A 3-Dimensional Geological Model of the Oak Ridges Moraine Area, Ontario, Canada

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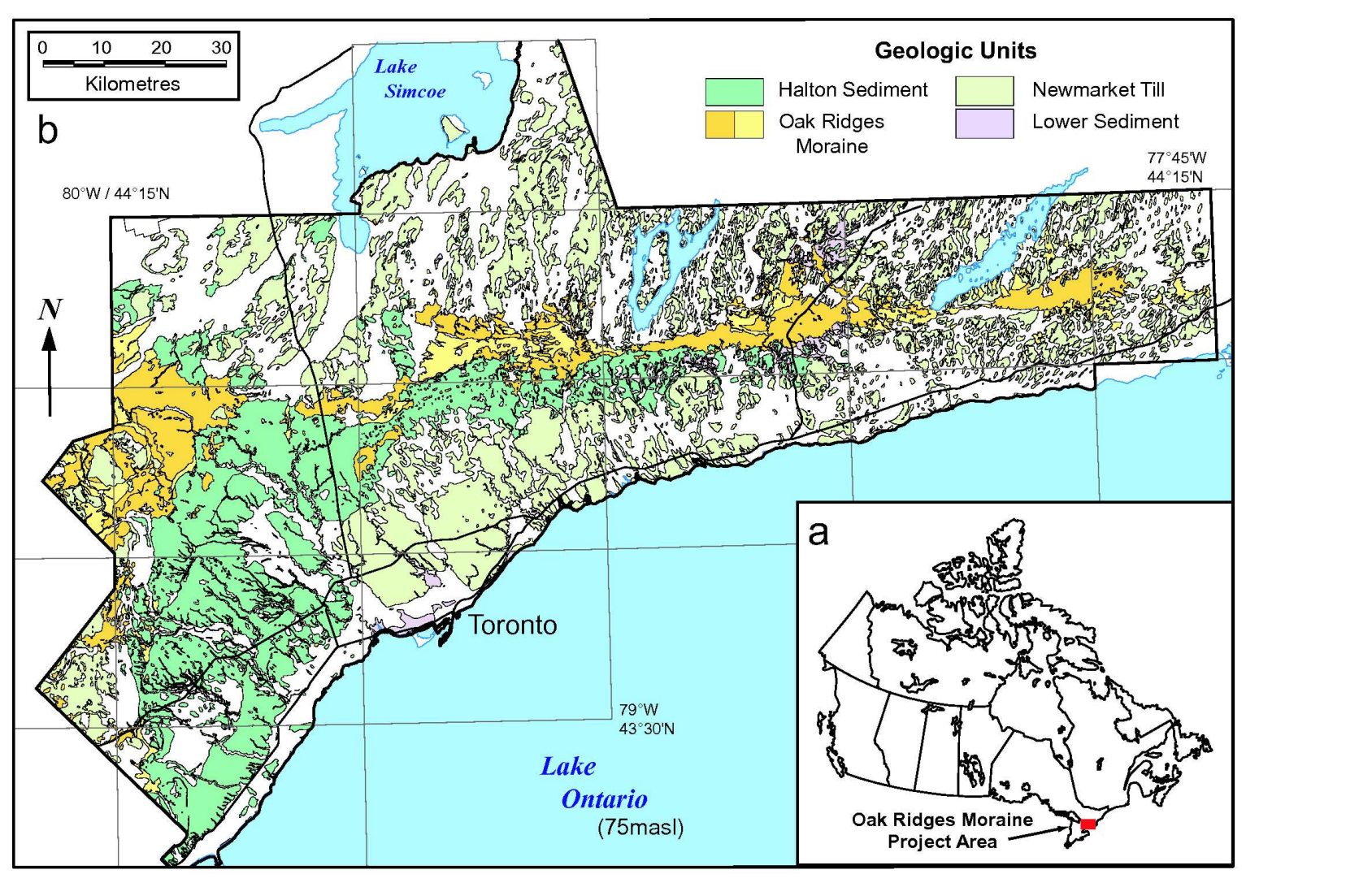

Figure 1. a) Location of study area in Canada. b) Simplified geology of the study area indicating the surface exposure of the main stratigraphic units. White areas are amalgamated, minor geological units.

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Introduction

A 3-D stratigraphic model has been developed as part of a regional geological study of the 11,000 sq km Oak Ridges Moraine (ORM) and Greater Toronto (GTA) areas, southern Ontario, Canada (Figs. 1, 2; Sharpe et al., 2002; Logan et al., 2006). Knowledge of the composition and geometry of geological strata are important for regional groundwater resource assessment and management. Rendering a regional stratigraphic framework in a 3-D structural model provides context for site-specific work and ongoing hydrogeological analysis. The framework provides vital input for groundwater flow modeling (e.g. Holysh et al., 2004).

This paper provides an overview of model development, principal Quaternary stratigraphic units, and interpolated bedrock structual surface. Derivative isopach maps for each of the stratigraphic units are highlighted (maps 1 – 4). These maps are supplemented with information on stratigraphic context, data support, and sediment characteristics.

Model Development

Stratigraphic Framework

The lithostratigraphic framework (Karrow, 1967) has been re-interpreted using basin analysis principles and event stratigraphic concepts (Fig. 2; Sharpe et al., 2002). A key revision is the mapping of a regional unconformity that is defined by drumlinized Newmarket Till and tunnel channels (Barnett et al., 1998; Sharpe et al., 2004). To permit mapping of the regional stratigraphy using archival data, the lithostratigraphic framework was simplified to five principal units: 1) Paleozoic bedrock, 2) Lower sediment, 3) Newmarket Till, 4) Oak Ridges Moraine and channel sediment, and 5) Halton Till. Lower sediment comprises 10 formations that are stratigraphically beneath Newmarket Till. These formations have limited subsurface data (~6 %), which prevents consistent spatial delineation (Fig. 2; Karrow, 1967).

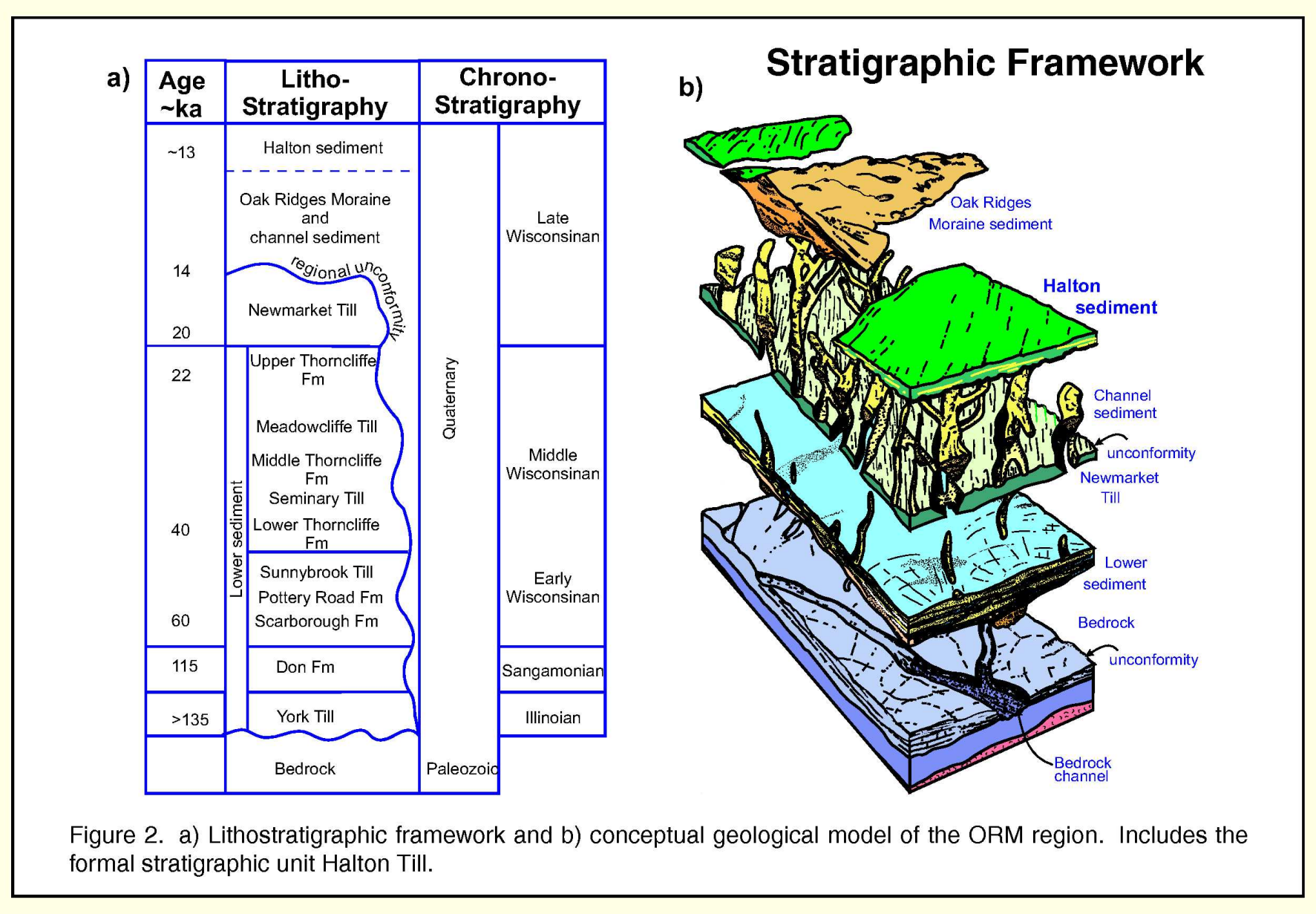

Figure 2. a) Lithostratigraphic framework and b) conceptual geological model of the ORM region. Includes the formal stratigraphic unit Halton Till.

Data

Data, on which the stratigraphic framework is based, were assigned to three classes for model construction. Primary training data consist of surface geological maps (Sharpe et al., 1997) and subsurface data with reliable geological integrity (Logan et al., 2006). The subsurface component included: i) continuous cored boreholes, ii) measured sections, iii) seismic reflection, and iv) ~5000 geotechnical and hydrogeological boreholes. Secondary data consists of Ontario Ministry of the Environment (MOE) water well records. Following verification of location accuracy and declustering, this dataset was reduced from > 60,000 records to 22,000 records. A third set of data consisted of extrapolation rules developed from map polygons (e.g., tunnel channels). The model data were all geographically registered to NAD 83 and a 30 m grid cell digital elevation model (DEM; Kenny et al., 1999) used as an elevation datum (+/- 3m).

Regional Digital Elevation Model

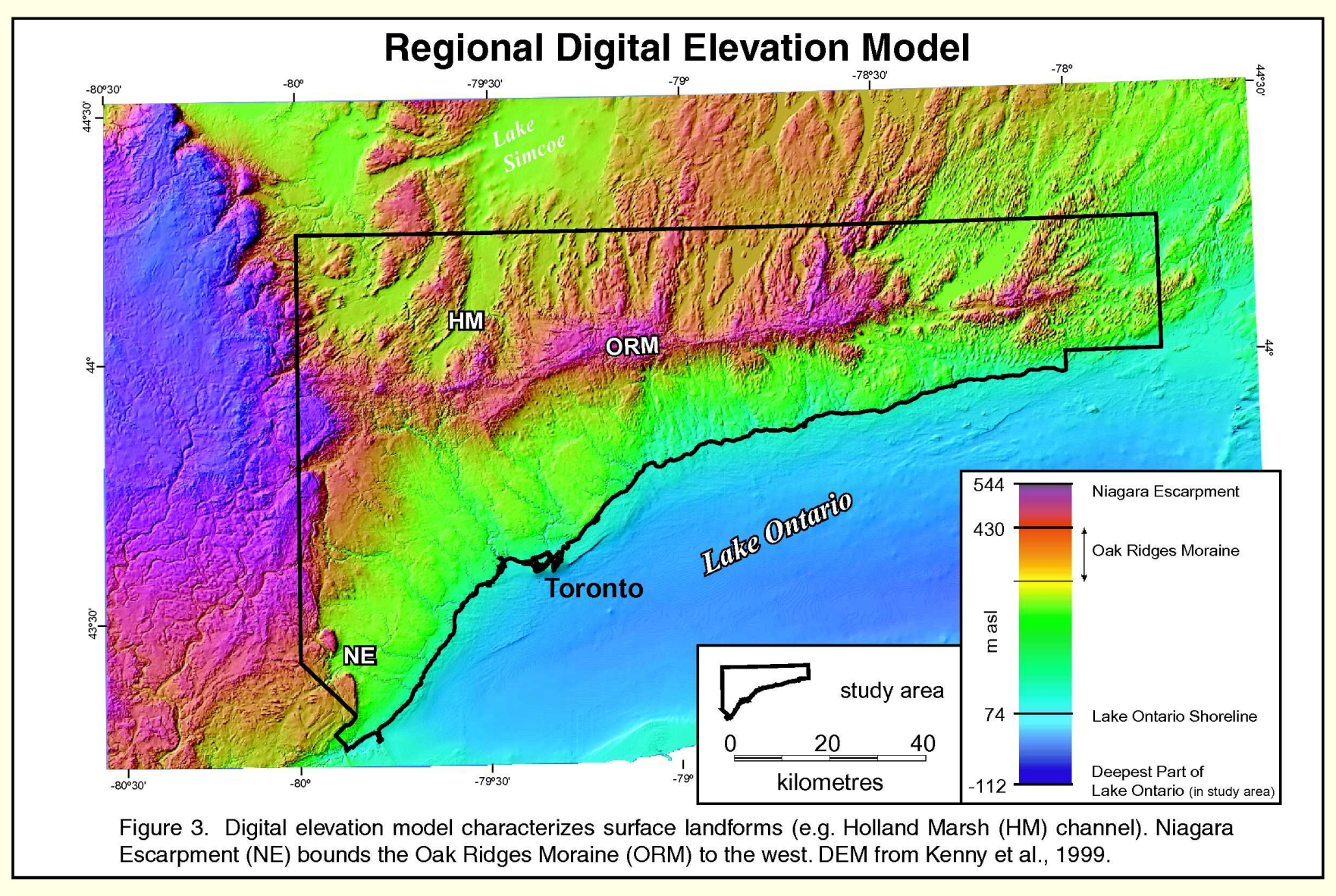

Figure 3. Digital elevation model characterizes surface landforms (e.g. Holland Marsh (HM) channel). Niagara Escarpment (NE) bounds the Oak Ridges Moraine (ORM) to the west. DEM from Kenny et al., 1999.

Methods

A semi-automated expert system using MapInfo Pro ® and Microsoft ® Visual Basic for Applications © was used to construct the model in an iterative process (Fig. 4; Logan et al., 2006). Step I involved interpolation of training surfaces using high-quality data and surficial geological maps to delineate units (Fig. 4). Step II used this training framework to guide stratigraphic coding of the MOE water well records using expert rules (Logan et al., 2006). All data were used in step III to interpolate final stratigraphic surfaces at a 30 m grid cell size (e.g., Fig. 5).

Stratigraphic Modelling Framework

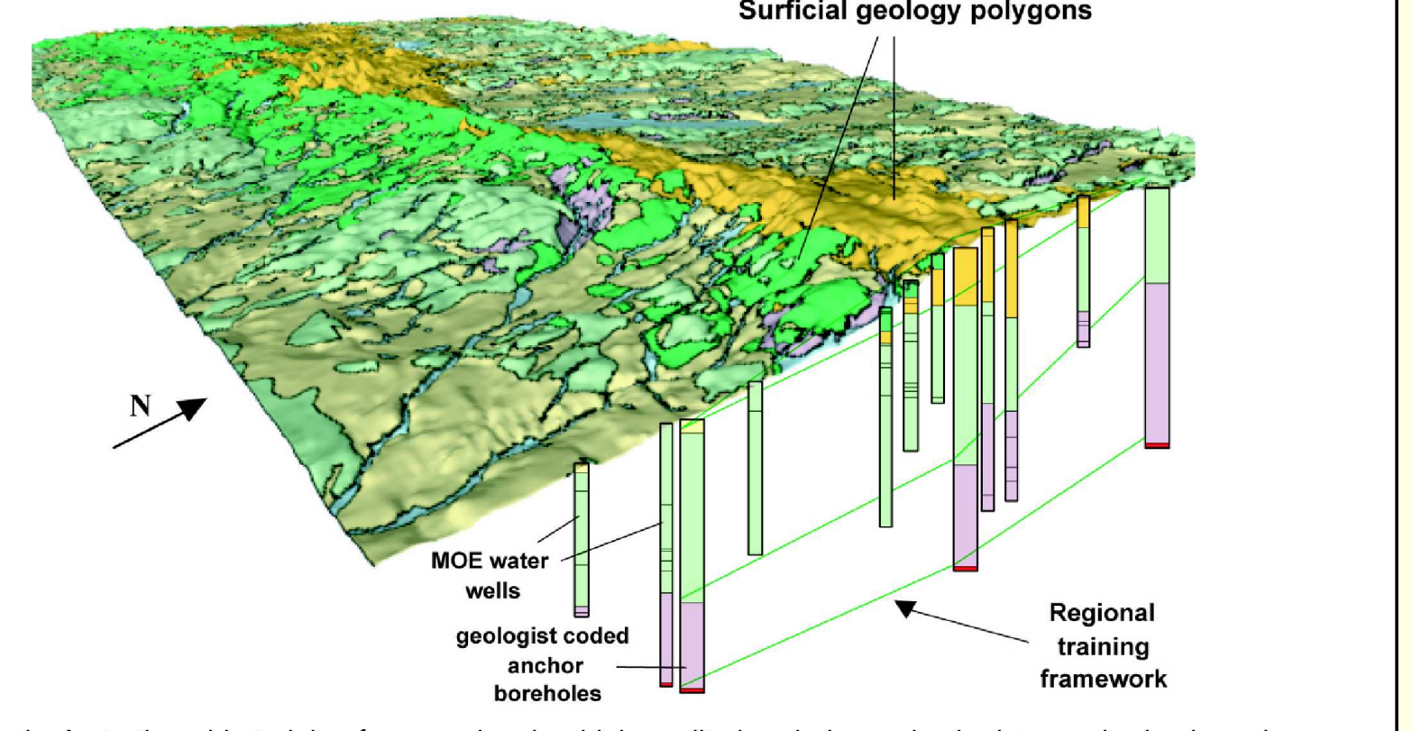

Figure 4. A stratigraphic training framework using high-quality boreholes, seismic data, and rules based on field knowledge were used to guide the automated stratigraphic interpretation of water well material codes.

Bedrock Structural Surface

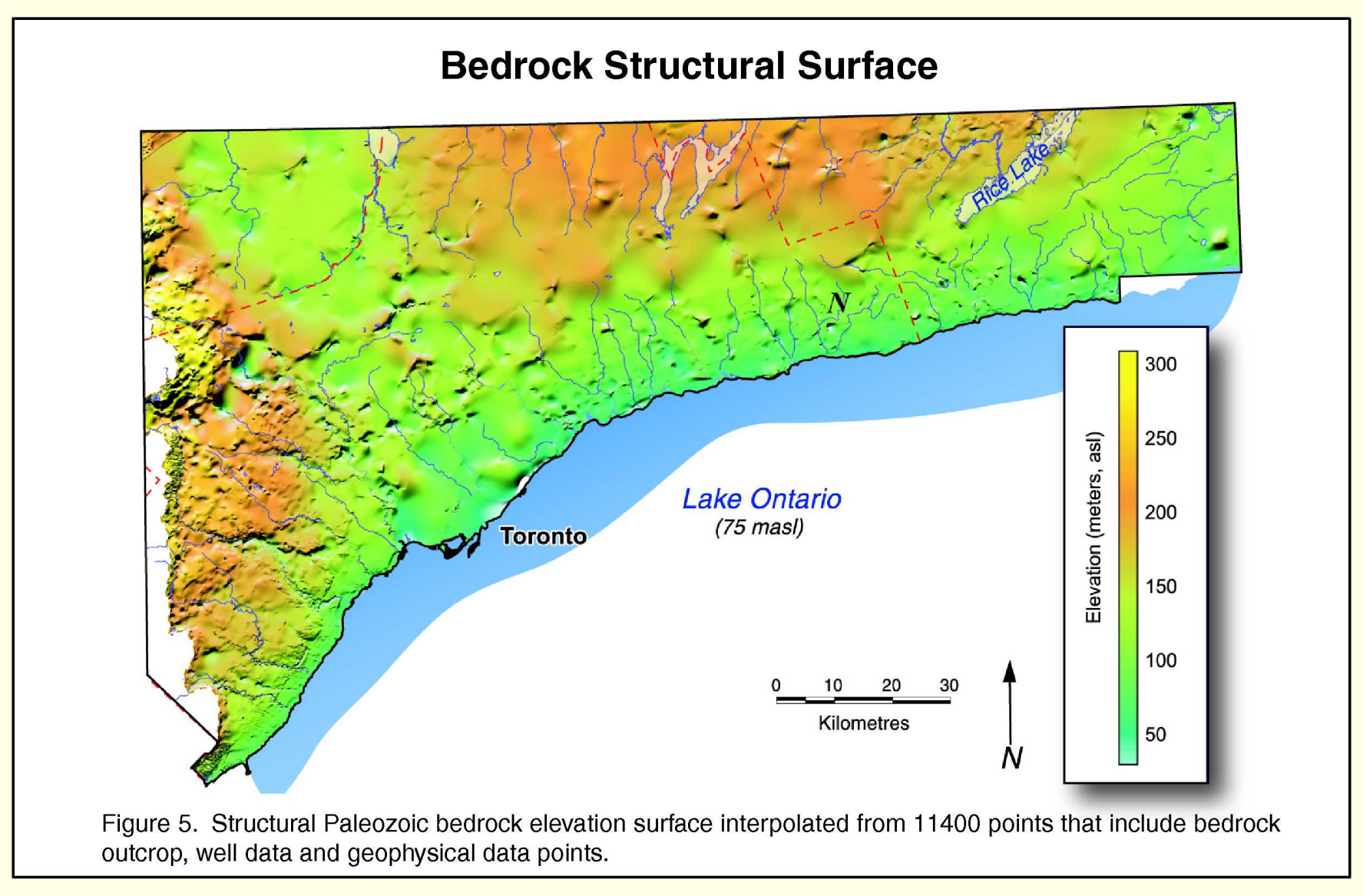

Figure 5. Structural Paleozoic bedrock elevation surface interpolated from 11400 points that include bedrock outcrop, well data and geophysical data points.

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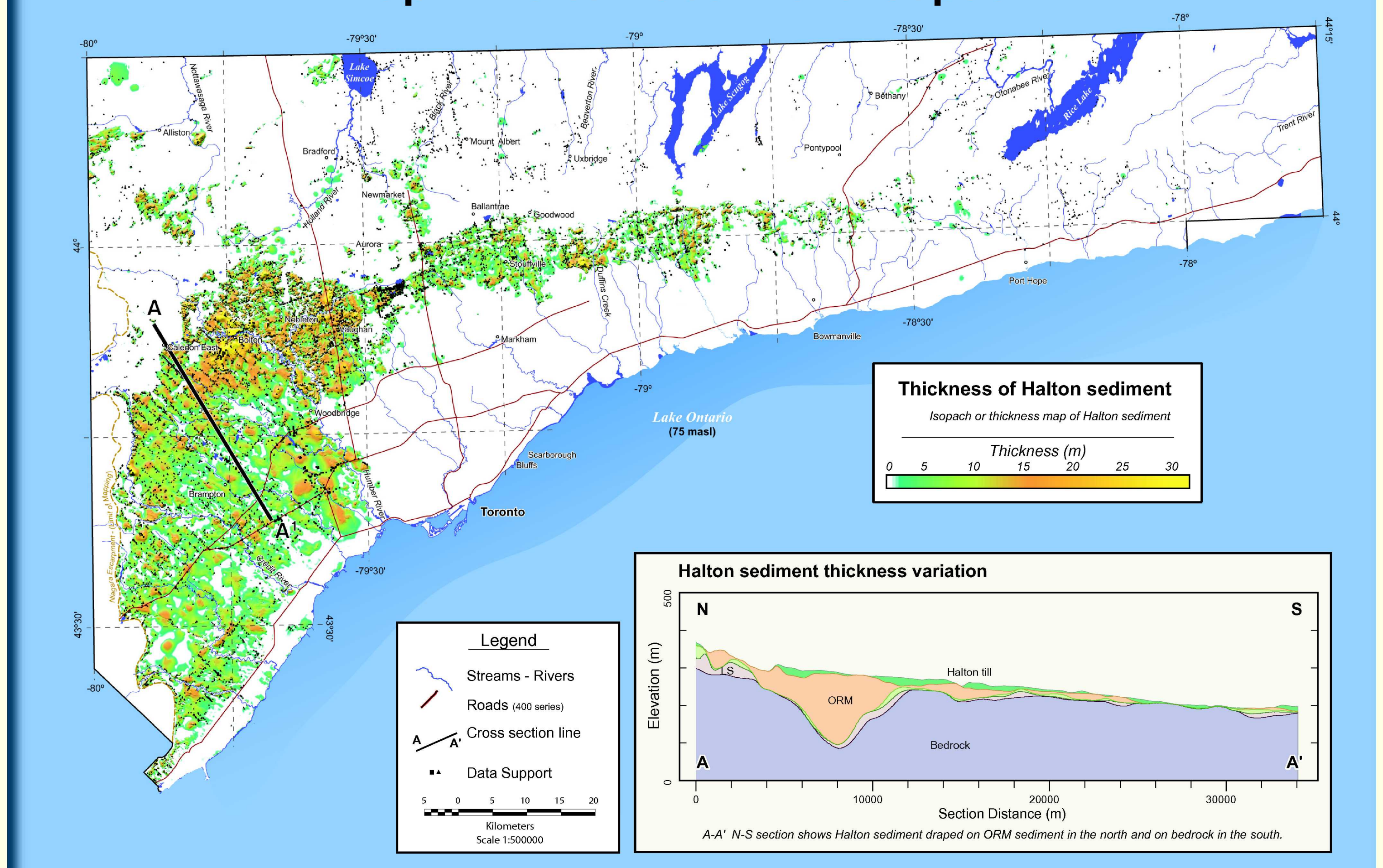
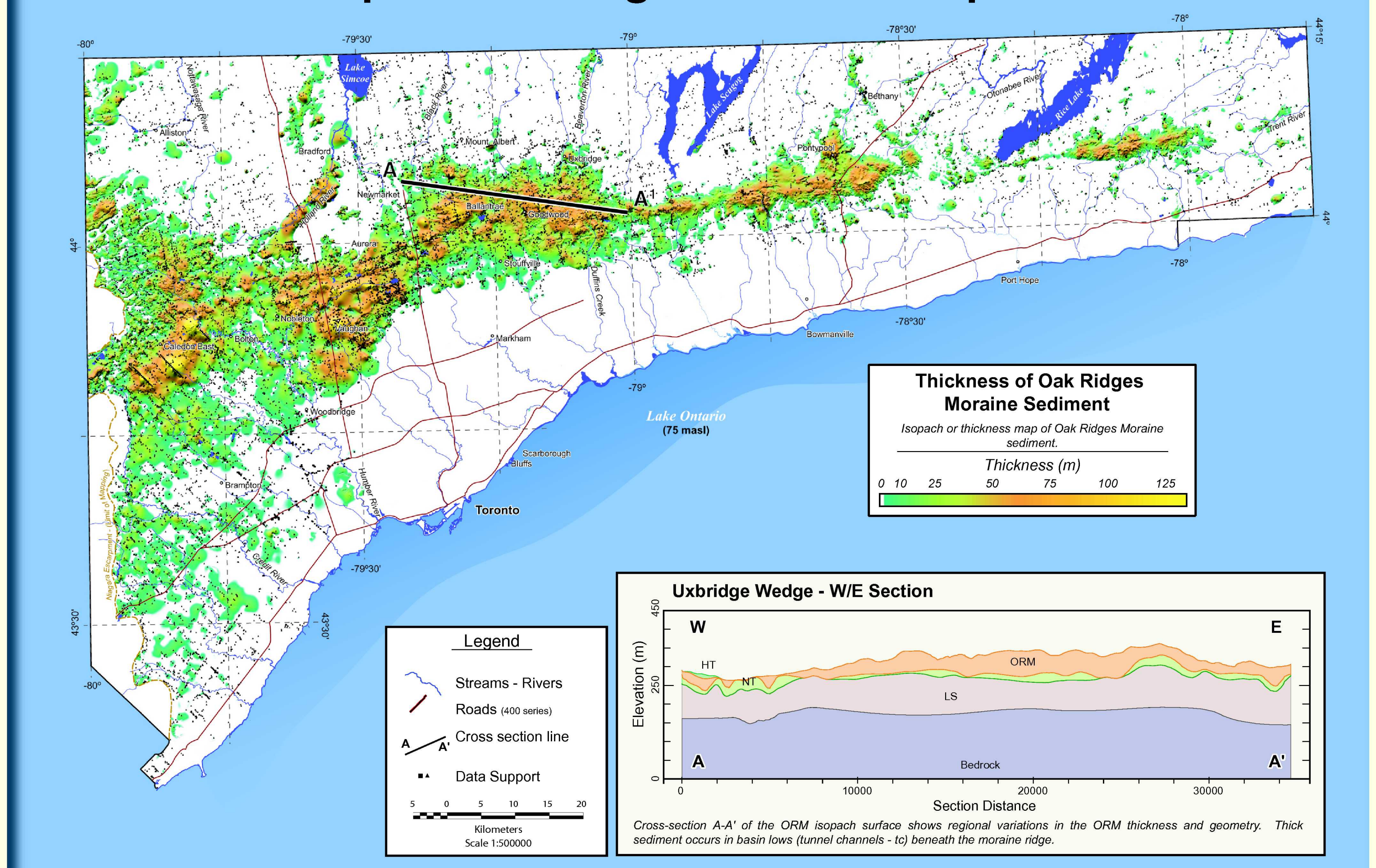
Map 1. Halton Sediment Isopach



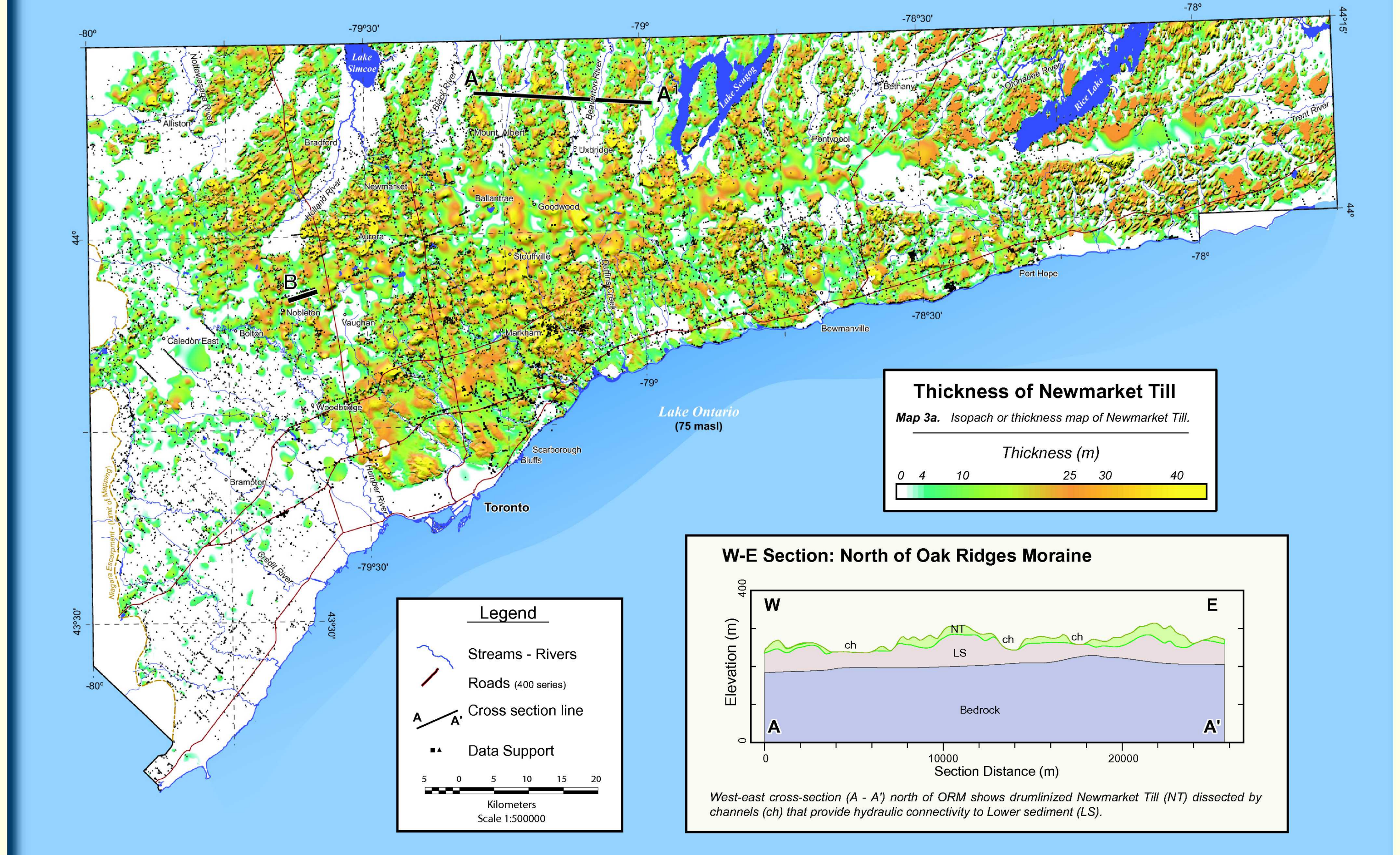
A-A' N-S section shows Halton sediment draped on ORM sediment in the north and on bedrock in the south.

Map 2. Oak Ridges Moraine Isopach



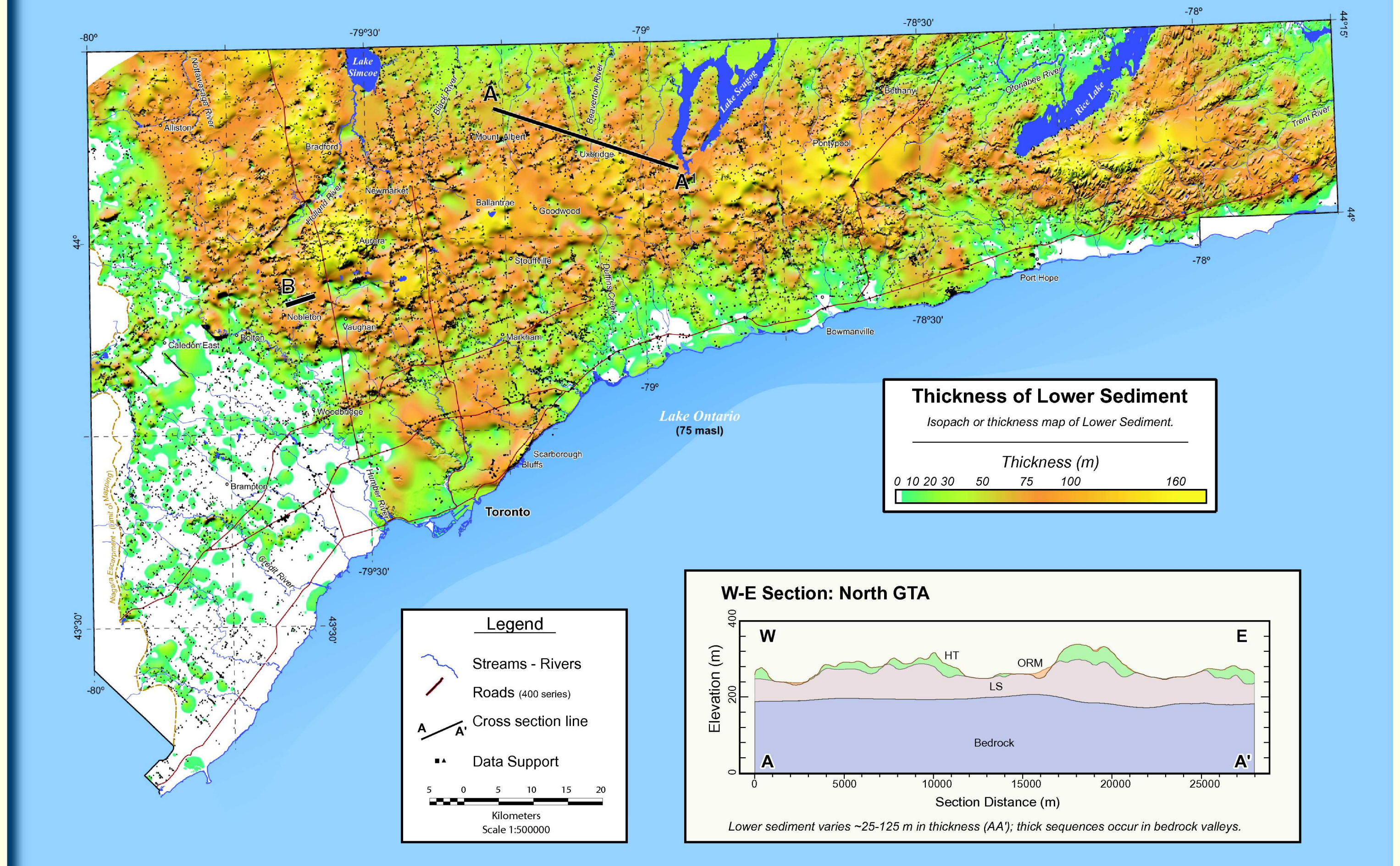
Cross-section A-A' of the ORM isopach surface shows regional variations in the ORM thickness and geometry. Thick sediment occurs in basin lows (tunnel channels - tc) beneath the moraine ridge.

Map 3. Newmarket Till Isopach



West-east cross-section (A - A') north of ORM shows drumlinized Newmarket Till (NT) dissected by channels (ch) that provide hydraulic connectivity to Lower sediment (LS).

Map 4. Lower Sediment Isopach



Lower sediment varies ~25-125 m in thickness (AA'); thick sequences occur in bedrock valleys.

Halton Sediment

The Halton Sediment isopach map includes several Late Wisconsinan units (Kettleby, Wentworth tills) that overlie ORM deposits (Fig. 2). This unit is generally <15 m thick but locally can be up to 30 m thick (Map 1) and it is most extensive west of Toronto toward the Niagara Escarpment (Fig. 1). Interbedded diamicton, silt-clay, and sandy sediment facies (Fig. 6) indicate a glaciolacustrine and subaqueous debris-flow origin for much of this unit (Sharpe, 1988). 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. 7; Russell et al., 2005a), and thins across bedrock platforms. 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.

Halton Sediment Facies

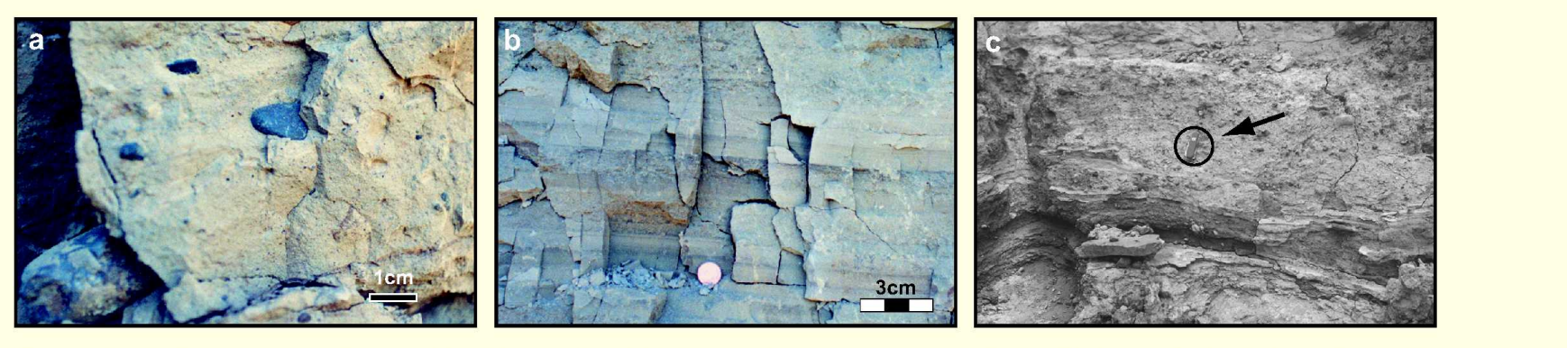


Figure 6. Texture, composition and bedding style of Halton sediment: a) massive to faintly laminated silt diamicton with pebbles; b) laminated silt and diamicton; c) interbedded sand, silt, and diamicton; knife (circled) is 10 cm.

Halton Sediment Stratigraphy

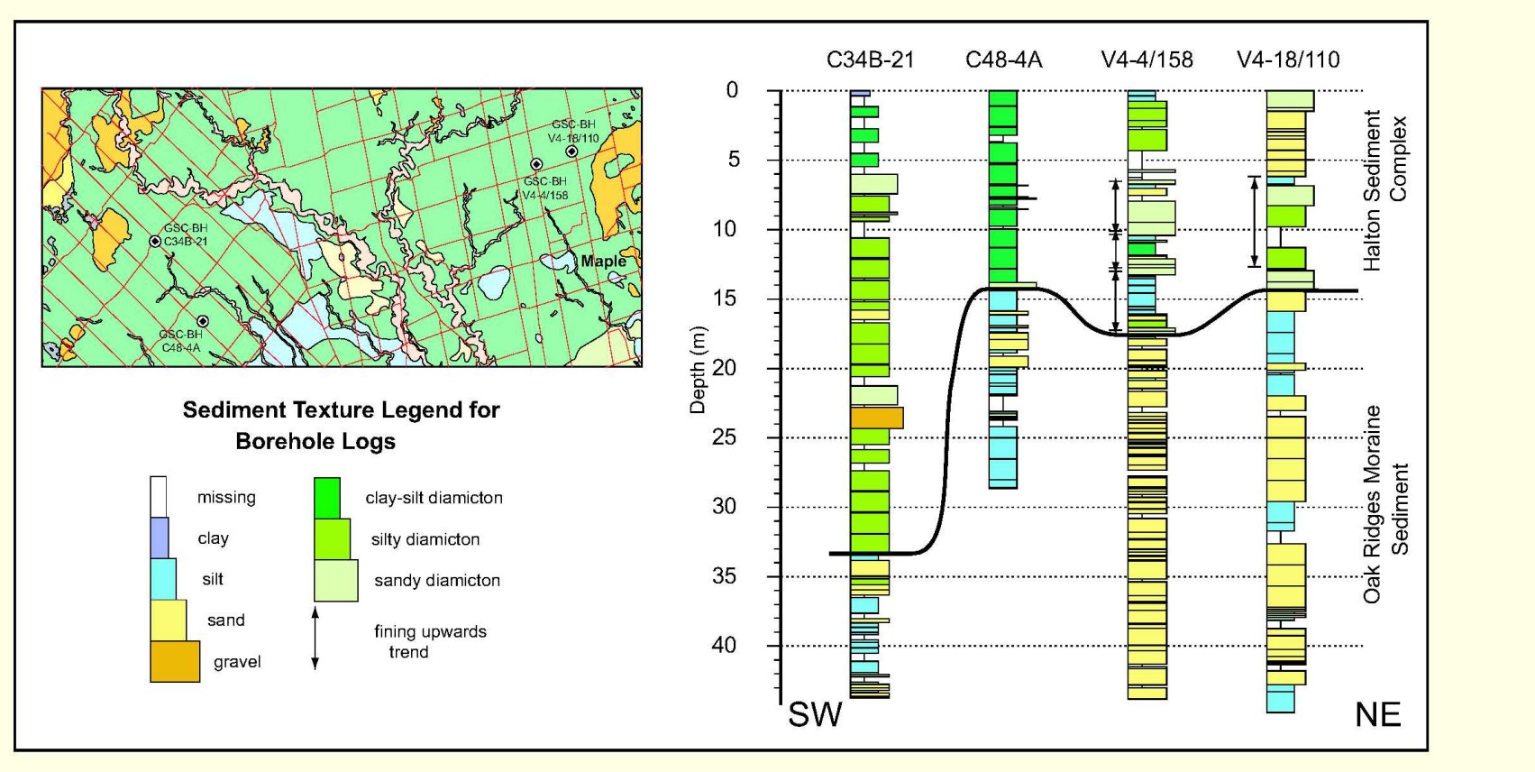


Figure 7. Sediment logs display changes in Halton sediment thickness, texture, and interbeds in the basin. The till unit is thickest in the southwest where silty diamicton predominates, and thinner in the northeast where it is more interbedded and sandy.

Oak Ridges Moraine Sediment

The 160 km, E-W trending ORM ridge covers ~1000 km^2 in four sediment wedges (Map 2, Fig. 1; Barnett et al., 1998; Russell et al., 2005b). ORM sediment overlies a regional unconformity, infills tunnel channels and forms a prominent east-west ridge. It consists mostly of silt and fine sand (Fig. 8) however gravel is prominent in eastern locales. Sediment can be mapped in three stratigraphic elements: i) tunnel channels, ii) basin rhythmites, and iii) ridge sediment (Fig. 9). Gravel is also prominent in tunnel channels and the overall fill succession fines upward (e.g. Pugin et al., 1999; Russell et al., 2003). Basin rhythmites are characterized by ~100 varves and cap tunnel channel fills (Russell et al., 2003). Predominant depositional settings of the ORM landform are subaqueous fans and eskers (Fig. 9; Russell and Arnott, 2003).

ORM is the major recharge area for the GTA region and supplies water to ~60,000 wells. This unconfined aquifer complex controls regional groundwater flow and contributes ~50% of all stream flow (Gerber and Howard, 2000). Hydraulic property variability and groundwater flow paths are controlled by sediment facies, stratigraphic architecture and distribution of bounding units (Fig. 9).

Oak Ridges Moraine Facies

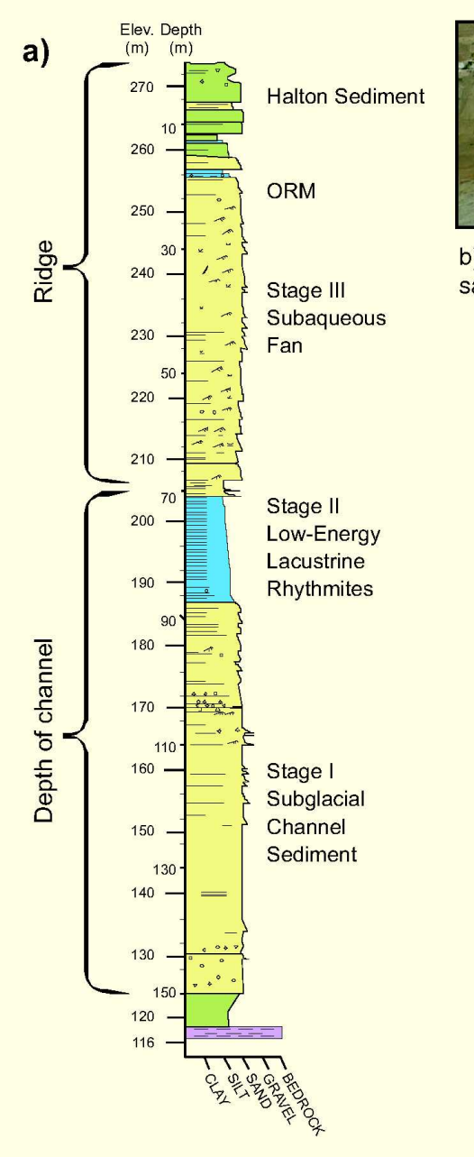
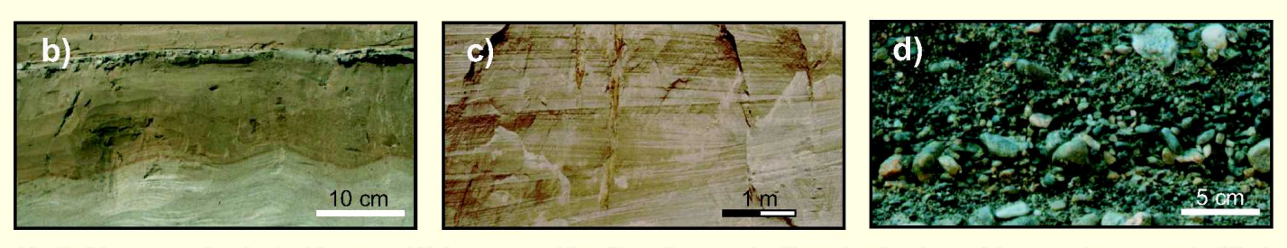


Figure 8. Sediment log shows three depositional episodes of the ORM: i) tunnel channel fill, ii) basin rhythmites, iii) subaqueous fan ridge building.



b) climbing cross-laminated fine sand fining upward to silt and capped with a clay laminae c) low-angle, cross-stratified sand, d) planar, open-work gravel.

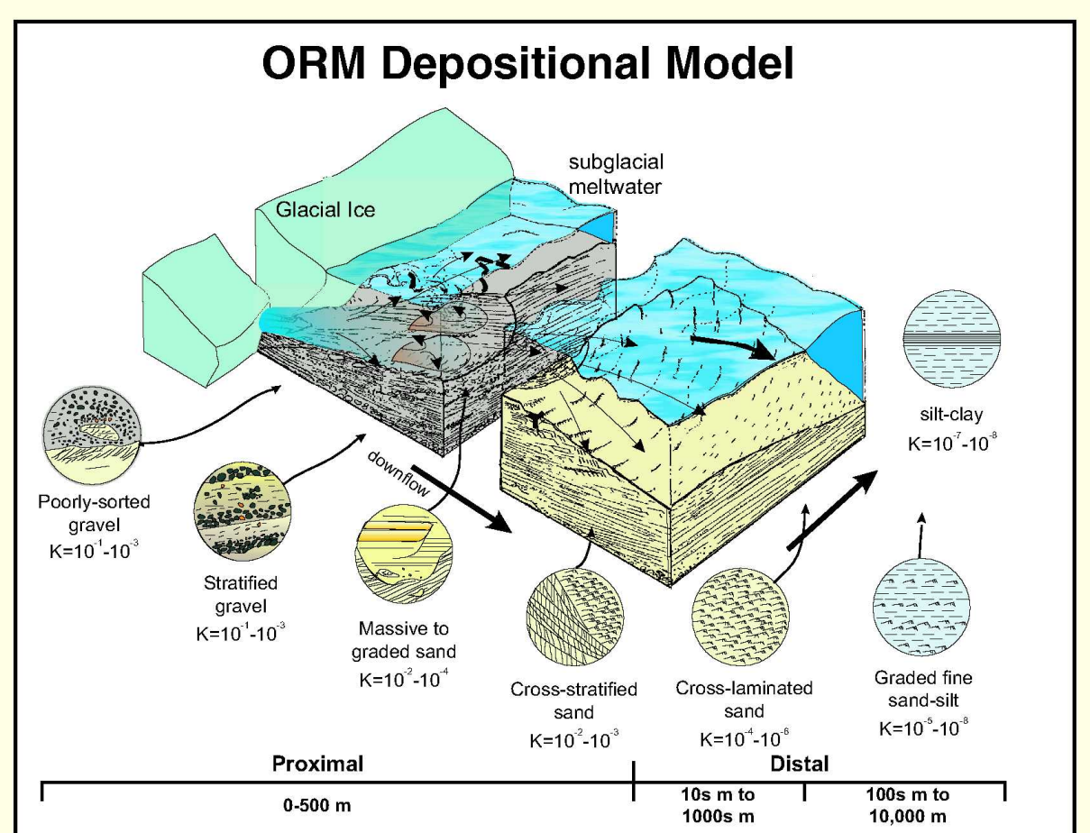


Figure 9. Subaqueous fan depositional model for part of the ORM (Russell and Arnott, 2003). Note: i) rapid downflow change from gravel to fine sand; ii) K values (m/s) of major facies (Freeze and Cherry, 1979); and iii) sand changes rapidly to silt-clay perpendicular to main flow.

Newmarket Till

Newmarket Till is a regional Late Wisconsinan unit that covers ~65% of the area (Fig. 1; Sharpe et al., 2005a). It consists of a dense, <50 m thick, stony, sandy silt diamicton, with thin sand and silt lenses (Fig. 10). Consistent composition and texture in outcrop, core, and geophysical signal (Pugin et al., 1999) make it a key subsurface marker (Pullan et al., 2002). Newmarket Till thickness is strongly influenced by an overlying regional unconformity and erosional landforms: drumlins and tunnel channels (Map 3; Sharpe et al., 2004). Tunnel channels may either completely breach Newmarket Till, or partially erode channel floors to yield varying thickness of till (Map 3; Fig. 11; Sharpe et al., 2005a; e.g., south of Holland Marsh). Newmarket Till may be thin where it drapes over thick subaqueous fan deposits (Lower sediment).

Groundwater flows through Newmarket Till aquitard via fractures (Gerber and Howard, 2000) and through hydraulic 'windows' in channel breaches (Sharpe et al., 2002). Quantitative analysis of structural patterns suggests that leakance through breaches in the aquitard is much greater than through till or fractures (Desbarats et al., 2001).

Newmarket Till Sediment Facies

Figure 10. Newmarket Till sediment facies, a) massive facies (m) with vague banding and stone lines; b) banded diamicton with laminated silt interbeds; c) massive, stony facies and tabular outcrop geometry.

Regional Unconformity Architecture

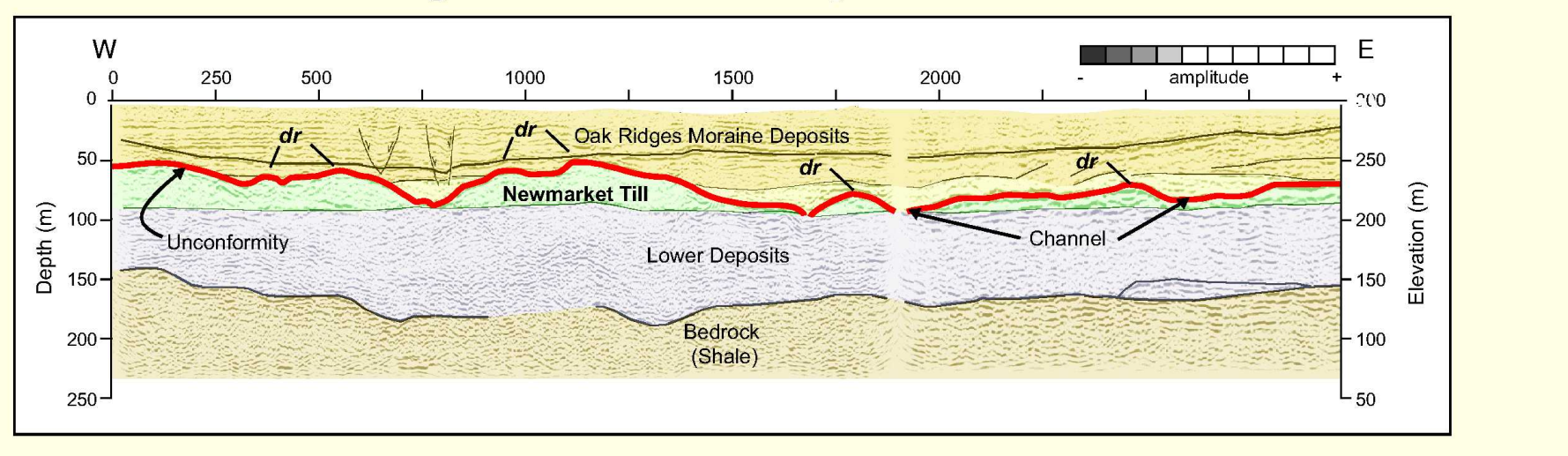


Figure 11. Interpreted seismic profile from 15th side road. Note ~50 m thick till (map 3; line B) and irregular eroded surface of drumlins (dr) and channels. Newmarket Till has planar base over > 2 km profile.

Lower Sediment

Lower sediment occurs stratigraphically below Newmarket Till and is a grouping of the ten formations of Illinoian to mid-Wisconsinan age (~30-50 Ka). It forms ~70% of total sediment volume in the area and is up to 150 m thick (Map 4). Lower sediment is layered in 100 m high lake bluffs (Fig. 12) and in seismic profiles (Fig. 13). It has a planar upper surface and a horizontal internal architecture (e.g. Pugin etal., 1999). This tabular geometry is truncated where tunnel channels incise bedrock (Map 13). Lower sediment becomes thinner where bedrock rises towards Niagara Escarpment, west of Humber River (Map 4; Sharpe et al., 2005b). Lower sediment comprises sand, silt and clay, till, and distinctive organic-rich and fossil-bearing beds important for regional correlation (Fig. 13; 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 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).

Lower Sediment Facies

Figure 12. Lower sediment facies a) climbing ripples in fine sand in conformable contact with Newmarket Till. b) Rhythmites, silt (light) and clay (dark), may overlie fine sand. Scale card is 8.5 cm across. c) Organic-rich silt and fine sand (distinct grey beds below sands) form extensive tabular units in the Scarborough Bluffs. Bluffs are ~ 50 m high.

Lower Sediment Stratigraphic Architecture

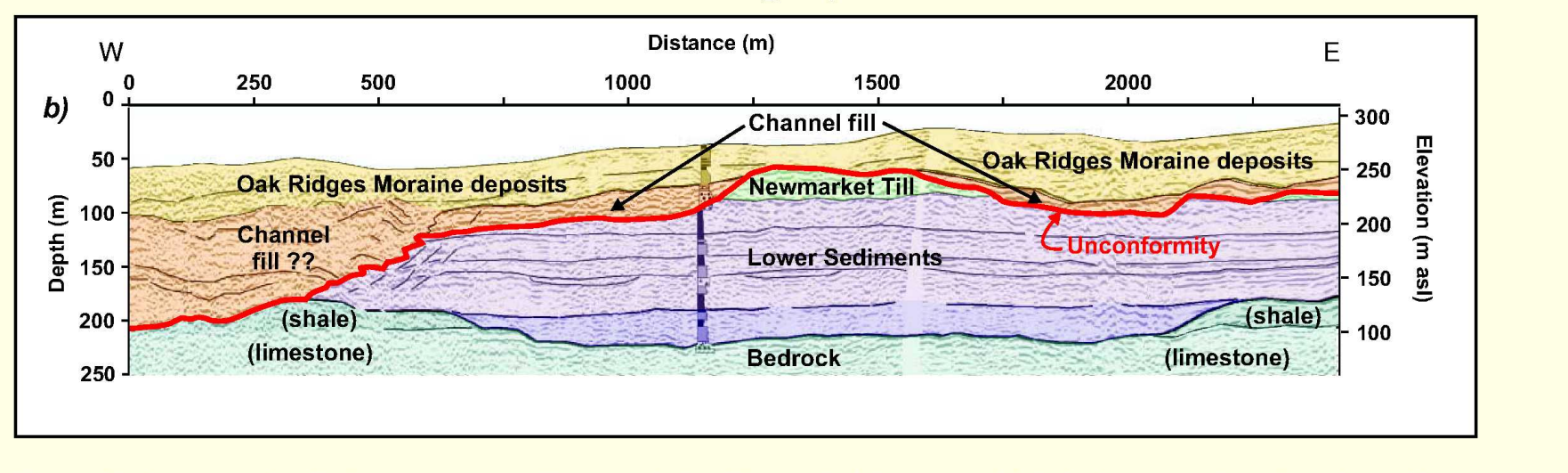


Figure 13. Interpreted reflection seismic profile (map 4; line B) reveals kilometers of tabular Lower sediment confirmed by a continuous sediment core sited along the seismic profile (Pugin et al. 1999). Note truncation of Lower sediment succession by tunnel channel at 0 to 1000 m on the profile.

Summary

A GIS based geological model has been developed for the Oak Ridges Moraine area. This model provides a framework for more site-specific studies and can be used as an exploration tool for groundwater resources. The value of this regional model has been demonstrated through application of the model to conduct environmental assessment, land-use development hearings, and for regional groundwater flow modeling (Bocking, 2006). The ability to update successive model versions in a timely fashion, as new data become available, demonstrates the utility of semi-automated modelling (Logan et al., 2005).

Acknowledgments

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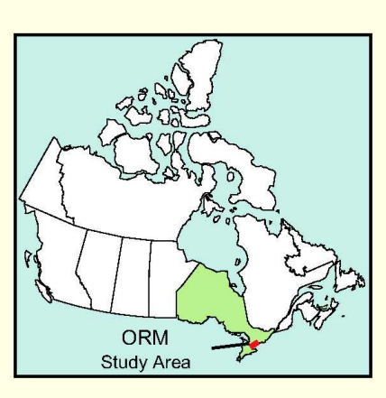

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