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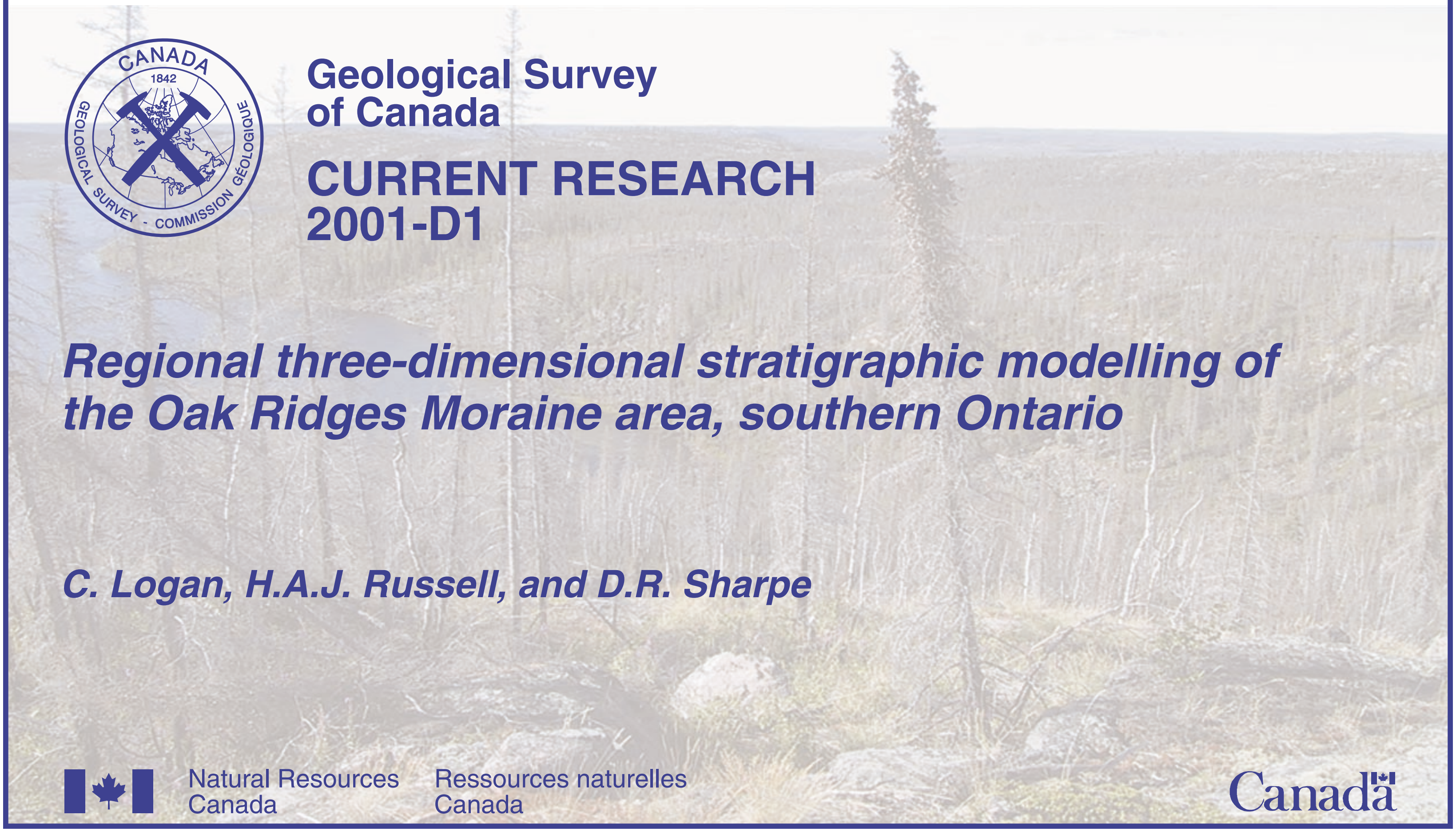

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Regional three-dimensional stratigraphic modelling of the Oak Ridges Moraine area, southern Ontario[1]

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[1] Contribution of the Oak Ridges Moraine NATMAP Project

Abstract

Geological and hydrogeological investigations of the Oak Ridges Moraine and Greater Toronto Area have been used to develop a regional stratigraphic framework. This framework is used to develop a data-driven stratigraphic model by integrating new field data with archival data in a relational database. A multistep approach is used that involves i) manual stratigraphic interpretation of subsurface data, ii) interpretation and integration of Ministry of Environment water-well data to refine elevation variability, iii) generation of individual stratigraphic surfaces that integrate geological map boundaries, and iv) generation of semiquantitative confidence maps. The structural elevation surfaces can be used to produce sediment-thickness maps and rendered three-dimensional volumes, and to constrain hydrogeological modelling. Municipalities, conservation authorities, and other agencies can use this stratigraphic model to provide a regional context and to improve the hydrogeological understanding of site-specific investigations.

Résumé

Les études géologiques et hydrogéologiques de la Moraine d'Oak Ridges et de la grande région de Toronto ont permis d'élaborer un cadre stratigraphique régional. Ce cadre servira à mettre au point un modèle stratigraphique construit à l'aide de données en intégrant les nouvelles données de terrain aux données archivées dans une base de données relationnelle. La démarche multiphases adoptée comprend i) l'interprétation stratigraphique des données de subsurface effectuée manuellement, ii) l'interprétation et l'intégration des données du ministère de l'Environnement collectées dans des puits artésiens afin de perfectionner la variabilité des élévations, iii) la création de surfaces stratigraphiques individuelles qui intègrent les frontières des cartes géologiques et iv) la production de cartes de confiance semi-quantitatives. Les surfaces d'élévation structurale peuvent être utilisées pour dresser des cartes de l'épaisseur des sédiments et des volumes tridimensionnels et pour fixer des limites à la modélisation hydrogéologique. Les municipalités, les offices de la protection de la nature et d'autres organismes peuvent se servir de ce modèle stratigraphique pour élaborer un contexte régional et améliorer les données hydrogéologiques collectées lors d'études spécifiques à un site.

INTRODUCTION

Increasing urbanization in the Greater Toronto Area has created a need for an improved regional geological and hydrostratigaphic understanding. The Greater Toronto Area is the most urbanized region in Canada with about 15% of the country's population, and local development commonly creates conflicting demands on available groundwater resources. To ensure the continued supply of potable groundwater, a well developed understanding of the hydrogeological system is necessary, a key element of which is the stratigraphic architecture. To date, many detailed, site-specific studies in the Greater Toronto Area have been completed (e.g. Fenco-MacLaren Inc., 1994); however, these studies lack a regional framework into which hydrogeological knowledge can be integrated.

In the United States, the Regional Aquifer Systems Analysis (RASA) program completed regional aquifer studies that involved both delineation of the three-dimensional stratigraphy and application of such models for numeric groundwater-flow modelling (Sun et al., 1997). The Geological Survey of Canada has initiated a series of regional hydrogeology studies establishing regional three-dimensional stratigraphic and hydrostratigraphic models (e.g. Sharpe et al., 2000). The Oak Ridges Moraine and Greater Toronto Area hydrogeology study in southern Ontario was initiated in 1993 to develop a regional framework for the 11 000 km^2 area. This project has completed a range of studies focused on understanding regional hydrostratigraphy (e.g. Desbarats et al., 1998; Hinton et al., 1998). To help define this stratigraphic architecture, 50 km of reflection seismic data and 16 continuous cored boreholes have been interpreted. In conjunction with 1:50 000 surficial geological mapping, these data have been used to refine a conceptual architectural model of the area (**Fig. 1**; Sharpe et al., 1999). Unfortunately, these data are too sparse and clustered to produce acceptable interpolated stratigraphic surfaces for the entire study area. It was therefore necessary to integrate them with archival data (Russell et al., 1996). The most abundant and widespread archival data set is the Ontario Ministry of the Environment (MOE) water-well data set. Problems with the locational accuracy (Kenny et al., 1997) and reliability of geological descriptions (Russell et al., 1998a) constrains the way in which water-well records can be used. Nevertheless they are a suitable data source for regional study when integrated with control data. Additionally, water well records contain valuable hydrogeological data (e.g. flow rates, static water levels, screen intervals, etc.) making them an important data set for hydrogeological modelling.

Stratigraphic modelling has typically relied on numerous subparallel and perpendicular cross-sections as a guide for the production of structural and isopach maps. This approach was also adopted by many GIS-based stratigraphic models that used cross-sections from which tie lines were generated (e.g. Martin and Frind, 1997). By using interpreted geological cross-sections rather than the primary data, the degree of heterogeneity in the data is reduced and the modelling process is simplified (e.g. Alms et al., 1996). During a preliminary modelling exercise, this approach was found to be labour intensive, operator dependent, and not amenable to the subsequent addition of new data or changes in stratigraphic coding. The ability to integrate new raw data was viewed as being crucial to the long-term success and continued use of these stratigraphic models.

This paper describes a modelling exercise of the Oak Ridges Moraine-Greater Toronto Area stratigraphy that contains discontinuous stratigraphic horizons. The stratigraphic model used disparate data sets and a regional stratigraphic framework as a guide (Sharpe et al., 1996). A control data set was assembled and hand coded to generate interpolated training surfaces. A set of rules developed from this exercise was then applied to the water wells guided by the training surfaces. The interpolation was completed independently for each of the stratigraphic units in a successive fashion, i.e. lower deposits, Newmarket Till, Oak Ridges Moraine sediment, Halton Till, and glacilacustrine and Recent deposits. These structural surfaces can be used to produce sediment-thickness (isopach) maps or rendered three-dimensional volumes with the appropriate software.

GEOLOGICAL SETTING

The Oak Ridges Moraine and Greater Toronto Area are underlain by Paleozoic bedrock that outcrops along the Niagara Escarpment and in river valleys (e.g. Brennand et al., 1997). Across most of the area, the bedrock is covered by a succession of Quaternary sediment that is up to 200 m thick (Russell et al., 1998b). For the purpose of regional three-dimensional mapping, this sediment has been grouped into five stratigraphic units, i.e. lower deposits, Newmarket Till, Oak Ridges Moraine sediment, Halton Till, and glacilacustrine and Recent deposits (Sharpe et al., 1997; **Fig. 2**).

The 'lower deposits' unconformably overlie Paleozoic bedrock, are up to 100 m thick, and consist of interstratified sand, silt, clay, and diamicton (e.g. Karrow, 1967; Eyles et al., 1985; Sharpe et al., 1996; Pugin et al., 1999). Overlying lower deposits, the Newmarket Till is up to 60 m thick and consists of a dense, sandy diamicton with <15% gravel (Boyce and Eyles, 2000). A regional unconformity forms the upper drumlinized and channelized Nemarket Till surface. Tunnel channels may extend to bedrock, truncating the Newmarket Till and underlying lower deposits (Russell et al., 2000). Tunnel channels are tens of kilometres long, <4 km wide, and up to 150 m deep. Overlying this unconformity is the Oak Ridges Moraine, which consists of four stratified sediment wedges that form a west-trending topographic high extending from the Niagara Escarpment 160 km east to Trenton. The moraine is up to 150 m thick and consists predominantly of rhythmically interbedded layers of silt and fine sand with local sandy gravel (Barnett et al., 1998). The fine-grained, silty Halton Till forms the surface unit over much of the southwestern part of the area and along the southern flank of the Oak Ridges Moraine. North of the moraine, the fine-grained Kettleby Till is likely stratigraphically equivalent to the Halton Till. The Halton Till is up to 30 m thick and generally thins northeastward. Thin deposits of glacilacustrine sand and silt occur across the area. Organic and alluvial deposits occur most extensively within incompletely filled tunnel channels and along postglacial river valleys.

DATA SOURCES

Newly acquired field and archival geological data were integrated in a relational database and GIS (**Fig. 3a, b**; e.g. Russell et al., 1996). New field data include shallow roadside, river, and lake bluff sections, boreholes, and seismic reflection data. Archival data include borehole data collected for hydrogeological and geotechnical studies, and MOE water-well data. Depth coverage of data sets ranges from shallow, predominantly <5 m deep mapping sites to complete sediment penetration to bedrock. Sediment descriptions from these data sets differ considerably in their level of detail, ranging from thorough lithological descriptions of continuously cored sediment (e.g. GSC drillcore, Russell et al., 1998b) to one- or two-word descriptions of rotary drill cuttings by well drillers (e.g. MOE water wells, Russell et al., 1998a). Fifty line-kilometres of reflection seismic data have complete penetration to bedrock for strategic areas in the central part of the moraine where sediment thickness is greatest.

Ministry of the Environment water well records are the most extensive data set with approximately 55 000 wells in the area; however, because of the availability of shallow groundwater supplies, wells generally penetrate only a small part of the total stratigraphy. By interpolating well-bottom elevations and comparing the result to a bedrock elevation surface (Brennand et al., 1997), it is estimated that 60% of the complete sedimentary basin volume is not intercepted by water wells. A 30 m grid-cell topographic digital elevation model (Kenny et al., 1999) provides a common reference for all data. Surficial geology mapping at 1:50 000 and 1:20 000 scale provides additional stratigraphic control for the model (e.g. Sharpe et al., 1997).

METHOD

The stratigraphic architecture of this area can be regarded as a succession of complex, three-dimensional bodies that, individually, are discontinuous and can vary in thickness and elevation. The strategy used in this model was to interpolate the top of each unit as a continuous surface throughout the study area. Because these surfaces could not be produced simultaneously, care was taken to ensure that where a unit was discontinuous, its surface and those above and below coincided exactly. Simple grid subtraction then yields the correct sediment thickness. A conservative method of interpolation was therefore needed that honoured the original data as much as possible. Natural

Neighbour interpolation was selected because it has minimal smoothing and gridded surfaces honour all data points. This method uses a Voronoi tessellation to calculate area-based weights for each data point and is therefore able to handle large variances and gaps in the data coverage (Watson, 1999). Data analysis and processing were completed using Microsoft® Access 2000© Visual Basic for Applications©. GIS interpolation of point data was completed using Triangular Irregular Networks (TIN) and Natural Neighbour interpolation in MapInfo© and Vertical Mapper™.

The modelling process can be separated into four stages, as follows: I) data pre-processing, II) training surface interpolation, III) MOE water-well stratigraphic coding, and IV) final stratigraphic surface interpolation. Data pre-processing prepared the data for the subsequent interpolation and automatic coding stages. A training surface was generated from manually coded records of the control data set and used to guide MOE water-well record interpretation. Automatic stratigraphic coding of water wells used a series of rules for each unit that was applied sequentially with depth. Using a linear decay factor for distance from control points, this initial coding was then modified by comparison with the training surface. This comparison was necessary because the range of sediment descriptions for each stratigraphic horizon was not mutually exclusive and therefore stratigraphic coding based on texture alone would have been inadequate. The two data sets were then integrated and the final stratigraphic surfaces were interpolated.

Stage I: data pre-processing

The data set was first divided into two groups, a control data set and the MOE water-well records. The control data set consists of field sites, continuous core, reflection seismic data, and geotechnical data along with the surficial geology map coverage. These data contain adequate sedimentological descriptions and accompanying data that permit confident stratigraphic interpretations. Forming the second data set, the MOE water-well records are more difficult to classify stratigraphically because they are of lower quality in terms of sediment description. Subsequent data pre-processing can be separated into tasks carried out on the entire data set, the control data set, or the MOE water-well records.

To establish the integrity of the complete data set, four tasks were completed, i) elevation assignment, ii) location verification, iii) material description coding, and iv) map polygon code assignment. To assist in the subsequent location verification and provide a standard elevation source, the elevation for each data site was appended from the Oak Ridges Moraine–Greater Toronto Area digital elevation model (Kenny et al., 1999). Location verification for the control data set was completed manually by reference to the source data. For the MOE water-well data a systematic approach was applied that checked the UTM co-ordinates of water-well records against the Ontario Base Mapping lot and concession fabric and elevation of the Oak Ridges Moraine–Greater Toronto Area digital elevation model. This analysis identified that 30% of the data were likely incorrectly located (Kenny et al., 1997) and these data were therefore omitted from the model.

The primary lithological descriptions in the different data sets ranged from freehand descriptions (geotechnical) to either a five- or three-word adjective/noun description of GSC and Ontario Geological Survey (OGS) field descriptions and MOE water-well records, respectively. To permit the seamless integration of the data, a coding system was developed that permitted 10 basic descriptions (Russell et al., 1998a). The geological content of MOE water-well records was increased by this system, for example by recoding descriptions such as ‘stony clay’ to ‘diamicton’ (Russell et al., 1998a).

The foundation for the model was 1:50 000 surficial geology mapping (Sharpe et al., 1997). Accordingly, the surface unit of all data within each map polygon was assigned the polygon stratigraphic code. This ensures conformity across all data sets and in particular between manually coded data and the water-well data.

The control data set was then manually coded for stratigraphy and each record was checked to ensure that the complete stratigraphy was present. Where stratigraphic units were absent, a null unit of zero thickness was inserted at the appropriate depth. This permitted lateral pinch-outs, truncations or areas of nondeposition to be defined. All stratigraphic unit intervals were flagged as ‘1’ (non-zero thickness, full penetration of a stratigraphic horizon), ‘2’ (non-zero thickness, ends within a stratigraphic horizon), ‘3’ (zero-thickness unit at a known elevation, appended between two units), or ‘4’ (zero-thickness unit of unknown elevation, appended to the bottom of the record) (**Fig. 4**). These codes were used to identify the type of record interval when the individual stratigraphic data sets were assembled for interpolation. Only those units that matched the correct unit code and with an interval type of ‘1’, ’2’, or ‘3’ were included in primary data sets. All intervals of type ‘2’ were checked to determine if their lower depth could correct or ‘push-down’ primary surfaces. Type ‘4’ intervals were not used.

To complete the preparation of the control data set, surficial geology map polygon vertices were converted to a point-data coverage. These points represent mapped contacts between stratigraphic units. Because the selection of map polygon points must also account for missing stratigraphy, points are included in the data set for the oldest adjacent mapped unit and in data sets for all younger stratigraphic horizons (**Fig. 5**). By using map polygon points this way, all interpolated surfaces are forced to mesh with mapped units throughout the area.

A final declustering step remained for the MOE water-well records. Preliminary work with the data identified that these data were geologically too heterogeneous and commonly too clustered to permit completion of a successful surfacing program. Statistical declustering was not used because wells having the most complete sediment record were needed. The best quality wells in a 500 m grid cell were determined by ranking the wells on the basis of two criteria, 1) their total depth and 2) their potential for recording enough units to reflect geological variation. Overall, declustering reduced the data set by 55% to 18 161 records, or <2/km². The number of 500 m grid cells that contained at least one water well was reduced by only 1.5% after declustering.

Stage II: training surface interpolation

All manually coded records except those flagged ‘4’ were selected and combined with corresponding points from map polygon boundaries (**Fig. 6a, b**). These primary data were then interpolated to produce a continuous surface representing the top contact of the stratigraphic horizon (**Fig. 6c**). This surface was then checked using borehole intervals that incompletely penetrated the stratigraphic unit to ensure that all the data were honoured (**Fig. 6d, e**). Those records that penetrated the surface were identified as ‘push-down’ data. The surface was then interpolated a second time, integrating these data with the primary data sets. Slight differences in the interpolated surfaces can produce surface mismatches that were resolved by forcing lower surfaces to be coincident with the overlying surfaces in overlap areas. Finally, areas of the surface that corresponded with mapped geology polygons were stamped with the elevation of the topographic surface digital elevation model (**Fig. 6f**).

Stage III: MOE water-well stratigraphic coding

To integrate regional geological knowledge into the automatic stratigraphic coding, data on depth to top of each training surface (stage II) and distance buffer value were appended to water-well records. Starting from the surface unit of each water well and progressing down, the following five steps were followed to code the stratigraphy (**Table 1**): i) use initial stratigraphic code assigned to the top interval; ii) check material code rules; iii) check thickness and elevation rules; iv) check spatial constraints and miscellaneous rules; and v) verify stratigraphic coding with stage I training surface. A proximity analysis was completed to determine the degree of influence that control data had on the automated stratigraphic coding process (**Fig. 6 g, h**). Because of the large area and complex form of the stratigraphic surfaces, attempts to quantify overall spatial variability using variance analyses were inconclusive. A conservative estimate was therefore made for each stratigraphic unit based on field knowledge. This 'range of influence' buffer was different for each stratigraphic unit and involved a linear decay away from control sites. A stratigraphically coded contact applied to a water well was considered to be in agreement with the training surface if the elevation was within a tolerance range specified for each training surface. Otherwise, the contact was changed to match the nearest applicable sediment interval within the tolerance range. The tolerance range increased from ±1 m to 10 m as the maximum range of influence increased from 0 to the given range of influence. Beyond the range of influence (e.g. 1–2 km), the training surfaces had no effect on the water-well coding. Because adjacent fine-grained units (e.g. silt, clay, and fine sand) are often merged into unrealistically thick, homogeneous units in water-well records, the training surfaces are used to condition the location of stratigraphic boundaries for such units. Coarse-grained water-well units (e.g. sand and gravel) have dimensions that are more representative of depositional units found in continuous core and in the field, therefore no change was permitted in the elevation of these stratigraphic codes.

Stage IV: stratigraphic-surface interpolation

Following stratigraphic coding, the water wells were integrated with manually coded data into one data set. The sequence of steps outlined in stage II (*see* above) was then repeated using the combined data set with the exception that water-well push-down points were used only if they were at least 1 km away from any control point.

Glaciolacustrine sand and Recent organic and alluvial deposits form the uppermost unit. The surface of this unit is equivalent to the topographic digital elevation model and thus, its volume can be derived by simply subtracting the final Halton Till surface from the topographic digital elevation model.

CONFIDENCE ESTIMATION

The accuracy of a grid cell on any given surface is directly related to the proximity and relative quality of nearby data points. Confidence grids were produced for each stratigraphic surface to establish an estimation of potential error on depth. A distance buffer was first made around each data point up to the same maximum range of influence used for the stratigraphic water-well coding (Table 1). To account for the lower accuracy in water-well records and push-down data, the range of influence was halved and quartered, respectively. Each distance buffer grid value was divided by the maximum range to yield a grid value that varied from 0 to 1 radially outward from the data points. Multiplying these grid values by 10 m (i.e. the estimated variance of the data set at the maximum range of influence) provides an approximation of the depth error for any grid cell. This method assumed a linear relationship between separation distance and variance. This was not found to be the case in all trial areas, but because of the scale of the model, a single mathematical function that would satisfy the entire data set could not be well defined.

A confidence surface was produced for the stratigraphic surfaces by combining confidence buffers of each data type and imposing a zero-elevation error value for exposed portions of units as defined by geology map polygons.

This method of confidence estimation allows the model to be easily queried at any location to provide an indication of potential accuracy. In contrast to simple point-density plots or estimation variances derived through kriging, these confidence grids attempt to account for the relative data quality by varying the buffer ranges based on data source.

APPLICATION OF THREE-DIMENSIONAL MODELLING IN THE OAK RIDGES MORAINE

Stratigraphic surfaces derived from geological data allow watershed and site-specific studies to be carried out using the most consistent and reliable three-dimensional subsurface information available.

Current site-development studies in Richmond Hill can be used as an example to illustrate the usefulness of a regional stratigraphic model. The regional thickness map of the Oak Ridges Moraine and related sediment indicates thick aquifer material beneath the proposed development sites (**Fig. 7a**). It shows that the site is located on very thick, permeable sediment at a topographic high. A corresponding depression in the Newmarket Till surface and a thin to absent Newmarket Till suggest the presence of a channel as seen in cross-section (**Fig. 7b**). Hence, aquifers of lower deposits may be hydraulically connected to surface aquifers via more permeable sands of the Oak Ridges Moraine and channel-fill sediments. Consequently, site investigators may need to verify the potential absence of aquitard material by drilling to an adequate depth to establish the site stratigraphy and confirm the thickness of channel aquifer sediments. Local water wells alone are not deep enough to show this architecture.

DISCUSSION

Limitations

The quality of interpolated stratigraphic surfaces is dependant on the quality, quantity, and spatial distribution of the data. Reflecting these variables, no two surfaces in the same model will have the same level of quality assurance. The surface distribution of borehole records gives some indication of the potential model accuracy at a given location, but because few boreholes actually penetrate the complete sedimentary sequence, there is a marked decrease in the number of datum points available for defining older, buried stratigraphic units. The lack of complete penetration of the stratigraphy in the archival record is based primarily on the high cost of drilling. Investigating agencies will drill only to depths necessary to satisfy their specific requirements. This is also true for water wells. The Oak Ridges Moraine is typically thick and contains aquifers adequate for domestic water supply. Consequently, 60% of the sediment thickness is not intercepted by water wells below the Oak Ridges Moraine. This problem is particularly acute along tunnel channels where few wells extend beyond the upper third of channel fill. It has also been a long-standing problem for the interpolation of the bedrock surface beneath the Oak Ridges Moraine and has generated an ongoing misunderstanding concerning the bedrock configuration in this area (e.g. *see* Brennand et al., 1997).

The clustered spatial distribution of the data is closely linked to the levels of urban and rural development. Archival geotechnical and hydrogeological boreholes are often clustered in areas of focused investigation or along major roadways in and around urban centers. Water wells are consistently more abundant in areas dominated by rural residential development closer to Toronto. Fewer records are available from urban areas that switched to water from Lake Ontario in the 1930s.

Stratigraphic successions in glacial deposits are commonly modelled as layer-cake architectures. Detailed mapping, reflection seismic surveys, and core logging indicate that the stratigraphy in the Oak Ridges Moraine area is more appropriately modelled as incised channels, i.e. a jigsaw-puzzle geometry. The amount of data coverage required to successfully delineate elements of these two types of stratigraphic architecture differs significantly. For a layer-cake model, approximately 1 well/km^2 is considered to be adequate, whereas for a jigsaw-puzzle geometry, approximately 4 wells/km^2 are necessary (Weber and van Geuns, 1990). As a result, the data coverage of this study combined with the paucity of deep wells along the anticipated downflow channel trends highlight what may be a common problem in applying more complex but realistic stratigraphic models in glaciated terrain. Specifically, features such as drumlins (~1 km long, <500 m wide) and tunnel channels (tens of kilometres long, <3–4 km wide) are difficult to identify given their geometry and the resolution of this regional model. To fully resolve these structures, greater data density is required than is commonly available at this scale.

The delineation of stratigraphy from water wells is also hampered by the lack of geological information in the original descriptions (e.g. Russell et al., 1998a). Certain terms (e.g. clay) are overused, whereas others (e.g. till), although mapped extensively, are rarely used. This then makes it difficult to adequately define unique criteria for specific stratigraphic units. In areas beyond the range of influence of control points, the model is forced to rely on general rules and constraints to interpret water-well textural descriptions.

Because this model relies on expert knowledge both in the use of geological mapping and the application of rules and constraints in automated water-well interpretation, it is, of course, inherently dependant upon the validity of the underlying conceptual geological model. Therefore the model is being continually tested and verified by geologists familiar with the area and modified as new data warrant.

SUMMARY

Derived stratigraphic surfaces provide a regional model of the Oak Ridges Moraine–Greater Toronto Area using a well documented procedure that integrates regional geological knowledge. This model can be used for reconnaissance in regional land-use planning, for establishing stratigraphic setting in site-specific studies, and for establishing an improved framework to aid regional hydrostratigraphic groundwater flow modelling. As recently noted (LeGrand and Rosen, 1998), the integration of this type of regional information into the preliminary stages of site-specific studies should help to improve their cost-effectiveness. In addition, groundwater modelling that relies exclusively on water-well records for geological and stratigraphic control can be significantly improved by the use of these techniques. The Oak Ridges Moraine–Greater Toronto Area stratigraphic model was designed to provide a regional-scale framework for smaller, more focused stratigraphic investigations. The confidence grids provide an indication of the model quality at any given location and should be used in conjunction with the stratigraphic surfaces when assessing site-specific areas of interest. Digital release of all surfaces and confidence grids are anticipated.

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REFERENCES

Alms, R., Klesper, C., and Siehl, A.
1996: Three-dimensional modeling of geological features with examples from the Cenozoic lower Rhine Basin; *in* Geological Modeling and Mapping, (ed.) A. Forster and D.F. Merriam; Plenum Press, New York, New York, p. 113–133.

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

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Kenny, F.M., and Pugin, A.
1998: On the origins of the Oak Ridges Moraine; Canadian Journal of Earth Science, v. 35, p. 1152–1167.

Boyce, J.I. and Eyles, N.
2000: Architectural element analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada; Geological Society of America, Bulletin, v. 112, no. 1, p. 98–118.

Brennand, T.A., Moore, A., Logan, C., Kenny, F.M., Russell, H.A.J., Sharpe, D.R., and Barnett, P.J.
1997: Bedrock topography of the Greater Toronto and Oak Ridges Moraine areas, southern Ontario; Geological Survey of Canada, Open File 3419, scale 1:200 000.

Desbarats, A.J., Hinton, M., Logan, C., Russell, H., and Sharpe, D.
1998: Geostatistical modeling of leakance in the Newmarket Till aquitard, Oak Ridges Moraine, Ontario; Geological Society of America Annual Meeting, Toronto, Ontario, October 26–29, p. A-402.

Eyles, N., Clark, B.M., Kaye, B.G., Howard, K.W.F., and Eyles, C.H.
1985: The application of basin analysis techniques to glaciated terrains; an example from the Lake Ontario Basin, Canada; Geoscience Canada, v. 12, no. 1, p. 22–32.

Fenco-MacLaren Inc.
1994: IWA landfill site search, Metro/York region: Step 6 hydrogeological report sites V3B, V4A, V4D; Interim Waste Authority Report, prepared by M. Gomer, Fenco MacLaren Inc., January 1994.

Hinton, M.J., Russell, H.A.J., Bowen, G.S., and Ahad, M.E.
1998: Groundwater discharge in the Humber River watershed; *in* Groundwater in a Watershed Context, (ed.) A.R.Piggott; Canadian Water Resources Association, Burlington, Ontario

Karrow, P.F.
1967: Pleistocene geology of the Scarborough area: Toronto; Ontario Ministry of Natural Resources, Report 46, 108 p.

Kenny, F.M., Chan, P., and Hunter, G.
1997: Quality control of the positional accuracy of records in Ontario's water well database using automated GIS techniques; *in* Conference Proceedings, Geomatics in the Era of RADARSAT GER 97, Ottawa, May 24–30, 1997.

Kenny, F.M., Paquette, J., Russell, H.A.J., Moore, A.M., and Hinton, M.J.
1999: A digital elevation model of the Greater Toronto area, southern Ontario, and Lake Ontario bathymetry; Geological Survey of Canada, Ontario Ministry of Natural Resources, and Canadian Hydrographic Service; Geological Survey of Canada, Open File D3678 (CD-ROM).

LeGrand, H.E. and Rosen, L.
1998: Putting hydrogeological site studies on track; Ground Water, v. 36, p. 193–194.

Martin, P.J. and Frind, E.O.
1997: Modeling a complex multi-aquifer system: the Waterloo Moraine; Ground Water, v. 36, no. 4, p. 679–690.

Pugin, A., Pullan, S.E., and Sharpe, D.R.
1999: Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario; Canadian Journal of Earth Sciences, v. 36, p. 409–432.

Russell, H.A.J., Brennand, T.A., Logan, C., and Sharpe, D.R.
1998a: Standardization and assessment of geological descriptions from water well records: Greater Toronto and Oak Ridges Moraine areas, southern Ontario; *in* Current Research 1998-E; Geological Survey of Canada, p. 89–102.

Russell, H.A.J., Logan, C., Brennand, T.A., Hinton, M., and Sharpe, D.R.
1996: A regional geoscience database: an example from the Oak Ridges Moraine NATMAP / Hydrogeology Project; *in* Current Research 1996-E; Geological Survey of Canada, p. 191–200.

Russell, H.A.J., Logan, C., Moore, A., Kenny, F.M., Brennand, T.A., Sharpe, D.R., and Barnett, P.J.
1998b: Sediment thickness of the Greater Toronto and Oak Ridges Moraine NATMAP areas, southern Ontario; Geological Survey of Canada, Open File 2892.

Russell, H.A.J., Sharpe, D.R., Pullan, S.E., and Barnett, P.J.
2000: Form and sedimentary fill of tunnel channels beneath the Oak Ridges Moraine, southern Ontario: the Holland Marsh and King City channel system; Geological Survey of Canada, Open File 3841.

Sharpe, D.R., Barnett, P.J., Brennand, T.A., Finley, D., Gorrell, G., Russell, H.A., and Stacey, P.
1997: Surficial geology of the Greater Toronto and Oak Ridges Moraine area, southern Ontario; Geological Survey of Canada, Open File 3062, scale 1:200 000.

Sharpe, D.R., Barnett, P.J., Russell, H.A.J., Brennand, T.A., and Gorrell, G.
1999: Regional geological mapping of the Oak Ridges Moraine, Greater Toronto Area, southern Ontario; *in* Current Research 1999-E; Geological Survey of Canada, p. 123–136.

Sharpe, D.R., Dyke, L.D., Hinton, M.J., Pullan, S.E., Russell, H.A.J., Brennand, T.A., Barnett, P.J., and Pugin, A.
1996: Groundwater prospects in the Oak Ridges Moraine area, southern Ontario: application of regional geological models; *in* Current Research 1996-E; Geological Survey of Canada, p. 181–190.

Sharpe, D.R., Hinton, M.J., and Russell, H.A.J.
2000: Groundwater resources in the Oak Ridges Moraine, Greater Toronto area; *in* GeoCanada2000, Proceedings with Extended Abstracts, Geological Association of Canada, Calgary, Alberta, 29 May–2 June.

Sun, R.J., Weeks, J.B., and Grubb, H.F.
1997: Bibliography of regional aquifer-system analysis program of the U.S.Geological Survey, 1978–96, 97-4074.

Watson, D.
1999: The natural neighbour series manuals and source codes; Computers and Geosciences, v. 25, p. 463–466.

Weber, K.J. and van Geuns, L.C.
1990: Framework for constructing clastic reservoir simulation models; Journal Petroleum Technology, p. 1248–1253, 1296–1297.

Geological Survey of Canada Project 930042

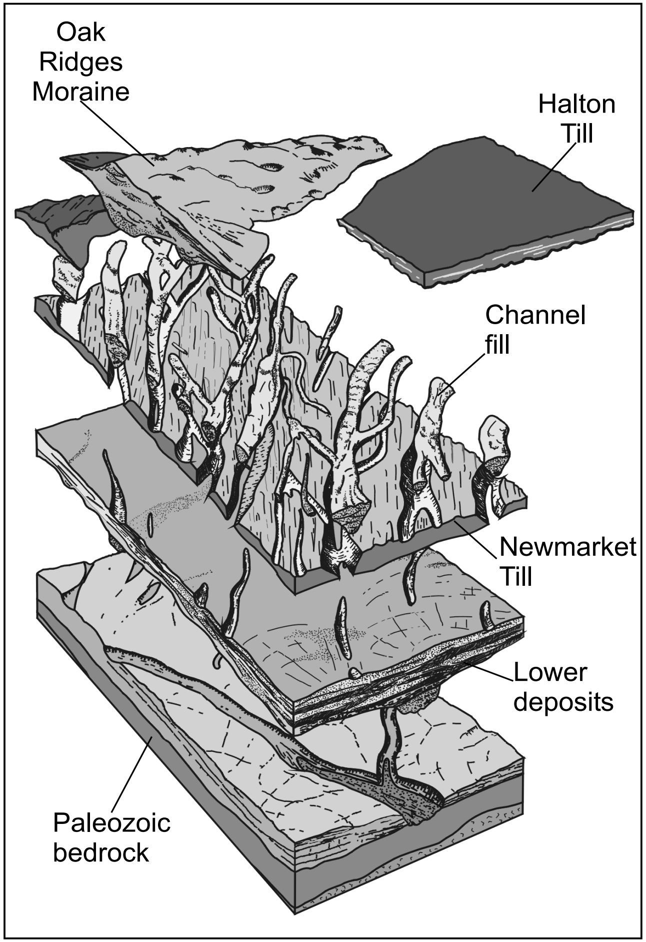


Figure 1. Conceptual model of the stratigraphic framework of the Greater Toronto Area (Sharpe et al., 1996). Note that uppermost glacilacustrine and Recent deposits are not shown.

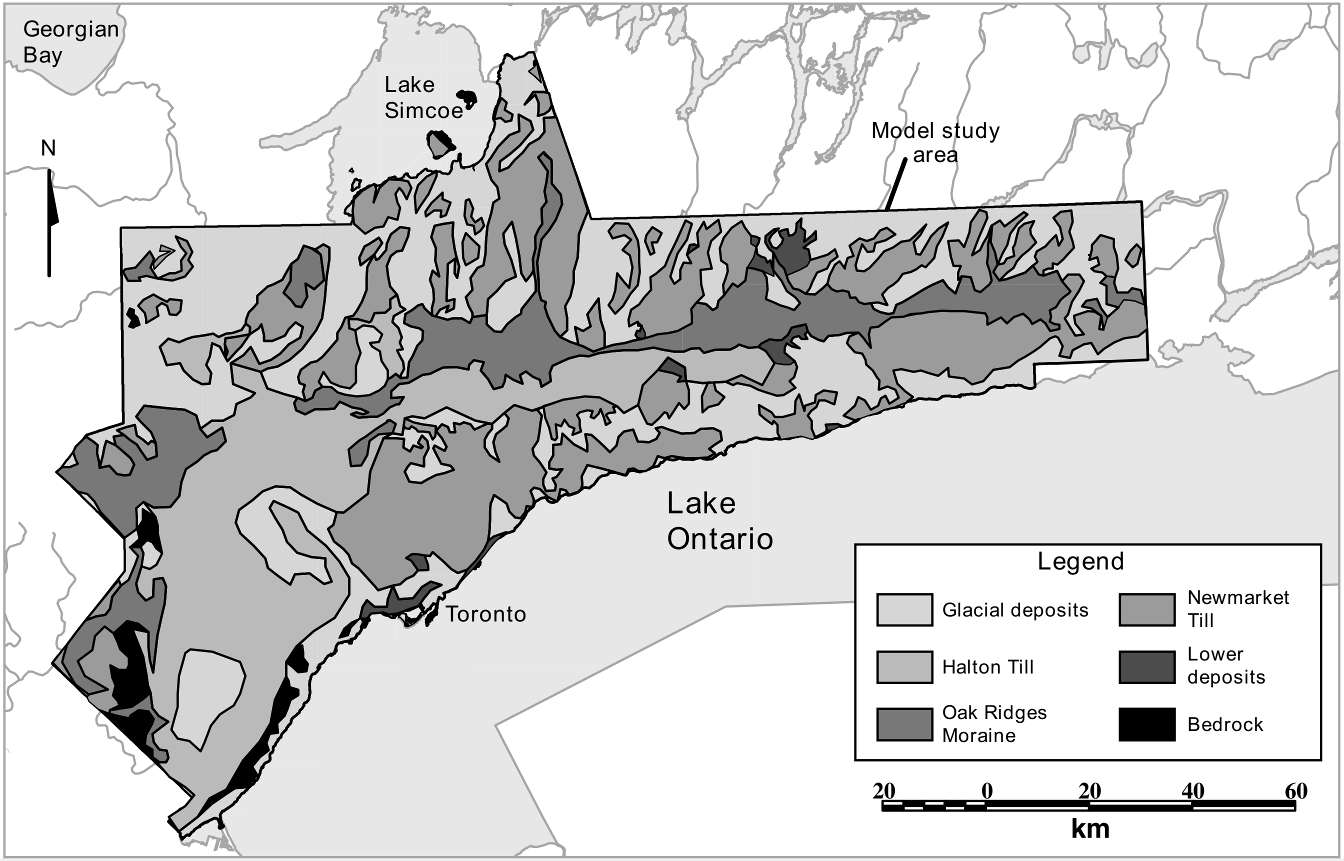


Figure 2. Generalized surficial geology of the Greater Toronto Area and Oak Ridges Moraine region, southern Ontario (*modified from* Sharpe et al., 1997).

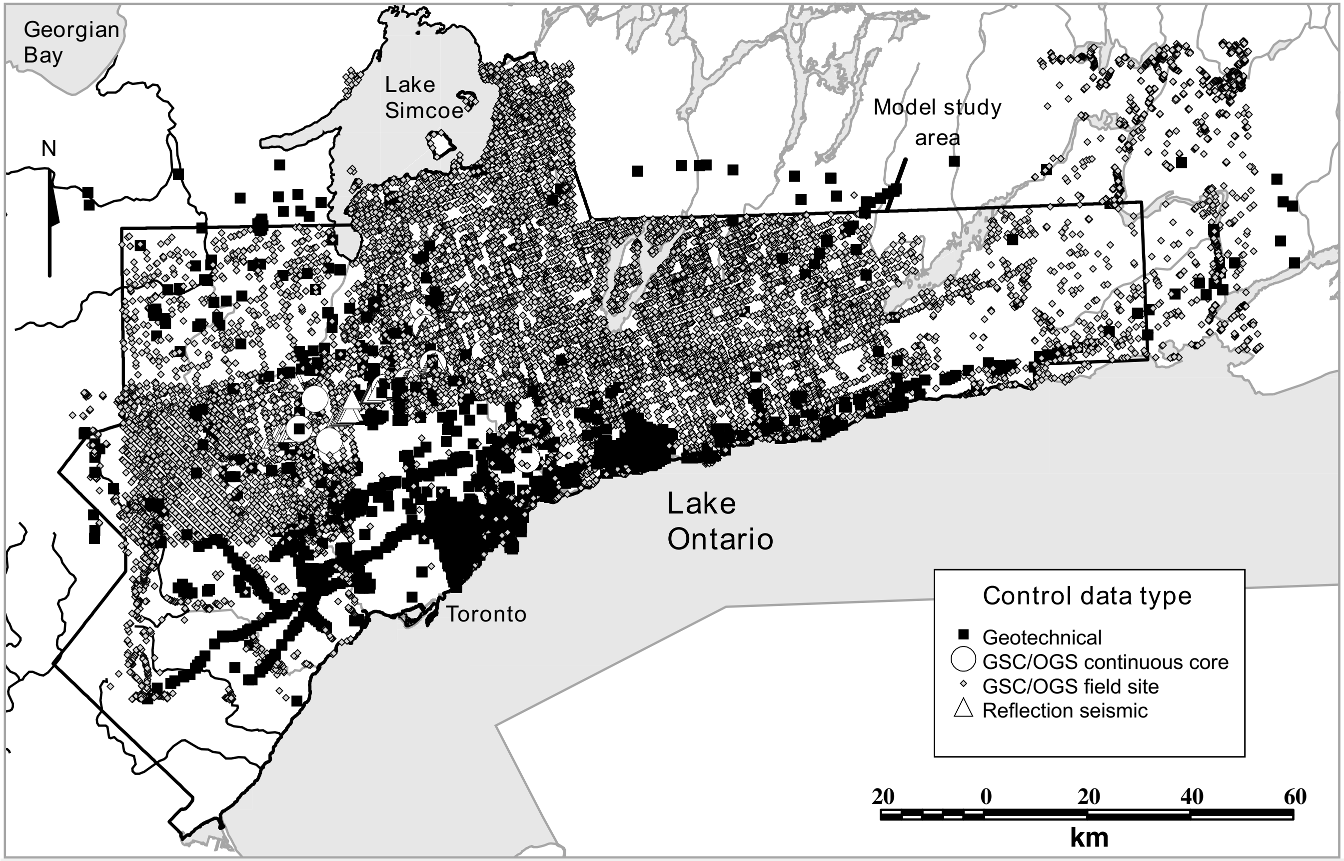


Figure 3. a) Control data distribution

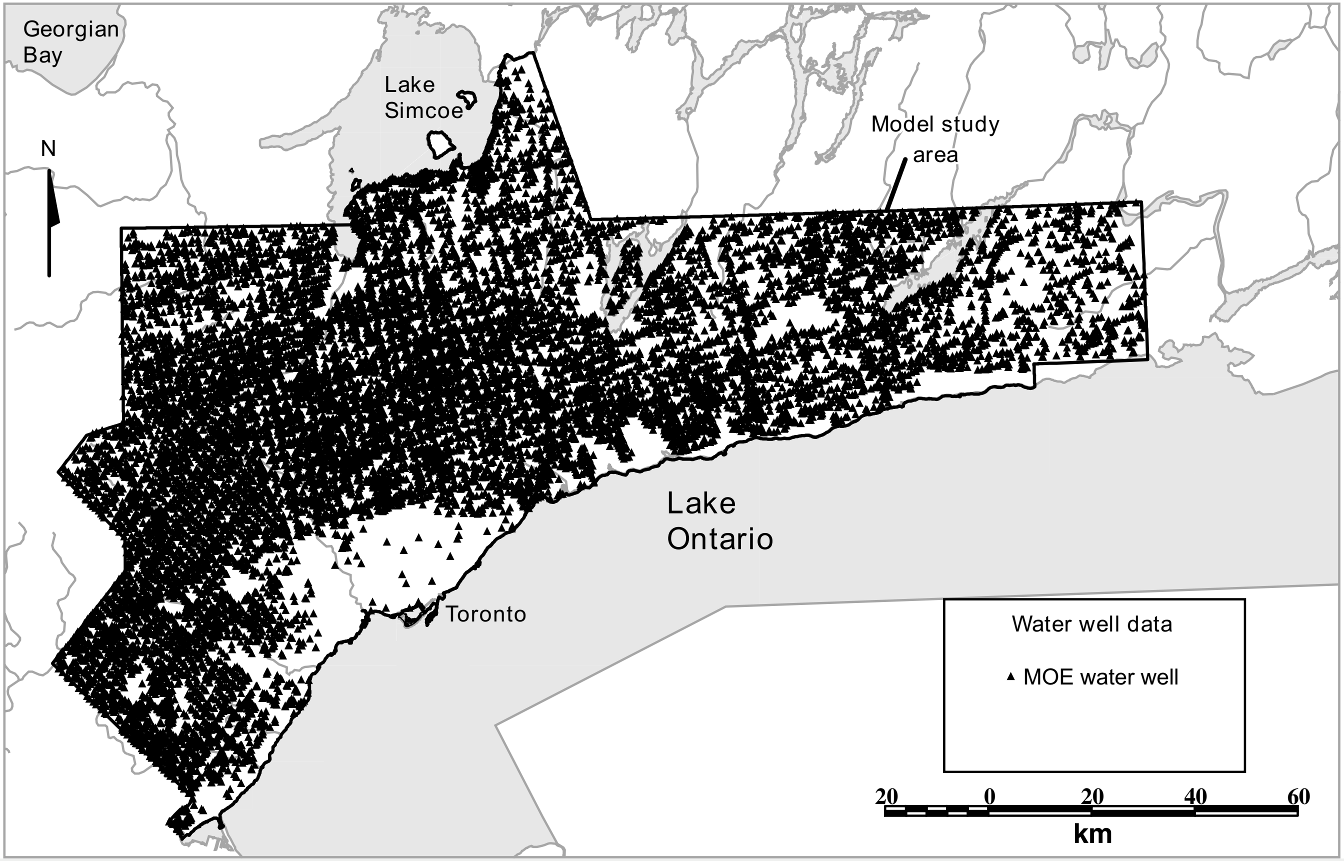
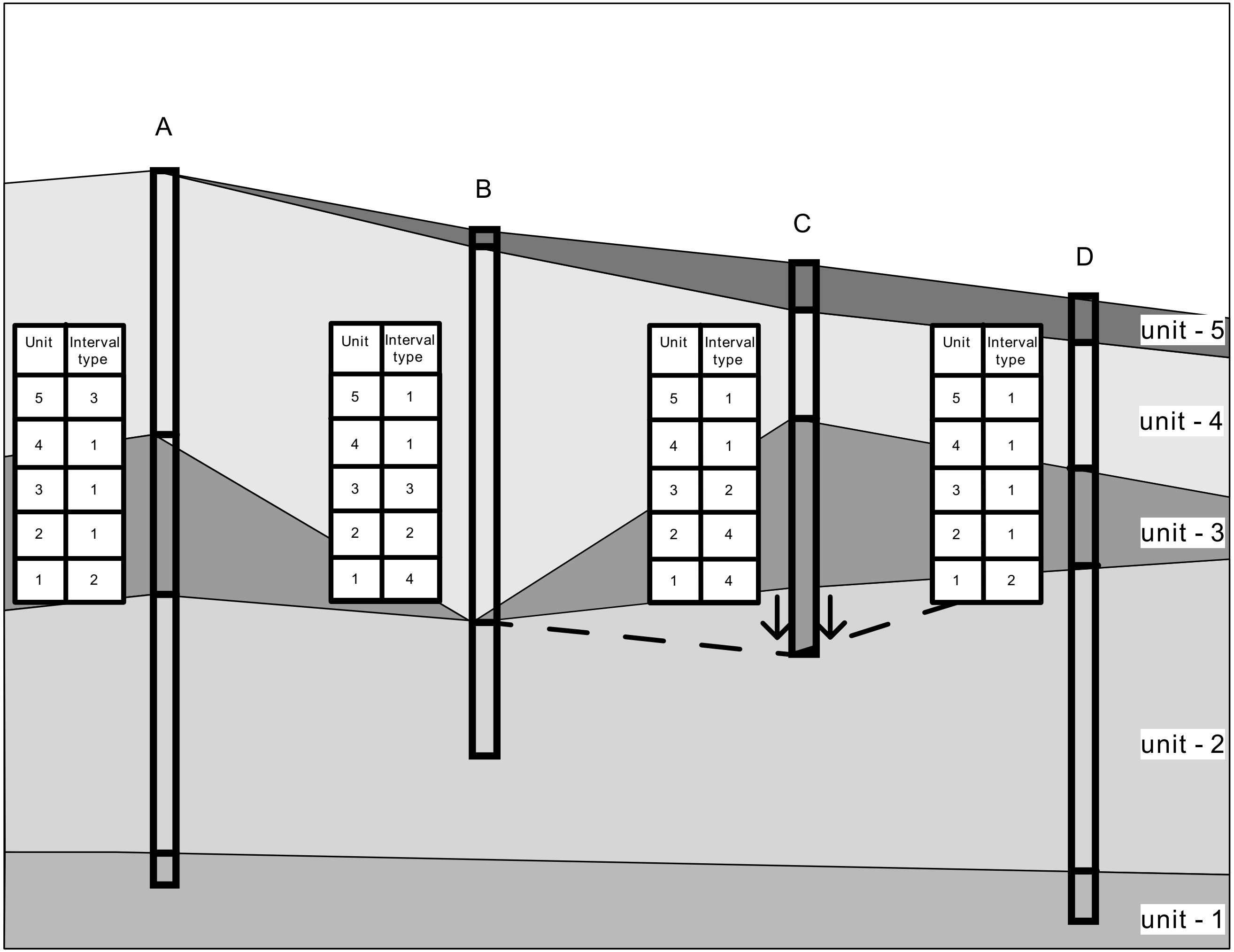


Figure 3. **b**) Selected Ministry of the Environment water wells based on 500 m grid cell.



Unit	Interval type
5	3
4	1
3	1
2	1
1	2

Unit	Interval type
5	1
4	1
3	3
2	2
1	4

Unit	Interval type
5	1
4	1
3	2
2	4
1	4

Unit	Interval type
5	1
4	1
3	1
2	1
1	2

Figure 4. Examples of borehole unit coding for use in surface interpolation and for surface push down. Tables represent borehole codes in a database. Boreholes A and B both show zero-thickness intervals that can be used to define surfaces (i.e. type ‘3’). Borehole C shows a condition where the bottom elevation of the last non-zero interval (i.e. type ‘2’) can be used to ‘push down’ the older stratigraphic unit below as indicated. Borehole D has all units present.

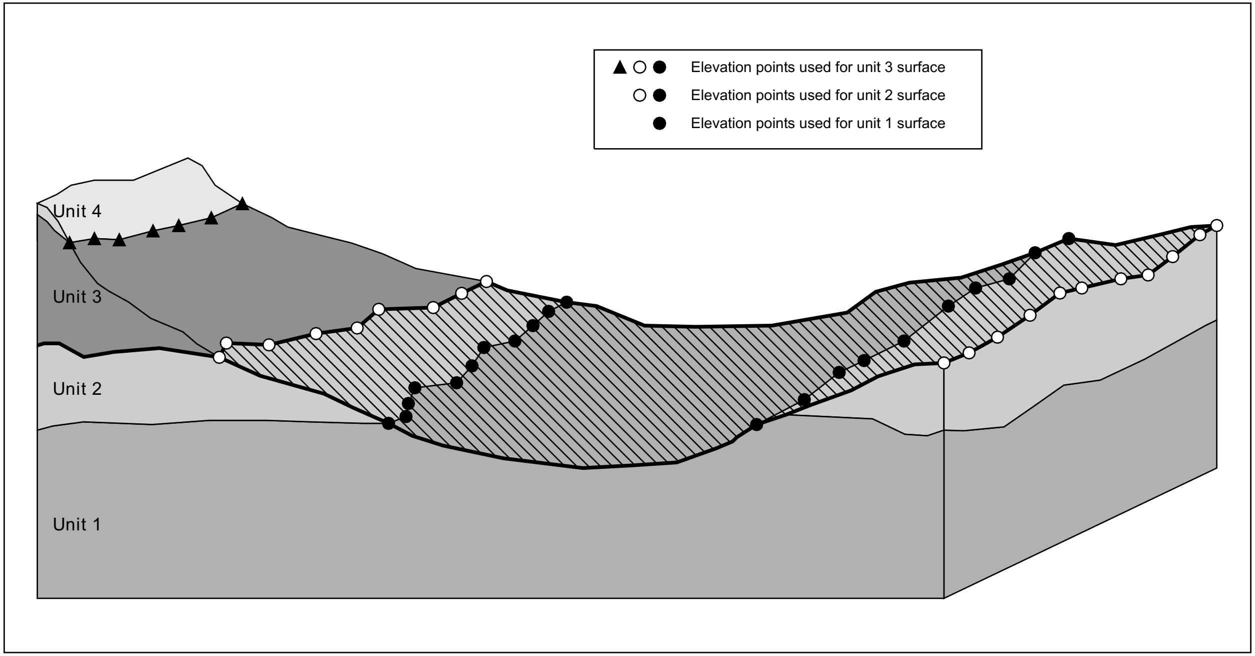
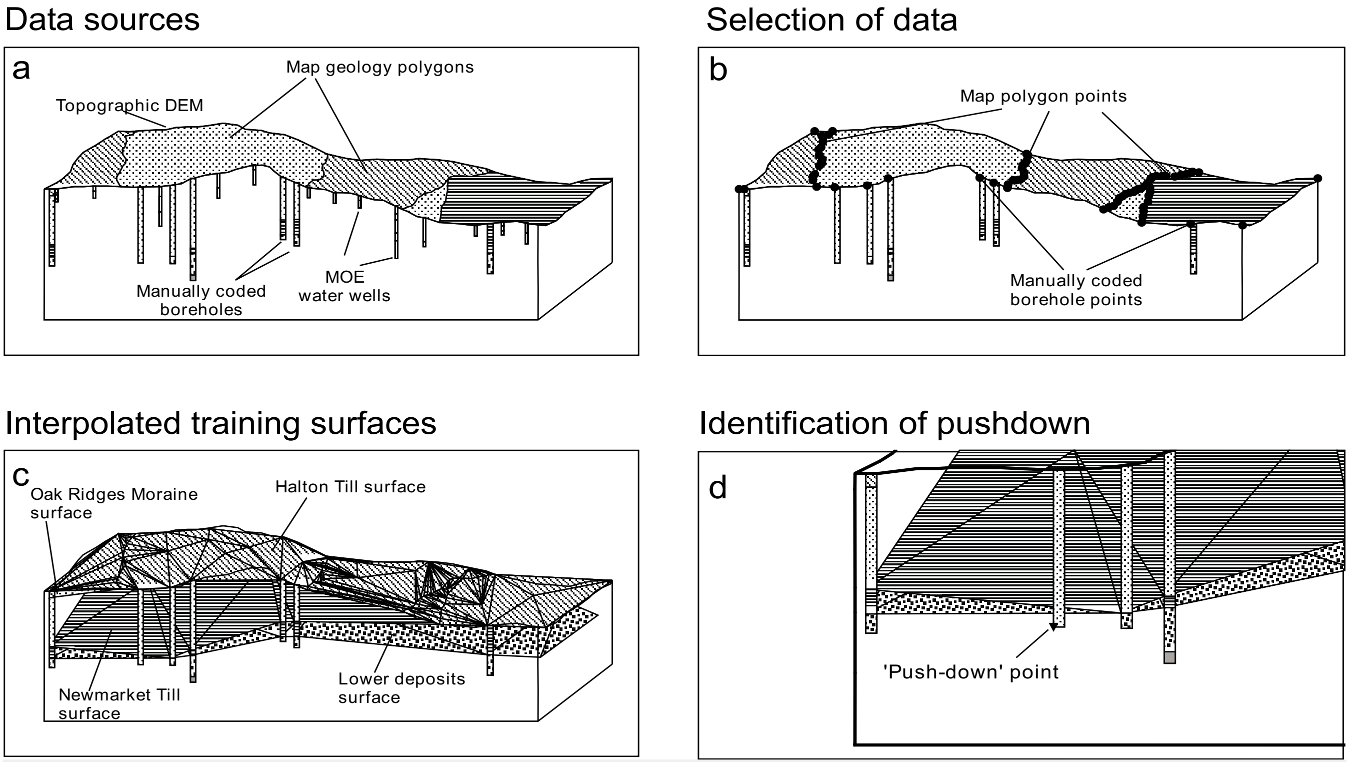


Figure 5. Schematic block diagram illustrating how map polygon points are selected for addition to control data sets. The surface of unit 2 is outlined as an example.



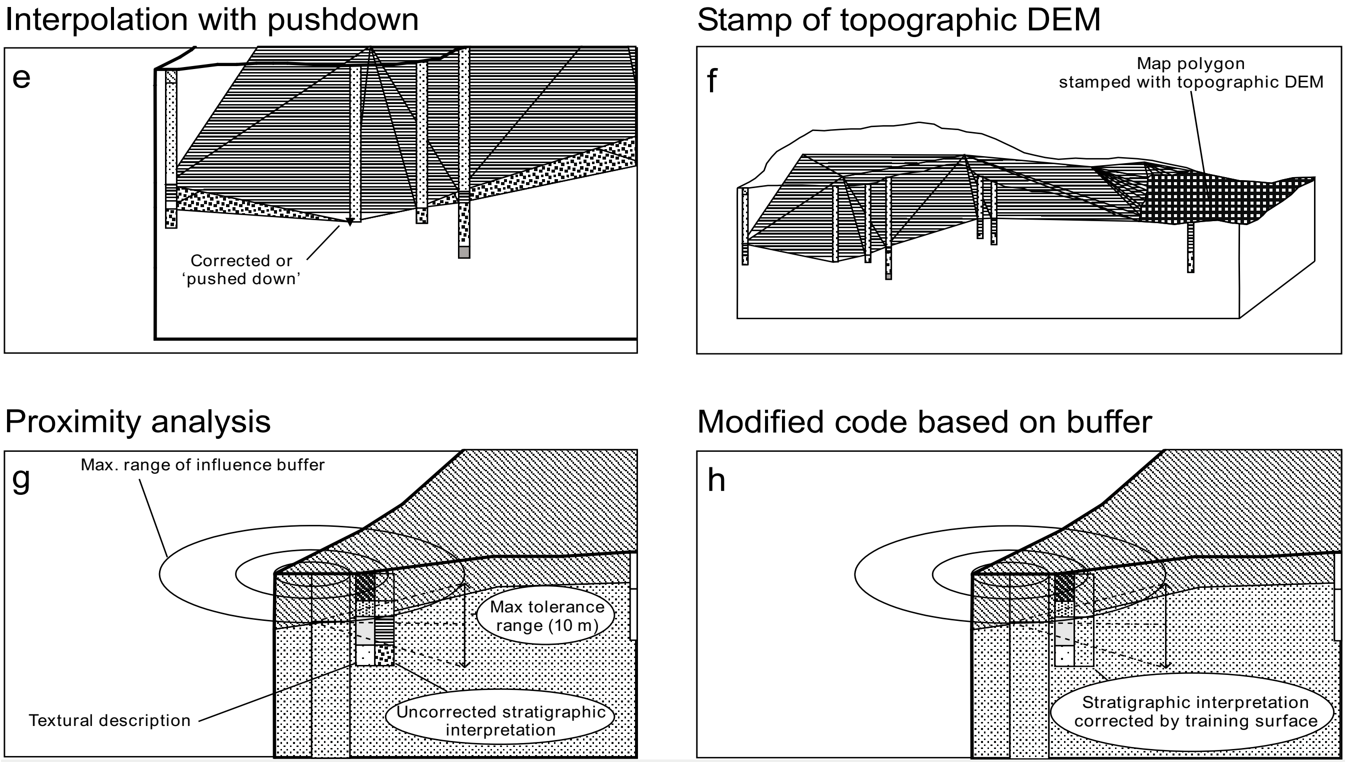
Data sources

Selection of data

Interpolated training surfaces

Identification of pushdown

Figure 6. Schematic illustration of the process used in generating the stratigraphic surfaces. DEM = digital elevation model



Interpolation with pushdown

Stamp of topographic DEM

Proximity analysis

Modified code based on buffer

Figure 6. (cont.)

Figure 7. a) Oak Ridges Moraine sediment thickness map. Note the variation in sediment thickness across the Richmond Hill sites.

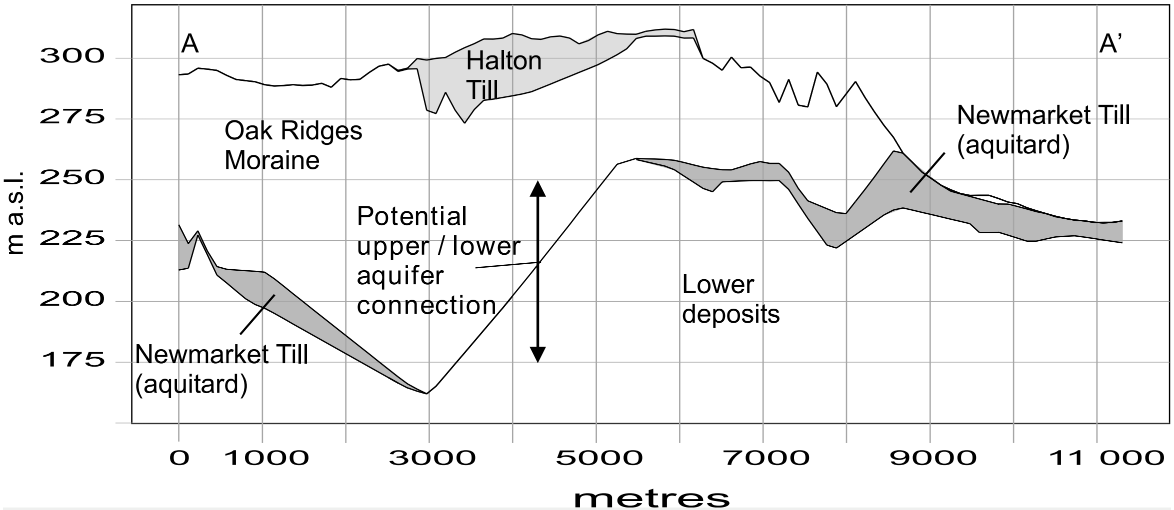


Figure 7. b) Cross-section A-A’ through all stratigraphic surfaces.

Table 1. Ministry of the Environment water-well automated coding constraints and/or rules. Note that the maximum thickness rule for Newmarket Till reflects the estimated average thickness (i.e. 30 m) and not the maximum thickness in continuous core of 60 m.

Stratigraphic unit (code)	Acceptable materials	Training surface range of influence	Maximum unit thickness	Maximum interbed thickness	Spatial rules	Maximum elevation	Miscellaneous rules
Halton Till (5)	-clay -silt -clay-silt diamicton -sand-silt diamicton -silt-sand diamicton As interbeds only: -gravel -sand	1 km	-South of Humber river: 30 m -North of Humber river: 10 m	5 m	Restricted to areas of mapped Halton Till north of the Iroquois Shoreline / Humber River	No restrictions	Must be coded continuously from surface or below Recent deposits. Silt-sand diamicton is only allowed if it is continuous from the surface.
Oak Ridges Moraine (4)	-silt -sand -gravel	1 km	No restrictions	10 m	-Restricted to areas of mapped Halton Till and Oak Ridges Moraine -Restricted to tunnel channels in the north	No restrictions	Silt is only allowed if it is continuous from surface and if a sand or a gravel unit exists below it.
Newmarket Till (3)	-sand-silt diamicton -silt-sand diamicton	2 km	30 m	- 5 m - 8 m if Oak Ridges Moraine present	No restrictions	No restrictions	
Lower deposits (2)	(any material)	2 km	No restrictions	No interbeds allowed	No restrictions	310/340 m a.s.l.	