Regional hydrogeological studies: The value of data collected from continuously cored boreholes.

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ABSTRACT
Continuously cored boreholes referred to as "Golden Spikes" provide a geological framework for groundwater studies in Southern Ontario. Core is logged in bed-by-bed detail with emphasis on material description, bed contact and erosion surfaces, and sampled for physical properties. Boreholes are logged for downhole geophysical properties, and installed with piezometers for hydrogeological monitoring. Sedimentological and stratigraphic information collected from Golden Spikes, when combined with field mapping, surface geophysics and water well records can provide a three-dimensional geological history of a sedimentary basin.

RÉSUMÉ
Des forages avec des carottes continues dénommés "Golden Spikes" fournissent un cadre géologique pour les études d'eaux souterraines dans le sud de l'Ontario. Chaque carotte est diagraphée au détail de chaque couche, l'accent étant mis sur la description matérielle, les contactes entre les couches et l'érosion des surfaces, et est échantillonnée pour les propriétés physiques. Les forages sont diagraphés pour les caractéristiques géophysiques, et installé avec piézomètres pour des suivis hydrogéologiques. Lorsque les informations sédimentologiques et stratigraphiques recueillies auprès des Golden Spikes sont intégrés avec les résultats de cartographie géologique, de géophysique en surface et les données des puisatiers, ils peuvent fournir une histoire géologique en trois dimensions d'un bassin sédimentaire.

1 INTRODUCTION

About 9 million Canadians rely on groundwater for their daily domestic needs (Environment Canada 2008). In Ontario, the management of water supply is directed by the Clean Water Act of 2006. Part of this Act addresses "source water protection" by mandating municipalities to develop science based plans to protect both surface and ground water environments that are used for municipal drinking water supplies.

The Geological Survey of Canada (GSC) collects high quality data to support the development of conceptual and GIS-based 3D geological models that are essential elements for groundwater management decisions. These geological models are based on the integration of sedimentology, stratigraphy, hydrology, geophysics, geochemistry and fluid history (Sharpe et al., 2003). Ultimately, these models provide the ability to accurately characterize the geometry and properties of aquifers and aquitards for analysis of groundwater systems in glaciated terrains.

2 DATA COLLECTION FOR GEOLOGICAL MODELS

The GSC has applied a basin analysis approach to data collection and interpretation in Southern Ontario (Fig. 1) in order to support the construction of a range of geological models. Basin analysis involves the integration of related geosciences to understand the geologic history and stratigraphic architecture of a sedimentary basin. The cornerstone of basin analysis is the collection of data that will advance the understanding of the geological history of a sedimentary basin. Within any basin analysis study, an array of geological data needs to be collected for the development of predictive, process based models. These data include geological maps, outcrop studies, core data, downhole geophysics, and seismic reflection data. A key element of this data collection is a series of continuously-cored boreholes that are logged in detail including observations on bed contacts and erosion surfaces and may contain physical property measurements completed on core samples, downhole geophysics, and instrumented for hydrogeological monitoring. The term "Golden Spike" has been coined to describe these boreholes (Sharpe et al., 2003a).

Geological basin model development falls into two distinct styles: 1) predictive, process-based models and 2) GIS-based, data-driven models. The development of process-based models serves to assist geological interpretation and development of GIS-based models (Logan *et al.,* 2001). Process models also provide regional context for site-specific studies (LeGrand and Rosen, 1998, 2000). Examples of these models include depositional models (e.g. Russell et al., 2003) and event stratigraphic models (Sharpe et al 2003). In GIS based modeling, stratigraphic interpretations of logged core and associated seismic profiles are used to help interpret more abundant, lower quality archival data such as water well records (Logan et al., 2006).

This paper provides an overview of the methodology supporting the Golden Spike inventory the GSC has collected in Southern Ontario.

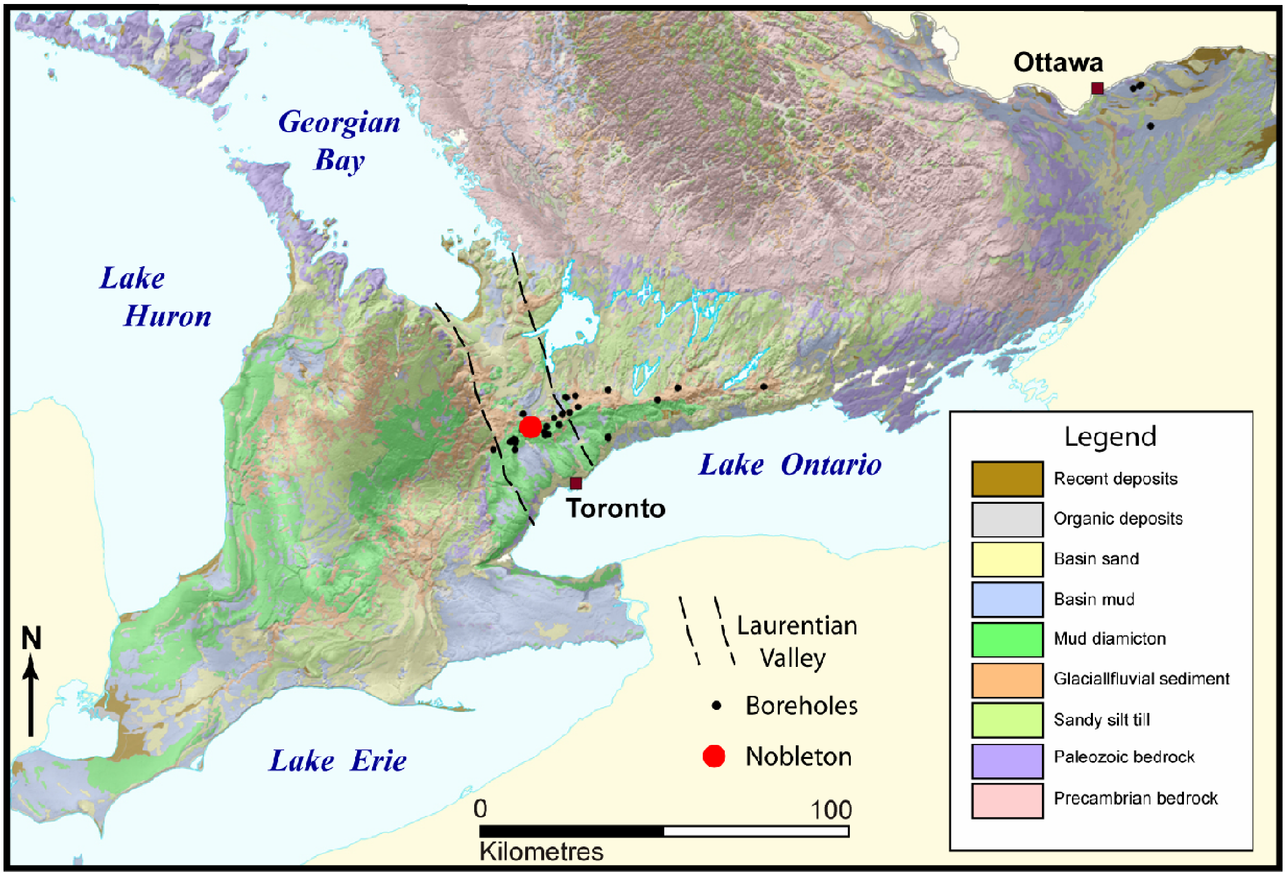

Figure 1. Surficial geology of southern Ontario draped over a DEM and displaying the location of Golden Spike boreholes with the Nobleton borehole highlighted in red (modified from Barnett, et al., 1991).

3 CORED-BOREHOLES

Continuously-cored boreholes logged by the GSC are concentrated in the Greater Toronto Area (GTA) and the South Nation River (Fig. 1; e.g. Logan et al., 2008; Sharpe et al., 2003; Russell et al., 2003, 2006). The distribution of this dataset of more than 20 boreholes represents collaborative GSC investigations with Regional Municipalities (e.g. York, Durham) and Conservation Authorities in the GTA and the South Nation River Watershed (e.g. Cummings and Russell, 2007). Golden Spike boreholes have been collected to ground truth or investigate a variety of geological and geophysical situations that link directly to hydrogeological issues. They are used to provide improved insight into the sedimentary facies and stratigraphic architecture, (e.g. tunnel valleys, eskers, bedrock valleys). In order to provide a comprehensive stratigraphic dataset, these boreholes are drilled to bedrock where possible.

3.1 Continuous Core Collection

Relatively intact undeformed core with high core recovery is an important element for detailed sedimentological studies. A number of approaches have been used to drill Golden Spikes (e.g., mud rotary, sonic coring); however, the most successful and cost effective drilling solution has been mud rotary drilling with wireline recovery of a core barrel. However, sonic coring, has been used successfully for collection of large-diameter sediment cores for stratigraphic and geochemical sampling in areas of thick diamicton successions (Averill, et al., 1986). This technique, however, is more prone to cause selective liquefaction, fluidization and hydroplastic deformation than mud rotary methods (e.g Smith and Rainbird, 1987). Furthermore, sonic coring is generally limited to penetration depths of <100 metres. The mud rotary technique, generally returns less disrupted cores and is not constrained to shallow depths. Additionally the Christensen core barrel drill stem handling and problems of side wall collapse associated with successive re-entry of the hole is also greatly reduced.

Coring is usually completed in five foot sections (runs) with recovered core discharged into pre-split, 3 inch (7.5 cm) diameter, PVC tubing. To achieve > 90% core recovery the drilling team requires extensive experience and detailed knowledge of drilling mud management. This is important not only in permeable units such as gravel but also to obtain adequate core recovery in sand and mud successions. Mud management involves a combination of the correct drilling fluid selection as well as proper re-circulation of drilling fluids.

All core logged by the GSC is stored at the GSC sample storage facility in Ottawa. Cores are stored in PVC tubes that are sealed and shrink-wrapped to prevent excessive drying. The inventory contains cores that are more than 10 years old. Under current, non climatic controlled storage conditions older core suffers appreciable deterioration due to failure of core packaging material and excess drying. This is particularly problematic for sandy sediment which looses much of its cohesive properties with moisture loss. Mud and diamicton can commonly be re-hydrated using sponge or steam baths (e.g. Cummings and Arnott, 1998).

3.2 Borehole Construction

Boreholes are drilled to bedrock to obtain a complete record of the surficial succession thus increasing confidence in the interpretation of basin stratigraphy. Often multiple boreholes are drilled to varying depths to accommodate a range of needs, including artesian conditions, nested piezometers, or the necessity to install borehole casing to depth. Where artesian conditions have been anticipated, a shallow (< 10 m) hole has been drilled for geophysical logging as the main hole is cased with steel to ensure control of water pressure. Deeper Extension of steel casing to depth may be required in boreholes where coarse, high yield units have been encountered and threatened to compromise the ability to complete the borehole.

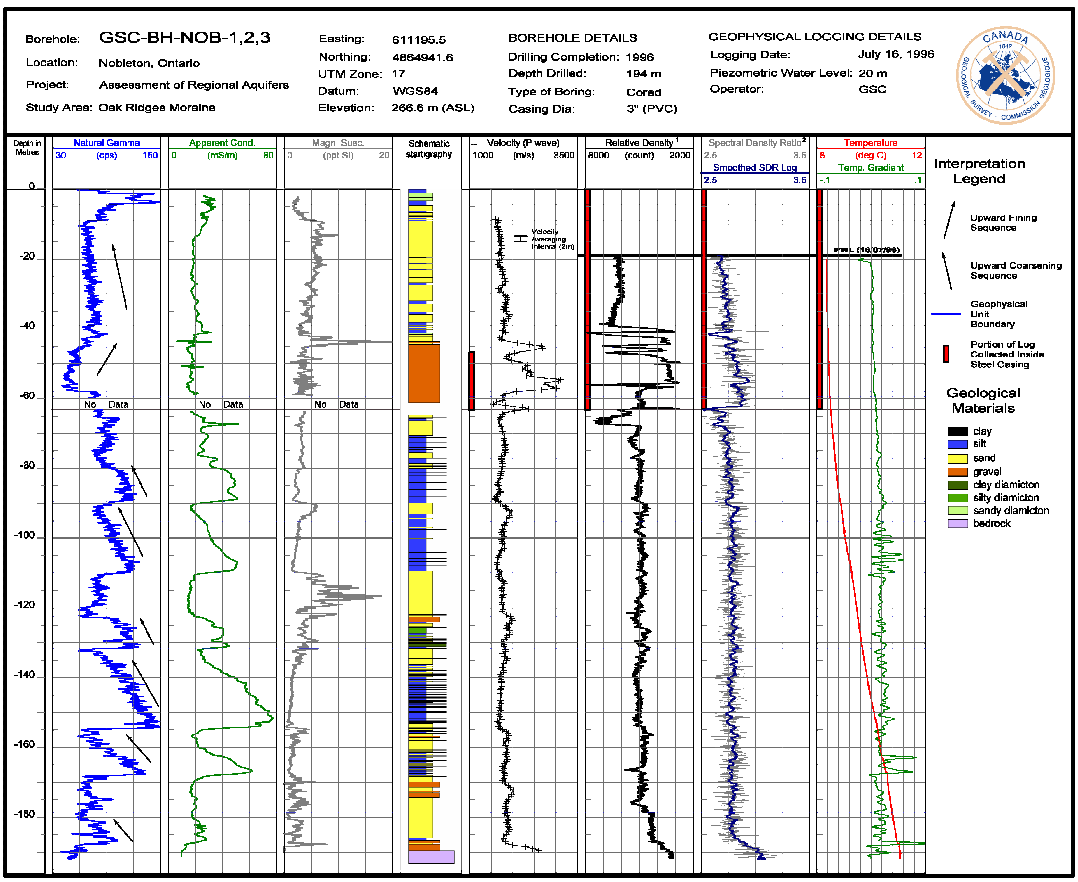

Figure 2. Geophysical logs and a graphical representation of the Nobleton borehole (from Logan et al., 2008).

To permit access for the geophysical tools, the boreholes are cased with 2.5 inch PVC tubing. PVC is preferred as steel casing results in subdued gamma signals and does not prevent conductivity and magnetic susceptibility logging (Pullan et al., 2002).

3.3 Downhole Geophysics

Downhole geophysical logging provides a library of geophysical signatures linked to the continuous core and permits improved velocity interpretation of accompanying seismic profile data. The standard suite of geophysical logs obtained includes: natural gamma, conductivity, and magnetic susceptibility (collected using the EM-34 sonde). Additional data collected include temperature, and spectral gamma (collected using an IFG system), and, P and S-wave velocity profiles to provide control for the interpretation and depth conversion of seismic profiles (Figure 2; Douma et al., 1999, Pullan et al., 2002, and Hunter et al., 1998).

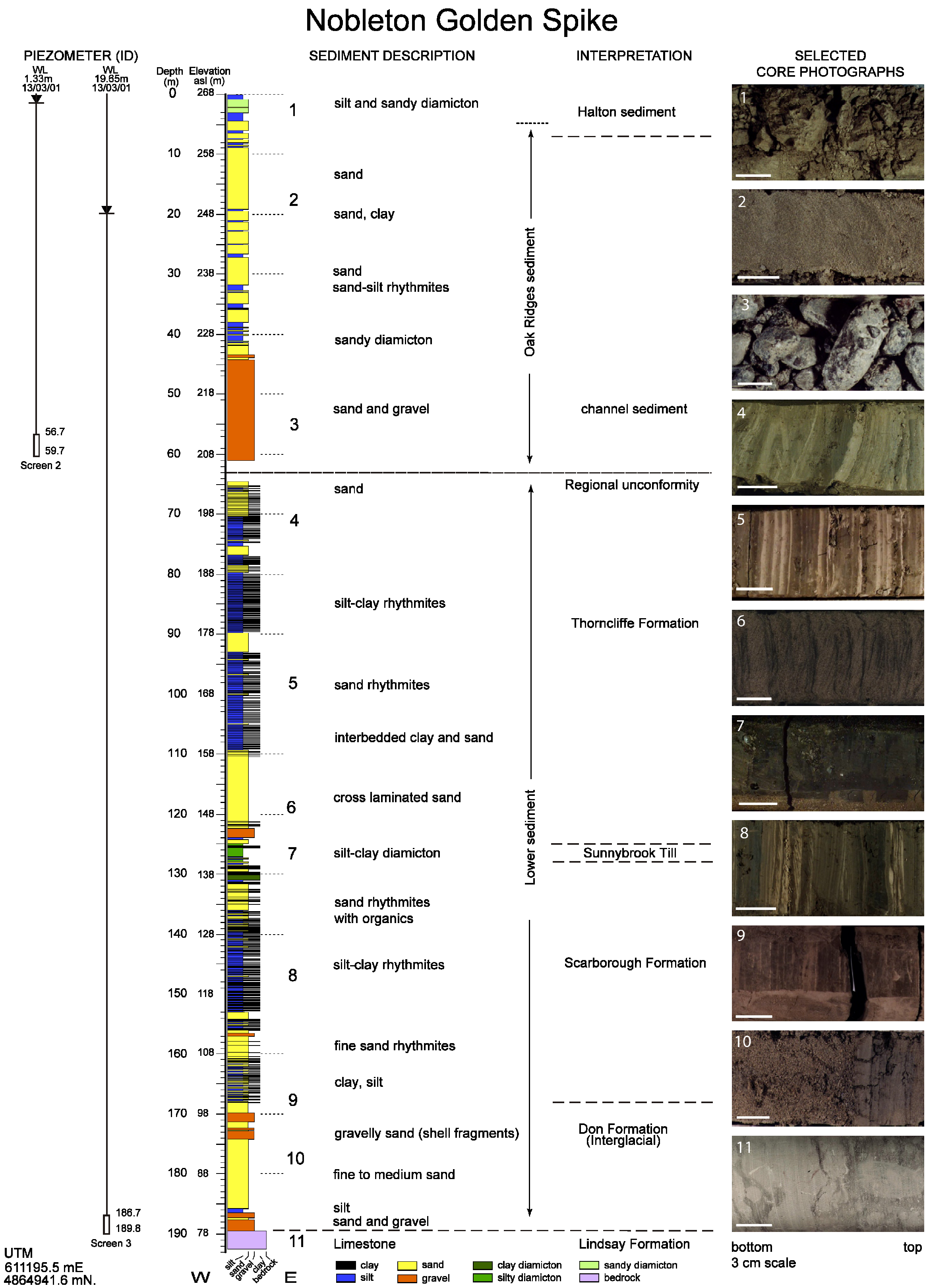

Figure 3. Generalized Nobleton core log with principal material description, formation names and selected representative photographs (from Logan et al., 2008)

3.4 Logging of Continuous Core

Core logging is commonly completed from 3 months to several years after drilling. Depending upon moisture content, the core is split in half with one portion being assigned for archive and the other for logging and sampling. In order to enhance textural contrasts, cores frequently require air drying on the logging table before being described. Often a smooth, fresh surface is produced by cutting and/or scraping the core with a knife. Core logging is completed on a detailed bed-by-bed basis with a description of unit contacts, erosional surfaces, thickness, texture, and sedimentary structures. Following this, the core is photographed using a SLR digital camera and a dual synchronized flash unit. Each 5 foot length of core is captured in up to five overlapping photographs of approximately 30 cm field of view. Following photography, the core is sampled for grain size, total organic carbon content and/or other lab analyses.

In the Nobleton borehole (Figure 3), the composite stratigraphy represents the most complete sequence of Quaternary deposits encountered to date north of the Scarborough Bluffs. It contains six of the regional Quaternary stratigraphic units overlying the bedrock Lindsay Formation: Lower Sediment consisting of the Don and Scarborough formations, Sunnybrook Till, and Thorncliffe Formation. The upper third of the borehole intercepts the Oak Ridges Moraine and Halton Sediment. The regional Newmarket Till is absent in this borehole, presumably due to its erosion during the formation of the tunnel channel feature. The geological formation boundaries have been determined from a combination of collected core samples and geophysical logs (Fig. 3).

3.5 Hydrogeological Monitoring

Golden Spikes provide a unique opportunity for the installation of piezometers and hydrogeological monitoring since the geological context is well established by the detailed logging and by the seismic reflection surveys. Golden Spike sites were instrumented with at least one piezometer (in the cored borehole) but typically, additional piezometers were installed in separate holes to provide a nested site for the monitoring of vertical gradients and the characterization of groundwater chemistry. Monitoring of GSC piezometers typically included the installation of dataloggers for the measurement of groundwater levels and groundwater chemistry sampling. Currently, responsibility for the monitoring and maintenance of the piezometers has been assumed by local agencies (Municipalities, Conservation Authorities) and several of these nests have been integrated into the Ontario Provincial Groundwater Monitoring Network.

3.6 Data Storage and Viewing

Data are captured and displayed in a Microsoft Access database and accessed through a user friendly viewer interface (e.g. Logan et. al., 2008). The database application provides a means of entering, checking, and inspecting related data tables in a simple graphic format. The custom interface consists of four primary sections: 1) unit description, 2) borehole photo viewer, 3) sample data viewer, and 4) a graphical material log, (Figure 4). Related tabular data are synchronized and displayed on a dynamic graphic log plot. Additionally, digital photographs of the core can be used to query the recorded sediment texture and geophysical data via related depth fields.

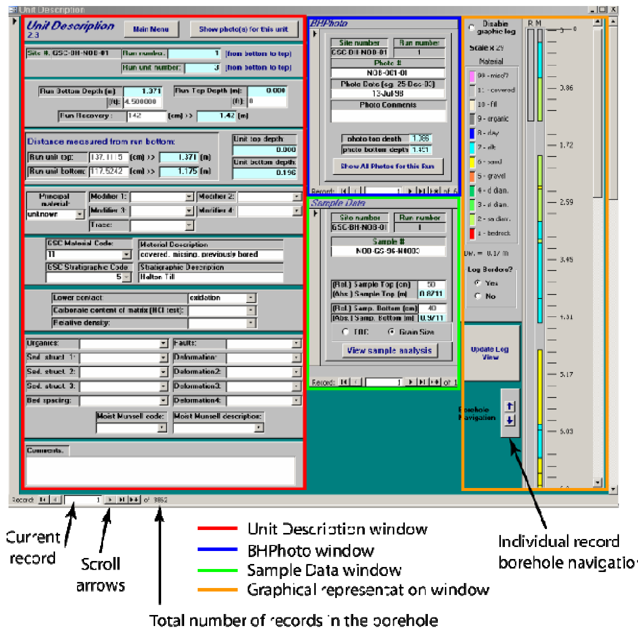

Figure 4. Interface to the borehole database. Data can be accessed by clicking any unit in the graphical representation of the borehole window.

4 MODEL DEVELOPMENT

A primary objective of the Oak Ridges Moraine study was the development of a regional framework for site specific and municipal scale ground water studies. To achieve this objective in a large study area of > 10,000 km^2 a basin analysis approach was employed (Sharpe et al., 2003). In order to advance the understanding of the geological history of the area, multiple datasets were collected, including surface geological mapping, outcrop sedimentology, seismic reflection data and borehole data. This data provided a framework and a predictive capacity for both regional geological variation and spatial aquifer heterogeneity. This paper has outlined the data that is collected within the context of the continuous cored borehole program. Data from these boreholes have been instrumental in the construction of a number of geological models that range in complexity from interpretative cross-sections, 3-D stratigraphic architecture process orientated depositional models to GIS based stratigraphic models.

Initial model development involved the correlation of Golden Spike data and Ontario Geological Survey (OGS) borehole records to construct a cross-section of the Oak Ridges Moraine that illustrated the subsurface continuity of the Newmarket Till and the presence of buried tunnel valleys (Sharpe et al., 1994). This cross-section interpretation of borehole data, landform analysis, and reflection seismic interpretation then allowed the development of an architectural stratigraphic model (Figure 3; Sharpe et al., 1996). These two progressive steps in model development provided the knowledge framework for the development of the GIS 3-D structural model. Development of a GIS based 3-D geological model was initiated with development of a database using a common set of sediment and stratigraphic terminology Integration of Golden Spike data with geological mapping, geotechnical boreholes, and seismic data provided a training dataset. This dataset was used to

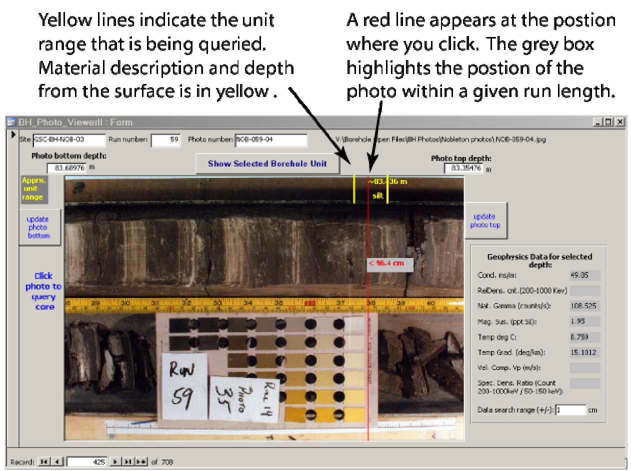

Figure 5. Interface to the borehole photograph database. Data can be accessed by clicking on the sediment in the photograph. This action will also display available geophysical data for the selected unit.

generate a continuous training surface that could be used within the expert system approach to constrain the automatic stratigraphic coding of the ~20,000 water wells used in the construction of the geological model. This training surface approach was considered necessary as the water well records have known issues pertaining to data description reliability and resolution. For the Oak Ridges Moraine model (Figure 6), each surface was rendered individually and constrained by using a variety of GIS map-layer queries to insure conformity. A detailed discussion of the role of GIS and expert knowledge in 3-D modelling is presented in Logan, et al., (2006).

For any specific stratigraphic unit of the regional geological model, detailed process orientated models are available to provide a predictive framework of the variability of sediment facies and architecture. For example, data from two Golden Spikes permitted the development of a conceptual process model for the tunnel channel fill element of the Oak Ridges Moraine stratigraphic unit (Russell et al., 2003). This process depositional model was only possible due to the detailed sedimentological descriptions recorded in the logging of the Golden Spikes.

5 VALUE OF GOLDEN SPIKES TO HYDROGEOLOGICAL STUDIES

The information provided by Golden Spikes supports several aspects of hydrogeological studies, including:
i) development of hydrogeological conceptual models, ii) development of groundwater flow models, iii) recognition of local and regional geological, hydrostratigraphic and hydrogeological settings, iv) identification of site specific conditions, and v) geostatistical characterization of geologic, geophysical or hydrogeologic properties.

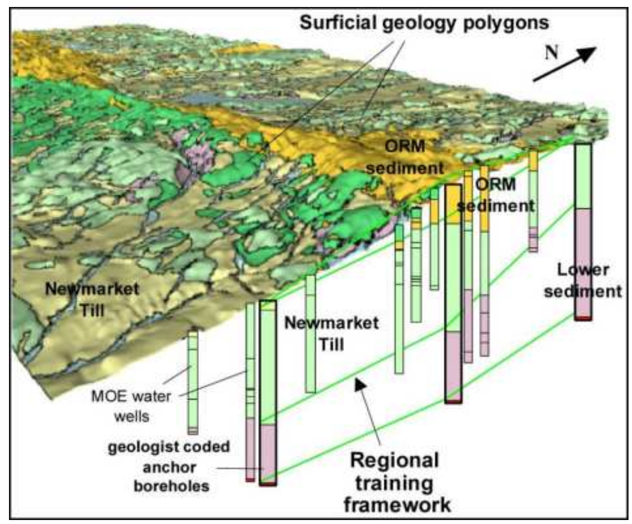

Figure 6. A schematic representation of a data-driven stratigraphic model with geological control. Golden Spikes (wide logs), linked to surface geology, provide a reference grid to 'train' water well records (narrow logs).

A sound conceptual understanding of the geological framework and the groundwater flow system is essential for groundwater studies (LeGrand and Rosen, 2002; Hinton et al., 2007). Golden Spikes permit improved understanding of basin history and the development of models of geological processes which supports improved conceptual hydrogeological understanding. Conceptual hydrogeological models become particularly useful to generalize and make predictions in areas where only limited data is available. As demonstrated in the previous section, Golden Spikes support development of stratigraphic models which constrain the stratigraphic interpretation of nearby water well records. Together, the stratigraphic model and the hydrogeological conceptualizations are important elements for the development of groundwater flow models since the stratigraphic model provides the geological architecture and the hydrogeological conceptualizations assist the interpretation of hydrostratigraphy, groundwater flow and boundary conditions.

The importance of recognizing the geological, hydrostratigraphic and hydrogeological settings at the local and regional scales is often underestimated. In the Oak Ridges Moraine area, the use of Golden Spikes along with seismic profiles demonstrated the existence of a major regional erosional unconformity which represents erosion in large tunnel channels and subsequent infill with coarse grained channel deposits and Oak Ridges Moraine sediment (Figure 3; e.g. Pugin et al., 1999; Sharpe et al., 2003). Therefore, the areas subject to tunnel channel erosion can have considerably different sedimentological, stratigraphic and hydrogeologic settings compared to adjacent till upland areas. Delineation of tunnel channels and adjacent uplands provides a framework in which to recognize local and regional settings. In contrast, prior to the use of Golden Spikes, the dominant paradigm for the area was a tabular "layer cake" stratigraphic model based on the stratigraphy of the Scarborough Bluffs. Hydrogeological conceptualization and models of that time generally adopted this tabular model such that there was no recognition of tunnel channels and the significance of this hydrogeological setting. The Golden Spikes were important elements of the data required to develop and demonstrate the new paradigm.

The detailed information from the interpretation of the Golden Spikes also identifies the site specific conditions most relevant to the hydrogeology of the site. Recognition of depositional settings and the location of the site within the setting will provide insight into the horizontal and vertical patterns of aquifer sediments, their hydraulic properties and possibly their hydraulic boundaries. Similarly, it can provide insight into the effectiveness of aquitards through a better identification and characterization of aquitard materials (texture, compaction, nature of fracturing). The detail of information helps with both practical issues such as the instrumentation and monitoring of the site and conceptual issues related to the interpretation of results.

The detailed data that come from continuous coring and logging are often well suited for geostatistical analysis of sediment properties (Desbarats et al., 2005). This kind of analysis can provide more quantitative characterization of the spatial distribution of sediments.

Although each Golden Spike has revealed much about both the local and regional geological and hydrogeological context, the growing network of Golden Spikes from Southern Ontario is contributing to an even greater understanding of regional geological processes, settings and conceptualizations. Similarly, the value of these Golden Spikes will increase with the growth of associated datasets (surface and borehole geophysics, water levels and chemistry, physical properties) that are being collected.

5 SUMMARY

Collection, analysis and storage of continuous core in thick sedimentary successions is a technically challenging and a costly undertaking. Nevertheless Golden Spike data provide an enhanced data framework for subsurface mapping. The Nobleton borehole for example, has proven to be indispensable in the interpretation of other datasets (seismic) and for understanding the geological history of the Oak Ridges Moraine area. The enhanced geological understanding provides an improved predictive framework for understanding aquifer extent and heterogeneity in the respective basins. Combined with downhole geophysical measurements and piezometric installations these sites can be important long term ground water monitors with well constrained hydrostratigraphic context.

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7 REFERENCES

Averill, S.A., MacNeil, K.A., Hueault, R.G. and Baker, C.L. 1986. Rotasonic drilling operations (1984) and overburden heavy mineral studies, Matheson area, District of Cochrane. *Ontario Geological Survey, Open File Report 5569*, 61 p.

Barnett, P.J., Cowan, W.R. and Henry, A.P. 1991. Quaternary Geology of Ontario, southern sheet. *Ontario Geological Survey, map 2556,* 1: 1,000,000.

Cummings, D.I. and Arnott, R.W.C. 1998. A quick and inexpensive sample preparation method for ams microfabric analysis in fine-grained sediment; *Journal of Sedimentary Research,* 68, 700-701

Cummings, D.I. and Russell, H.A.J. 2007. The Vars-Winchester esker aquifer, South Nation River watershed, Ontario, *CANQUA Fieldtrip Guidebook, June 6th 2007. Geological Survey of Canada, Open File 5624,* 68 p.

Desbarats, A.J., Russell, H.A.J., Pullan, S.E. and Sharpe, D.R. 2005. Modelling the vertical succession of glaciofluvial sediments in a buried-valley aquifer using multivariant geostatistical simulation of grain-size distributions. In: *GIS and Spatial Analysis - 2005*

Annual Conference of the International Association for Mathematical Geology, Toronto.

Douma, M., Hunter, J.A., and Good, R.L. 1999. Borehole geophysical logging; Chapter 4 In: *A Handbook of Geophysical Techniques for Geomorphic and Environmental Research, ed. R. Gilbert, Geological Survey of Canada, Open File 3731*, p. 57-67.

Environment Canada, 2008 *http://www.ec.gc.ca/Water/en/nature/grdwtr/e_sixmil.htm*

Hinton, M.J., Sharpe, D.R. and Logan, C.E., 2007. Towards improved hydrogeologic conceptual models in the St. Lawrence Lowlands of southern Ontario. *60th Canadian Geotechnical Conference and 8th Joint CGS/IAH-CNC Groundwater Conference*, OttawaGeo2007, Ottawa, Ontario, Canada, October 21-24, 2007, 363-370.

Hunter, J.A., Pullan, S.E., Burns, R.A., Good, R.L., Harris, J.B., Pugin, A., Skvortsov, A., and Goriainov, N.N., 1998, Downhole seismic logging for high-resolution reflection surveying in unconsolidated overburden; *Geophysics,* 63, p. 1371-1384.

James, B.R. and Freeze, R.A. 1993. The worth of data in predicting aquitard continuity in Hydrogeological design. *Water Resources Research*, 29, 2049-2065.

LeGrand, H., and Rosen, L. 2002. Is hydrogeologic science on track? *Ground Water*, 40: 569.

LeGrand, H.E., and Rosen, L., 2000, Systematic makings of early stage hydrogeological conceptual models. *Ground Water*, v.38, p. 887-893.

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

Logan, C. E.; Knight, R. D.; Crow, H. L.; Russell, H. A. J.; Sharpe, D. R.; Pullan, S. E.; Hinton, M. J. 2008, Southern Ontario "Golden Spike" data release: Nobleton borehole. *Geological Survey of Canada, Open File 5809,* 2008; 29 p.

Logan, C., Russell, H.A.J., Sharpe, D.R. and Kenny, F.M. 2006. The role of expert knowledge, GIS and geospatial data management in a basin analysis, Oak Ridges Moraine, southern Ontario. In: *GIS Applications in the Earth Sciences* (Ed J. Harris), pp. 519-541. *Geological Association of Canada Special Publication # 44*.

Logan, C., Russell, H.A.J., and Sharpe, D.R., 2001, Regional three dimensional stratigraphic modelling of the Oak Ridges Moraine area, southern Ontario, In: *Current Research 2001-D1: Geological Survey of Canada*, p. 19.

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,* 36: 409-432.

Pullan, S.E., Hunter, J.A. and Good, R.L., 2002. Using Downhole Geophysical Logs to Provide Detailed Lithology and Stratigraphic Assignment, Oak Ridges Moraine, southern Ontario, *Current Research 2202-E8. Geological Survey of Canada, Ottawa,* pp. 1-12.

Russell, H.A.J., Pullan, S.E., Hunter, J.A., Sharpe, D.R. and Holysh, S. 2006. Buried valley aquifers: New data collection for municipal water supply and watershed management, Caledon East, Ontario. *Geological Survey of Canada, Open File 5275p*.

Russell, H.A.J., Arnott, R.W.C. and Sharpe, D.R. 2003. Evidence for rapid sedimentation in a tunnel channel, Oak Ridges Moraine, southern Ontario, Canada. *Sedimentary Geology*, 160, 33-55.

Russell, H.A.J., Peets, J., Gorrell, G., Sharpe, D.R. and Hunter, J.A.M. 2003. Pontypool 'Golden Spike' borehole data compilation. *Geological Survey of Canada, Open File 1746p.*

Sharpe, D.R., Dyke, L.D., Good, R.L., Gorrell, G., Hinton, M.J., Hunter, J.A. and Russell, H.A.J. 2003. GSC high-quality borehole, "Golden Spike", data - Oak Ridges Moraine, southern Ontario. *Geological Survey of Canada, Open File 1670p.*

Sharpe, D.R., Hinton, M.J., Russell, H.A.J. and Desbarats, A.J. 2002. The need for basin analysis in regional hydrogeological studies: Oak Ridges Moraine, Southern Ontario. *Geoscience Canada*, 29, p. 3-19.

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. *Current Research 1996-E: Geological Survey of Canada*, p.181-190.

Sharpe, D., Dyke, L. and Pullan, S. 1994. Hydrogeology of the Oak Ridges Moraine: partners in geoscience. *Geological Survey of Canada, Open File 2869*.

Smith, S.L. and Rainbird, R.H. 1987. Soft - sediment deformation structures in overburden drill core, Quebec. *Geological Survey of Canada, Current Research Part A; Paper 87-01A*, 53-60 p.