INTEGRATED 3D HYDROSTRATIGRAPHIC INTERPRETATION IN COMPLEX AQUIFER SYSTEMS

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ABSTRACT: Construction of aquifer and aquitard layer geometry is one of the most challenging aspects of ground water modelling. Simple interpolation of sparse point data (well picks) rarely produces layer surfaces that realistically represent the structure and continuity of complex hydrogeologic features such as channel and valley systems. Building on the Geological Survey of Canada's (GSC) extensive analysis of the Ontario's Oak Ridges Moraine (ORM) region, a team of hydrogeologists has extended and refined the GSC's version 1 stratigraphic model into a hydrostratigraphic framework in support of an eight-layer numerical groundwater flow model. The complexity of the ORM aquifer systems requires the full integration of borehole lithology picks, subtle hydrogeologic indicators, as well as expert intuition and conceptual understanding of the sedimentological processes. Database integration, flexible visualization, efficient layer picking tools, and the capture of expert intuition using 3D constraint polylines were all essential to the model construction process. The result is a hydrostratigraphic model that not only honours the borehole and well data, but also the conceptual understanding of the processes that formed the moraine.

RESUMÉ: La construction de la couche géométrie de l'aquifer et l'aquitard est l'un des aspects les plus difficiles dans le modelage de l'eau souterraine. L'interpolation simple de données de point épars (puits choisis) produit rarement les surfaces de couche qui représentent exactement la structure et la continuité des caractéristiques "hydrogéologiques" complexes tels que les systèmes de chaîne et de vallée. Construisant sur l'analyse intensive faite par la Commission géologique du Canada (CGC) sur le Oak Ridges Moraine (ORM) de l'Ontario, une équipe d'hydrogéologistes a prolongé et raffiné le modèle stratigraphique de la CGC en une structure hydrostratigraphique convenable pour un modèle d'eau souterrain numérique de huit couches. La complexité des systèmes aquifers du ORM exige l'intégration complète de lithologie de forage sélectionné, des indicateurs hydrogéologiques subtils, et finalement une intuition experte et une comprehension conceptuelle des procédés sédimentologiques. L'intégration de bases de données, la visualisation flexible, les outils efficaces pour sélectionner les couches, et le recours à une intuition experte utilisant la contrainte "polylines" en 3D sont tous essentiels au processus de construction du modèle. Le résultat est un modèle numérique qui fait justice non seulement aux données de puits, mais aussi contribue à la compréhension conceptuelle des procédés qui ont formé la moraine.

1. BACKGROUND

The Oak Ridges Moraine (ORM) stretches 160 km across southern Ontario from the Niagara Escarpment in the west to Trenton in the east (Figure 1). The moraine serves as the height of land separating southward flowing drainage towards Lake Ontario from northward flowing drainage into Lake Simcoe.

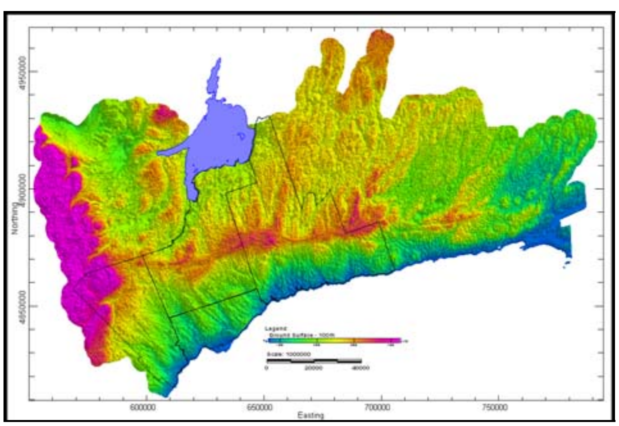

Figure 1: DEM of the Oak Ridges Moraine, Southern Ontario, Canada

The ORM has long been the focus of significant attention by the Provincial Government, as well as the public, owing to land development pressure from the rapidly growing communities across the Greater Toronto Area (GTA). The moraine is recognized as a regionally significant groundwater recharge area and its aquifers provide drinking water for over one hundred thousand residents. It also provides discharge to headwaters of many prominent Ontario streams (Gerber and Howard, 2002).

In the early 1990's a study of the hydrogeological significance of the ORM was prepared to investigate the role of the moraine in the hydrogeology of the area (Intera Kenting, 1990). In 1991, the Provincial government released guidelines for managing land uses on the moraine and several studies investigated technical and land use issues related to the moraine (e.g. Oak Ridges Moraine Technical Working Committee, 1994, Hunter et. al. 1996). This and other work resulted in the Oak Ridges Moraine Conservation Act, and the accompanying ORM Conservation Plan, in late 2001. These regulations significantly curtail development on the ORM

An improved hydrogeological characterization of the ORM is required because of increased land use pressure and extensive groundwater extraction. To better characterize the hydrogeological function of the ORM a project to construct a numerical groundwater model across the moraine was initiated in 2001. The modelling study is being directed and funded by a partnership of local government agencies with additional funding from the Provincial Government. The hydrostratigraphic interpretations presented in this paper form part of the model construction process.

2. PREVIOUS WORK

Environmental geoscience and geological history of the GTA has recently been reviewed by Eyles (1997). The lithostratigraphic framework for sedimentary deposits in the area is mainly based on Lake Ontario shoreline studies (e.g. Karrow, 1967). Development pressures prompted the Ontario Geological Survey (OGS) and Geological Survey of Canada (GCS) to revisit this area in the 1990's. The original stratigraphic framework was re-interpreted by Barnett et al., (1998) based on detailed geological mapping (Sharpe *et al*., 1999) and event stratigraphic concepts. In particular, a prominent late glacial unconformity (Figure 2) consisting of deep tunnel channel and drumlinized interfluves was mapped at the surface and identified beneath the Oak Ridges Moraine (ORM) from core and reflection seismic profiles (e.g. Pugin *et al*., 1999). These data show tunnel channels breaching the regional Newmarket Till aquitard and drew attention to significant implications for ground water flow systems (Sharpe *et al*., 2002).

Early studies identified many local aquifer systems (Sibul *et al*., 1977; Haefeli, 1970) and concluded that the groundwater divide coincides with the ORM crest (Haefeli, 1970). Recent groundwater modeling used a conventional lithostratigraphic framework, where continuous till aquitards are assumed to fully separate Scarborough and Thorncliffe formation aquifers from overlying ORM aquifers (e.g. Howard *et al*., 1995). Focused work on the Newmarket Till aquitard (Gerber and Howard, 2000; Desbarats *et al*., 2001) and recharge-discharge functions of the Oak Ridges Moraine (Gerber and Howard, 2002) is providing hydrogeological context for regional flow system analysis.

3. GSC STRATIGRAPHIC MODEL

The GSC/OGS event stratigraphic framework provided this project team with an excellent foundation on which to build the hydrogeologic model. As a result of their considerable expertise, the GSC was included in this project team as a senior review partner. The GSC provided two key inputs to this project:

1. A conceptual understanding of the stratigraphic framework and key glacial processes, and
2. A five layer digital stratigraphic model of the moraine.

The following description of the GSC stratigraphic framework illustrates the complex structure of the moraine. A brief description of the methodology used to construct the GSC digital stratigraphic model surfaces follows.

3.1. Conceptual Stratigraphic Framework

The ORM region is underlain by up to 200 m of sediment resting on Paleozoic bedrock. Bedrock outcrops along the Niagara Escarpment and in local river valleys near Lake Ontario. The Laurentian Channel, a poorly defined buried bedrock valley (Brennand et al. 1998) connecting basins in Georgian Bay and Lake Ontario, is inferred to have been an ancestral drainage route of the upper Great Lakes (e.g. Eyles *et al*., 1993). At Nobleton, a well defined ~50 m deep bedrock valley is mainly filled with Scarborough Formation sand and mud (e.g. Pugin *et al*., 1999). Its broader shale bedrock depression contains thicker Lower sediment sequences (Logan *et al*., 2001).

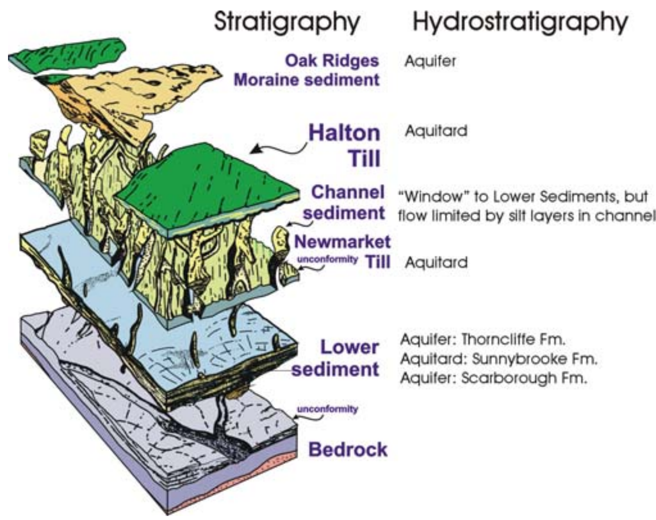

Figure 2: Stratigraphic framework of ORM region with 6 key elements: bedrock, Lower Sediment, Newmarket Till, Channels, ORM and Halton Till (from Sharpe *et. al*., 1999)

Overlying bedrock is a sequence of pre last-glacial sediment grouped as Lower sediment, including Scarborough, Sunnybrook and Thorncliffe Formations (Figure 2). Lower sediment is thickest within bedrock lows and up to 150 m thick (Logan *et al*., 2001). The overlying Newmarket Till is a regional stratigraphic marker due to its dense, sandy character and high seismic velocity (Pugin *et al*., 1999). Newmarket Till is locally up to 50 m thick (Boyce and Eyles, 2000), however, over much of the area it is much thinner (Logan *et al*., 2001). A regional unconformity forms the upper surface of Newmarket Till and the base of adjacent tunnel channels. Tunnel channels may extend to bedrock (Figure 3) and have depths to 170 m, widths of < 7 km and lengths > 40 km (Russell *et al*., 2002). Channel sediment forms the first stage of the ORM (Figure 2) and consists of gravel up to 20 m thick and medium to fine sand (Russell *et al*., 2002). Upper ORM sediment fines upward from isolated thick gravel to fine sand and silt often as subaqueous fan depositional units. ORM varies from < 50 m to ~200 m in thickness and changes from mainly gravel in the east to finer sediment in the west (Sharpe *et al*., 2002). Halton Till (Figure 2) consists of clay-silt diamicton beds and interbedded sand up to 30 m thick (Logan *et al*., 2001).

In summary, the combination of bedrock valleys, thick multi-layered sediment, extensive channel erosion (Figure 2) and multiple depositional trends has produced a highly complex aquifer system.

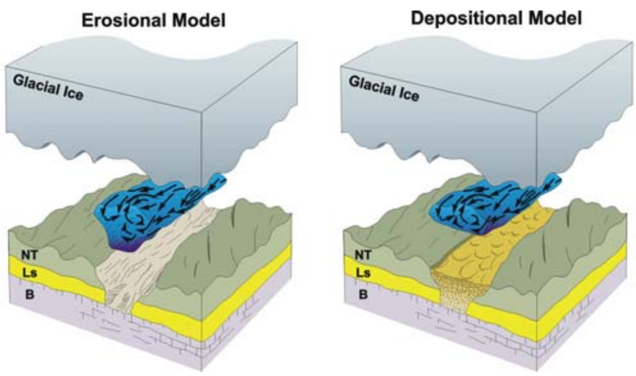

Figure 3: Erosional and depositional phases of tunnel channel formation. Depositional units fine upwards. (Sharpe *et al*., 2002)

3.2. Digital Stratigraphic Model

Construction of the digital stratigraphic model surfaces by the GSC (Logan *et al*., 2001) attempted to utilize data inputs as objectively as possible while minimizing the use of interpretative input (e.g., estimated channel margins). This approach to stratigraphic modelling is strongly influenced by data distribution and quality, and knowledge-based rules. Version I stratigraphic model (Logan *et al*., 2001) was also constrained by conceptual geological models (Sharpe *et al*., 2002), but they were not explicitly used in layer construction. Thus, the model depicts a relatively unbiased rendering of the data but may exhibit limitations (discussed in later sections) when used as direct import to a numerical flow model.

4. HYDROSTRATIGRAPHIC LAYER CONSTRUCTION

4.1. Objectives

The objective of this paper is to report the steps taken to build on the GSC stratigraphic model to produce hydrogeologic model layers. The GSC conceptual models and digital surfaces provided an excellent foundation, however, the following issues were identified in making the transition from stratigraphic to hydrostratigraphic model layers:

4.1.1. Lower Sediment unit subdivision

Characterization of Lower sediment into one stratigraphic unit (Figure 2) resulted in a maximum thickness of ~ 150 m for this unit. Due to sparse data support and a regional perspective this simplification was appropriate. For ground water flow modeling, however, this considerable thickness left little flexibility for adjusting the hydraulic conductivity of this extensive unit. Many of the municipal pumping wells in York Region tap into aquifers within the Lower sediment and it was decided that greater control on the permeability distribution of lower sediment was required for capture zone modelling. Although the data were sparse, preliminary cross-section work indicated sufficient lithologic variation to nominally subdivide Lower sediment into Thorncliffe, Sunnybrook, and Scarborough Formations (or equivalents). This stratigraphic assignment assumes correlation of these units from the Scarborough Bluffs and river valleys north of Lake Ontario. It is recognized that not all stratigraphic units are present throughout the study area.

4.1.2. Refinement based on GW indicators

A second issue became apparent as the GSC surfaces were reviewed and integrated with other hydrogeologic data on cross sections. Owing to the complexity and lithologic gradations within the formations it became apparent that stratigraphic layers and aquifer/aquitard boundaries were not always coincident. For example, in reviewing the GSC surfaces surrounding municipal supply wells in York Region, it was found that well screens were juxtaposed within or across the bottom of the Newmarket Till boundary, a known aquitard unit in the ORM area (Figure 2).

These observations led the project team to further integrate other hydrogeologic indicators into the layer refinement process. While well screen location proved to be a reliable co-indicator of aquifer position, other factors such as static water levels, “water found” indicators (driller’s notes) and stream patterns also proved useful. For these reasons, the model surfaces are referred to as “hydrostratigraphic” units, since their boundaries are biased towards aquifer/aquitard contacts. This refinement resulted in the majority of well screens lining up within aquifer units.

4.1.3. Continuity of valley and channel systems

The third issue that emerged was related to the representation of channel and valley systems within the model. Simple automated interpolation of sparse point data (well picks) rarely produces layer surfaces that realistically represent the structure and continuity of complex hydrogeologic features such as channel and valley systems. The interconnection of aquifers within these features is, however, considered critical to the movement of groundwater.

For example, simple automated interpolation tends to produce surfaces that exhibit anomalously low “bulls-eyes” that reflect individual wells located within a bedrock valley system. These isolated lows are true to the data, but in themselves they do not reflect the geological model of an elongate erosional channel system. Aquifer materials within these lows are thus isolated and flow systems cannot develop.

The GSC surfaces were generated from a combination of point gridding and rule based corrections (Logan *et al*., 2001). While their approach proved far superior to simple gridding, the scale and intended use of those surfaces did not require the strict continuity, especially of linear aquifers, deemed necessary for the flow model.

Based on the overburden conceptual models provided by the GSC, and a sub-aerial fluvial conceptual model of the Laurentian River valley system, the modelling team developed a new surface generation approach that both honoured the data as well as the conceptual models (expert intuition). This multi-step approach is described in the following sections of this paper.

4.2. Data Compilation

To support the modelling project a database containing over 140,000 wells and 2 million water levels was assembled, along with over 3 GB of spatial information. During data compilation, over 1000 hydrogeologic reports and 1800 large format maps and drawings were scanned and placed on a shared web server. The integrated relational database includes all geology, well construction, pumping records, water levels, stream flow measurements, and climate data for the area.

An efficient and comprehensive database structure was required to support the various analysis requirements, long-term growth and maintenance of a large data set. The selected database design was based on a refined version of the Earthfx Data Model. This groundwater database structure had over 4 years of development and refinement prior to selection for this project. Management and high-level access to the database was performed with the Sitefx Groundwater Data Management System. This software product provided an integrated set of data entry, reporting, validation and analysis tools.

Data management and database synchronization was a key issue during the interpretation phases of the project, as a team of hydrogeologists were simultaneously (and remotely) interpreting and editing the hydrostratigraphy. Coordination through regular meetings was also required to ensure consistency among the interpretation team.

4.3. Data Correction and Data Biases

Ontario Ministry of Environment driller's logs form the majority of the borehole information in the database. The accuracy and reliability of individual wells in this data set is frequently suspect, however, as a group, the logs provide significant useful subsurface information. Great care was taken to effectively use and visualize this data set, correct for known errors, and understand and minimize the impact of the intrinsic biases in the driller's logs.

Basic data location and elevation errors were addressed through field validation (using GPS) of over 5,000 of the wells. Correction to the high resolution DEM (10 m cell size) was also performed to minimize elevation errors. Highly erroneous or unreliable wells were excluded from analysis.

Comparison of water well records in the western Oak Ridges Moraine against detailed core logging from geotechnical, hydrogeological and sedimentologically-logged boreholes (Sharpe *et al*., 2002) showed the values of these high-quality records to "train' well records (e.g. Logan *et a*l., 2001). Thus, high quality "golden spike" wells and seismic picks were used during layer refinement. These and other higher quality wells were identified (and emphasized) using a variety of quantitative and qualitative measures. Frequently, lithologic data quality could be inferred by visually comparing clusters of wells on cross section. The owner of the well was also posted on section so that any wells drilled by a consultant or for a municipality could be given more weight in the interpretation process.

A standardized scheme to re-code driller's log descriptions was developed by 3 geologists who had detailed field geology experience in the area (Russell *et al*., 1998). Re-coded lithologic information helped identify driller tendencies but they could not be countered without the use of high-quality data. A significant bias was the use of the term clay, whereas quantitative field analysis suggested the material was more likely to be silt or fine sand. Similarly, drillers rarely use the term till. Re-coded log information was displayed on section during interpretation, however presentation of the raw lithologic descriptions was considered essential to the identification of unit boundaries and key indicator patterns.

Other biases and patterns were identified during the surface refinement process. As most drillers are hired simply to "find water", they frequently stop drilling as soon as they encounter a significant aquifer zone. Since tapping into the top few metres of a significant aquifer is all that is necessary to meet the needs of most private landowners, very little of the permeable aquifer material is actually documented within the driller's logs. As a result, the majority of driller's logs are actually a record of aquitard materials, with only the bottom most screened sand or gravel unit representative of the significant aquifer. Despite these biases, highly significant patterns were identified within the logs, as discussed in the following sections.

4.4. Data Visualization and Software Tools

The success of the layer refinement task was highly dependent on the integrated visual presentation and software analysis tools. Overall, display flexibility was perhaps the most important factor. During interpretation, the hydrogeologist would frequently change the map scale or vertical exaggeration, add or remove information based on database filter criteria, and move back and forth through the data in plan, cross section or 3D mode. This interactivity and flexibility allowed the interpreter to identify details and subtle patterns yet continue to understand the broader context.

The VIEWLOG 3D Borehole GIS software was used for all visualization, synthesis and interpretation tasks. The software provides an integrated set of GIS mapping functions (including 3D gridding and contouring), dynamic cross sectioning, real-time 3D fly-through, and borehole data display, editing and picking functions. The software directly connects to the relational database to avoid data duplication and allows the user to dynamically query and filter the visual presentation based on database criteria.

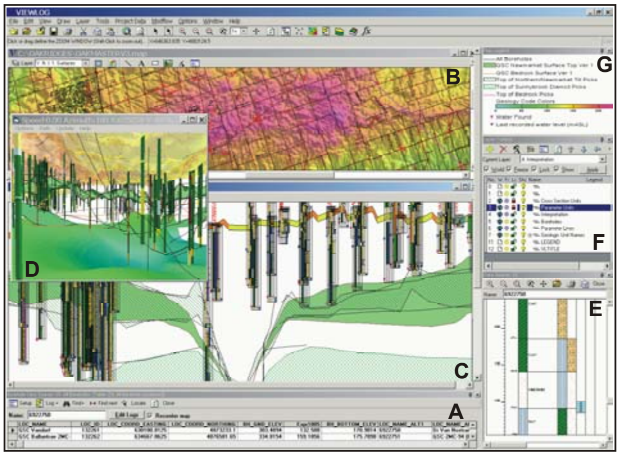

Figure 4: On-screen interpretation required the visual integration of large volumes and types of information. A=database table editing window, B=plan view map with hill-shaded DEM, C=cross section with 3D constraint polylines, D=real-time 3D fly-through window, E=well log details popup window, F=map layer control menu, G=legend.

Despite the fact that the data is highly three-dimensional, most interpretation was performed on cross sections. Real-time three-dimensional viewing provides a qualitative view of the data, however, for detailed and accurate layer picking, cross sections provide a more suitable framework. The use of the software's dynamic cross sections, which can be easily shifted back and forth through the dataset, were the most important aspect of the layer refinement methodology. At any point during the interpretation the vertical exaggeration could be adjusted, and the borehole offset changed to add or remove boreholes from the section. The cross sections could also be dynamically sliced through one or more geologic models, allowing units from the stratigraphic and hydrostratigraphic models to be easily compared. Finally, the surficial geology was also included on the sections as a color-coded band (using standard lithology colors) immediately below the ground surface.

Considerable effort was spent optimizing the presentation of the borehole data on cross section. The software permits any number of columns of lithology (raw codes, GSC recoding, etc.) and hydraulic information (well screen, static water level, etc.) at each well location. Lithology symbol patterns and colors were carefully chosen to fully represent the range of material codes and allow for the identification of subtle patterns and correlations. A popup window containing the well details, in either tabular or graphical form, was also available during the interpretation process. It was determined that the most appropriate display on cross section was to use all three columns of MOE geological descriptions, hydrogeologic indicators such as well screen interval in a fourth column, and the GSC recoded lithology in a fifth column.

The software's 3D polyline drawing functions were essential to capturing the expert's intuition during the interpretation process. As noted above, ensuring the continuity of channel and valley systems was necessary to allow the flow of water through these features. While well picking formed the majority of the interpretation task, 3D polylines were used to constrain and control the surface generation process (Figure 5). Polylines were added either perpendicular or parallel to the axis of the channel or valley feature. Each polyline was assigned to a hydrostratigraphic unit, and the individual vertex points in that polyline were then included in the gridding process. The conceptual drainage pattern in bedrock valley systems was created by adding polylines down the inferred thalweg cross section. The truncation and pinch out of layers at the edges of the tunnel channels was defined using polylines perpendicular to the axis of the channel feature. Plan view manual contouring was also integrated as necessary.

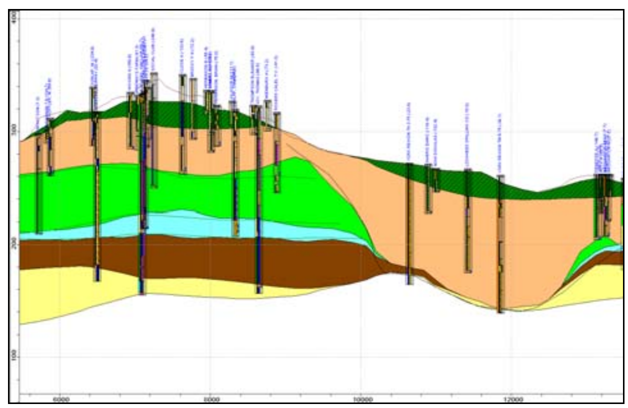

Figure 5: Cross section showing how 3D polylines were used to constrain tunnel channel geometry.

5. METHODOLOGY

The methodology for the creation of the refined hydrostratigraphic surfaces involved an iterative process of interpretation, gridding and refinement. Complex structures and patterns would emerge slowly, as time was spent viewing and interpreting the data. Group meetings were frequently held to review and discuss the emerging understanding of the system.

Elements of the GSC's rules-based approach to the generation of the stratigraphic surfaces (Logan *et al.*, 2001) were incorporated into the hydrostratigraphic interpretation methodology. In particular, their conceptual approach to the handling of "push downs" was particularly useful. A push down condition exists when a borehole partially penetrates a geologic unit: the next lower unit must exist below the bottom of the partially penetrating well, but how far below is unknown. The main differences between methodologies were: i) an increased emphasis on hydrologic indicators; ii) cross-section picking; and iii) the use of 3D constraint polylines. In summary, the following steps were used to generate the hydrostratigraphic surfaces:

5.1. Step 1: Picking and Pattern Identification

Units were picked on thousands of dynamically generated cross sections through the study area. Sections were viewed, at minimum, along every concession road, which occur approximately every 2 km. In more complex areas sections every 500 m were interpreted. Over 40,000 layer picks were made in boreholes along these sections.

Key patterns in the drillers logs and geologic structure emerged during this process, and were assigned to characteristic lithology symbols and colors. An important part of the display was the optimization of certain colours with specific MOE geological descriptors. One particular example was the coding of the descriptors “dense”, “hard”, or “packed” as a shade of bright pink. These descriptors appeared to be commonly applied to the Newmarket Till unit. The bright pink colour was therefore used as a guide to identify this unit. Other patterns, such as the combination of the clay and stones also emerged as reliable till indicators.

5.2. Step 2: Addition of 3D Polyline Constraints

During the cross section interpretation 3D polylines were added to constrain the gridding process. These polylines, either parallel or perpendicular to the axis of the channel or valley system, ensured that the continuity of the geologic structures. Polylines were also used to help constrain “push down” conditions. In total, over 10,000 polyline vertex points were defined.

North of the moraine the high resolution DEM was also an important source of information when interpreting the tunnel channels. Constraint polylines were used to extend the surficial expression of the tunnel channels down into the geologic model, but with few data to control depth.

5.3. Step 3: Pushdown Check

“Push down” condition handling was particularly important to the interpretation of the bedrock surface, because of the sparseness of the data and the potentially strong influence of the Laurentian River valley system. Overburden boreholes were plotted on plan view, with bottom hole elevation represented by scaled and gradationally color coded symbols. This allowed deep push down holes to clearly appear as large, bright symbols. Bedrock valley thalwegs were then interpreted on plan view, and cross sections along those thalwegs were then generated. Polylines were added to the thalweg cross sections to ensure that the bedrock surface correctly represented the decreasing elevation of the valley system. Other push down surface checks were performed in a similar manner to the GSC methodology (Logan et. al., 2001).

5.4. Step 4: Variogram Analysis and Interpolation

Once the picking, polylines and push down analysis was complete the surfaces were generated using variogram analysis and kriging.

5.5. Step 5: Rules-based Post Processing

Finally, the surfaces were crosschecked using a series of rules. The rules ensured, for example, that the layers did not cross. The rules were developed and applied in an order that reflected the distinctive characteristics of each hydrostratigraphic interface (i.e. unconformity, etc.) and the confidence and distinctiveness of the lithologic signature.

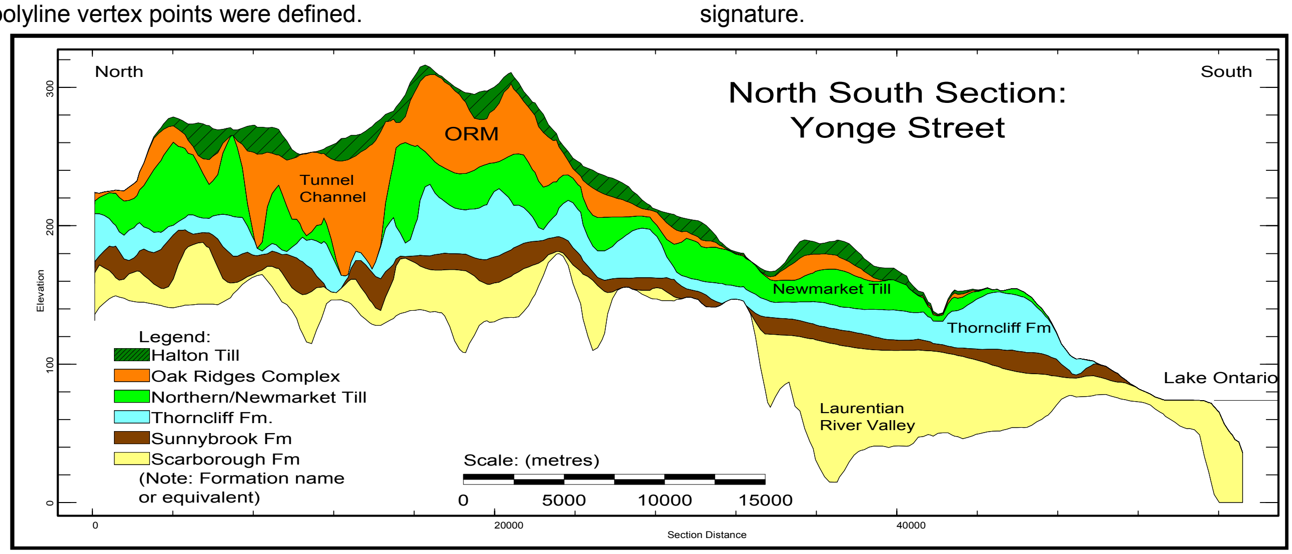

Figure 6: N-S Yonge Street hydrostratigraphic cross section. Note that this N-S section cuts the tunnel channel (NE-SW trend) and Laurentian River valley (NW-SE trend) obliquely.

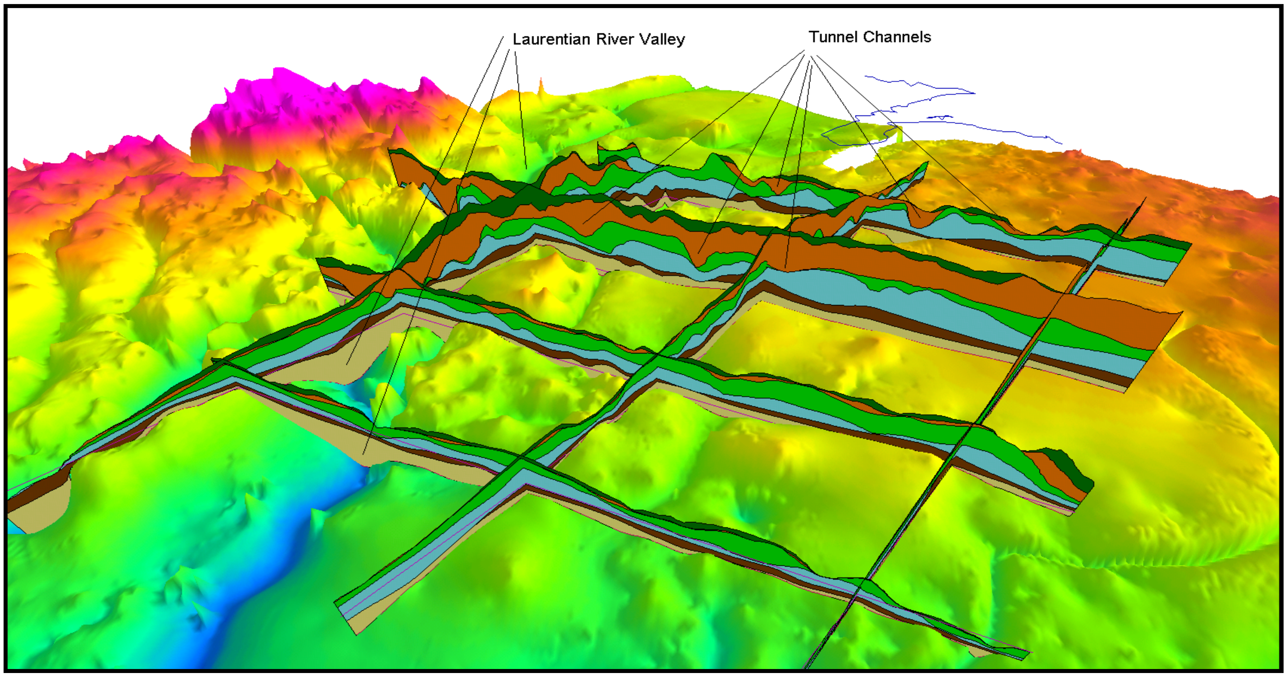

Figure 7: Bedrock surface and fence diagram of overburden layers. View from Toronto looking northwest. Width of 3D viewport is approximately 150 km. For overburden layer color legend see Figure 6.

6. RESULTS

The resulting hydrostratigraphic surfaces (Figure 6), whether constrained by hard data or by conceptual understanding, represent a significant advance in the understanding of the aquifer and aquitard layers within the ORM. A cross section perpendicular to the moraine axis (Figure 6) shows the hydrostratigraphic layers, with the tunnel channels and bedrock valley system obliquely cutting the section from the northeast and northwest. Figure 7 shows a 3D fence diagram through the core of the model area, with the bedrock surface below. A number of tunnel channels are visible on the fences. Other highlights of the analysis are discussed below.

As mentioned, patterns in well screens provided significant insight into the aquifer systems. Similarly, patterns in hardness, and combinations of the terms clay and stones (or clay and gravel) proved to be excellent indicator of the Newmarket Till, and to a lesser extent the Sunnybrook Formation. These patterns were critical to the identification and refinement of these key aquitard layers. The continuity of the tunnel channels that cut through the Newmarket Till surface has also been improved.

Perhaps the most significant improvement in the hydrostratigraphic model is related to the subdivision of the GSC's Lower Sediment unit. Together with the refinement of the bedrock surface (Figure 8), the Scarborough aquifer now exhibits considerable thickness in the deep Laurentian River valley systems. The groundwater flux through this unit is being evaluated with the flow model.

Other refinements in the conceptual model are still being evaluated. For example, the hydrostratigraphic model applies a more hydraulically active upper zone within the Newmarket till, allowing more flow within the shallow subsurface.

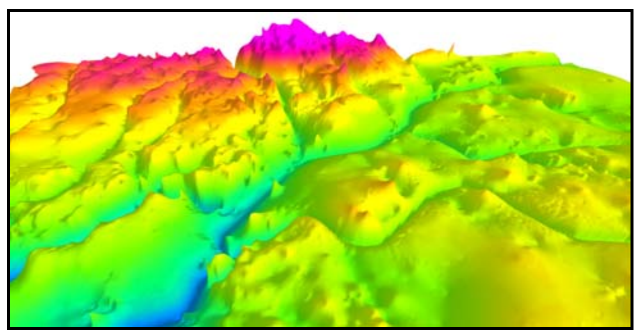

Figure 8 Bedrock valley systems looking west. Width of 3D view is approximately 100 km.

Depositional patterns have been identified in the distribution of sediments within the moraine (Barnett *et al*., 1998; Russell *et al*., 2002). Patterns observed during hydrostratigraphic layer refinement support these concepts. For example, three patterns of silt deposition were identified, including a fining upward sequence in the tunnel channels, fining westwards patterns in ORM fan deposits, and lacustrine deposits deposited at a later time in low lying areas, including the exposed tunnel channel valleys. Together the conceptual models of silt distribution and the observed pattern of silt within the logs proved to be key indicators of tunnel channel deposits.

7. CONCLUSIONS

The complex hydrostratigraphy of the Oak Ridges Moraine provides many challenges to the construction of a regional numerical groundwater flow model. Simple interpolation of sparse well picks is not sufficient to create a model that accurately represents the known geologic structures within the moraine. A new methodology, based on the GSC's stratigraphic approach, has been developed with an emphasis on incorporation of ground water and aquifer details. The new approach is time consuming, iterative and database intensive, but it has resulted in significant insight into the hydrostratigraphy of the moraine. The new approach suggests that simply adding more wells will not produce better surfaces: the key is to integrate and understand the data, and build upon an understanding of the processes that shaped the subsurface. Database integration, flexible visualization, efficient layer picking tools, and the capture of expert intuition using 3D constraint polylines are all essential to this process. The final result is a numerical model that not only honours the well data, but also the conceptual understanding of the processes that formed the moraine.

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