.

Absence of a deep ORM age tunnel channel aquifer system

AGS shows a 30 m deep ORM channel sequence above a deeper aquifer. Yonge Street aquifer is a deeper, older channel aquifer system and distinct from ORM channel aquifers (Fig. 1; Sharpe et al., 1996). Thalwegs of these subglacial channel systems can undulate over 50 m range, thus deeper channels may occur north or south of Aurora. However, available data do not support a deep ORM-age channel at Aurora.

Confining unit for Yonge Street aquifer

AGS reveals a silt-rich Newmarket Till and a rhythmically laminated silt-clay aquitard sequence that is different from other channel-like settings in the ORM region. Fine-grained sediment is common in water-well records in the Aurora basin and may record this pair of aquitard sediments. Gas in sand and gravel below the Newmarket Till silt-clay aquitard attests to the confined nature of the upper part of the Thorncliffe Formation aquifer system. Gas likely seeped upward from Whitby Formation shale and into the overlying Thorncliffe aquifer. NT could be broadly continuous in the Aurora basin, for example, based on the continuity of seismic reflectors across the E-W profile (Fig. 6). A deeper ORM channel model as proposed by others may not include Newmarket Till, and would presumably allow more recharge to aquifer sediments.

Yonge Street aquifer — a valley-constrained tunnel channel-esker fan complex

The conclusion that the Yonge Street aquifer is a valley-constrained channel-esker fan complex, likely the Thorncliffe Formation, allows for an improved conceptual hydrogeological model of the system (Fig. 9b). The depositional model can guide further aquifer assessment and hydraulic testing in the area. The Yonge Street aquifer is considered to occur along the general north-south axis of the Aurora basin topographic low, compatible with a channel and esker depositional setting. In addition, a number of municipal test wells show rapid yield changes from highly transmissive and well connected units (gravel), parallel to inferred approximately north-south paleoflow, to nearby east-west low-transmissivity, and less-connected units (silt-clay), perpendicular to (east-west) inferred paleoflow direction. These observations are consistent with an inferred channel-esker-fan complex; however, these predictions should be best tested with new high-quality seismic profiles, cored boreholes, and regionally co-ordinated hydraulic testing and monitoring.

While testing of the new conceptual model for the hydrogeology of the Thorncliffe Formation (lower sediments, Fig. 2) is required, it is expected that the new model will completely alter the spatial distribution of highly productive aquifers and aquifer heterogeneity.

It is also possible that the Yonge Street aquifer is connected to other geological units where Thorncliffe Fm channels did not erode all lower sediments. Thus, in this scenario, two hydraulically connected geological units, possible Scarborough Formation with vertical and lateral hydraulic connection from Thorncliffe Formation aquifer sediments, would form the aquifer system.

SUMMARY

High quality data from ~10 line-kms of seismic-reflection profiles and a 130 m deep, continuously cored borehole at Aurora have contributed to a significant updating to the regional geological model proposed by Sharpe et al. (1996, 2002a). This paper documents, for the first time, a channelized regional unconformity within the Lower Sediment unit in the subsurface north from the Lake Ontario bluffs. It also provides an improved characterization of the Yonge Street Aquifer and regional correlation of the extensive aquifer sediment of the Thorncliffe Formation. The erosion surface unconformably truncates the Scarborough Formation, eroding all the way to bedrock in channel arrays. Channel features on the erosion surface are up to 3 km wide and more than 100 m deep. Hydrostratigraphically, the implication of this surface is that overlying Thorncliffe Formation sediment has the potential for increased vertical and horizontal hydraulic conductivity with stratigraphically lower, coarse-grained, early Scarborough Formation sediment. Removal of lower aquitard sediment of Scarborough and Sunnybrook formations provides enhanced connectivity between potential gas in Whitby Fm shale and younger (Thorncliffe Fm) aquifer sediment. Thorncliffe Fm aquifer sediment forms an 80 m thick channel-fill succession of fining-upward gravel to sand sediment. Stratification of the gravel and sand suggests deposition within a north to south-orientated esker to subaqueous fan setting. Overbank fines (sand and silt) from channel or fan elements appear to be extensive beneath the Newmarket Till. Such a depositional system may have similarities in depositional styles with younger channel fills associated with ORM deposits (Sharpe et al. 2003b; Russell et al., 2003). The regional stratigraphy beneath Newmarket Till thus consists of channel sediments and inter-channel uplands of overbank fines. Regionally co-ordinated hydraulic testing and monitoring of these aquifer systems should be guided by this new predictive model.

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