Introduction - Basin Analysis and the Development of 3-D Geological Models for Regional Hydrogeological Applications

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This workshop is the third in an ongoing series discussing three-dimensional (3-D) geological model construction for groundwater applications. A central theme of the workshops has been development of techniques for reconciling disparate archival and high quality data sets to produce the most robust 3-D stratigraphic and hydrostratigraphic models possible. The first workshop focused on the use of archival water well records for the development of 3-D models (Berg and Thorleifson, 2001). The second workshop considered the widespread use of water well data to address questions of broader basin methodologies, techniques for collecting high quality data, and the need for geostatistical techniques in data interpolation (Thorleifson and Berg, 2002).

The value and pertinence of these workshops and the resultant interagency collaboration toward improved methodologies parallels recommendations by the National Research Council (NRC) (2000) for *Investigating Groundwater Systems on Regional and National Scales*. This NRC review highlights two important issues connecting geology and hydrogeology:

- Collaboration between scientists that permits geological information to be used in scaling up the results of a local groundwater study in areas where hydrogeological data are sparse or nonexistent.
- Characterization of heterogeneous aquifers at large and small scales through understanding links between geology and hydrogeology

In the United States, the Regional Aquifer Simulation Assessment (RASA) studies are one example of a multi-agency approach to regional groundwater investigations (Sun and Johnson, 1994). In Canada a more recent attempt to foster and develop such an approach is illustrated by Rivera et al. (2003) in the *Canadian Framework for Collaboration on Groundwater*. Reflecting the need for interagency collaboration, contributions to this workshop come from federal, state, provincial, and local level government organizations, universities, and consultants in Canada, the United States, plus the United Kingdom and Finland. The opening speakers of the morning session provide an overview of initiatives at the British Geological Survey (Jackson*), and the Geological Survey of Canada (Hanmer).

A proven approach to characterization of basin stratigraphy and reservoir (aquifer) heterogeneity is basin analysis. Basin analysis is a procedure commonly utilized by the petroleum industry, but it can be applied equally effectively to the study of groundwater systems at various scales. Basin analysis for regional hydrogeological studies has been summarized by Sharpe and others as a hierarchal and iterative approach that progresses from archival data analysis and data collection through a series of steps that include i) development of geological models, ii) development of hydrostratigraphic models, iii) development of groundwater flow models, to iv) full quantitative understanding of the groundwater flow system. A diverse suite of techniques can be integrated under basin analysis. For this workshop, Hunter has highlighted the value of downhole geophysics for development of improved stratigraphic architecture and characterisation of hydrostratigraphic units.

As expressed by Anderson (1989), geologists commonly build conceptual depositional models, whereas hydrogeologists require data-constrained grid models with geographic coordinates. To integrate their models with those of hydrogeologists requires that geologists move beyond the development of

*Citations with no date are included in this volume.

conceptual models to development of mathematical models that populate databases and create grid models that allow interpolatioin of geological characteristics (Keefer, Logan). This in turn demands an increased level of data management and standardization to fully support the variety of interpolation techniques available (Keefer, Soller, van Haaften).

Through basin analysis, geologists attempt to understand the geological history of a basin and develop an expert knowledge of the geological framework, leading eventually to data interpretation and interpolation. This knowledge of within the basin and vertical/lateral transition probabilities can then be integrated in geostatistical studies to provide much improved numerical models for hydrogeologists, particularly in areas where data are sparse. The geologist is thus strongly, and arguably, uniquely positioned, to provide stratigraphic inputs to a hydrostratigraphic framework (Logan, Kassenaar, Stone). Furthermore, geologists commonly have much physical property information, albeit in proxy format, that hydrogeologists need to populate their models of the spatial heterogeneity of hydrostratigraphic units (Hunter).

The development of stratigraphic framework models was a dominant theme of the first two workshops and continues to be of broad interest to workshop participants (Artimo, Bajc, Hansel, Lundstrom, MacCormack, Sarapera, Taylor). Robust models of the stratigraphic framework are critical elements of regional hydrogeology that commonly have received inadequate attention. Nevertheless, as demonstrated by issues like wellhead protection, the spatial characteristics of individual stratigraphic units must be identified (Russell). With an appropriate geologic framework in place, hydrogeologists are then able to refine the hydrostratigraphy and efficiently complete the tasks of groundwater flow modeling with improved confidence in the modeling results (Frind, Kassenaar, Meriano, Metesh, Michael, Ross)

The demand for more highly refined 3-D geologic and hydrologic information will continue to grow along with the growing needs for improved land use planning and resource management (Bridge, van Haaften). The 2002 water supply contamination in Walkerton, Ontario, through a combination of poor wellhead protection and water treatment practices, highlights the issues raised by the effects of land use on groundwater quality. In this instance 7 people died, more than two thousand people became ill (O'Connor, 2002), and the economic impact on the Ontario economy has been estimated to be in excess of 60 million dollars. The demand for well structured, digital, geological models to accompany appropriate conceptual geological models will become increasingly apparent as government agencies try to respond in a timely fashion to environmental problems and issues raised by conflicting land uses. As populations continue to expand into rural areas, these issues will continue to grow in importance. Furthermore, the data needed to build 3-D geologic frameworks will be critical in addressing issues of often conflicting large-scale agricultural, recreational, and industrial water demand.

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Recent glacial landscape. Esker ridge melting out of an inactive conduit at Stagnation Glacier, Bylot Island, Nunavut, Canada (Photo – C. Zdanowicz).

Wisconsin Episode glacial landscape. Flat glacial lake-plain topography in east-central Illinois looking southeast from a bedrock quarry. Above the bedrock is 10m of sediment consisting of till layers deposited by ice during 3 glacial episodes and geosols that developed during interglacials (Photo – A. Hansel).

Commentary -- Three-dimensional Geologic Modeling: Challenging our Terminology and our Understanding of Geologic Maps

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Introduction Significant advances in the process of making geologic maps have occurred since the mid 1980s with the advent of geographic information systems (GIS) and computer-assisted visualization tools. The computer has allowed us to analyze, store, and manipulate huge data sets and portray geologic information in ways that previously were not possible or took weeks or months to do by hand. Now, as can be seen in the many illustrations in this workshop volume, three-dimensional (3-D) illustrations such as block diagrams, fence diagrams, multiple cross sections, chair slicing, surface contour maps, isopachous maps, and pull-apart diagrams are becoming common ways to display geology.

As discussed in USGS Open-File Report 99-349 (Berg et al, 1999), the 3-D model shows the geometry of both surface and subsurface units. Because some of the erosional and depositional surfaces preserved in the stratigraphic record can be easily presented, snap shots of geologic time – the 4th dimension – become part of the model. Various perspective views can be reviewed, data can be checked for accuracy, and the geology can be interpreted to develop derivative maps. For example, a continuous and internally consistent 3-D geologic model is required to provide the most realistic portrayal of aquifer geometry and the variability of aquifer properties.

While traditional geologic maps remain quite useful, 3-D geologic models increasingly are being developed to portray subsurface relationships in an understandable fashion. This change is occurring for two reasons: 1) because software advances are making it practical to create these models using desktop computers, and 2) these models are excellent tools for defining, preserving, and communicating the geologist's understanding of the subsurface, especially to the informed layman. This communication advantage not only helps geologists present their findings to fellow geologists, but also helps non-geologists better understand geologic complexities and use geologic information to help solve real-world water and land-resource problems.

Two basic questions arise from our ever-increasing use of and reliance on 3-D maps, particularly those that portray the shallow subsurface:

(1) What has the technology done to our terminology: What do we mean by the words "models", "maps", and "illustrations"?
(2) What is the cause, relevance, and impact of this recent surge in shallow 3-D geologic modeling?

These may seem like moot points, but, they have been and continue to be the subjects of discussion and controversy.

What has the technology done to our terminology? What do we mean by the words "models", "maps", and "illustrations"? Recent technological changes have led to some confusion about the meaning and use of these terms "models", "maps", and "illustrations". The many desktop computer software packages that have contributed to the recent growth in 3-D mapping have had an impact on the meaning of the terms we use. Before the use of computers, our data were numbers and words and maps were maps. The maps were also typically 2-D representations of 3-D relationships. Illustrations of the geologic interpretations within 3-D volumes were very limited and tended to be thought of as fairly independent from data and maps. Now, 2-D and 3-D models and their supporting data are clearly linked, as are illustrations of subsequent model interpretations.

Definitions of "model" from Merriam-Webster's online dictionary include several listings that are important to our discussion, including: "a usually miniature representation of something; a description or analogy used to help visualize something that cannot be directly observed; a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs." From these definitions, it is clear that geologic maps, in any dimension, constitute models. In addition, the hand-drawn illustrations of 3-D geologic volumes also constitute models.

A 1998 article by J.H. Andrews lists 321 definitions of the word 'map' from 1649-1996 and sheds further light on the issue. Review of these definitions shows a common theme - that a map is a representation of any portion of the Earth. Below are a few selected definitions that seem particularly relevant to our discussion.

1649 - ….an artificial representation of the earth and water under that form and figure of roundness which they are supposed to have…(*Gregorri posthuma: or certain learned tracts written by John Gregorie, M.A. and chaplain of Christ-Church Oxford,* London, p. 257).

1721 - A representation of the earth or some particular part thereof upon a plain superficies (Nathan Bailey, *An universal etymological English dictionary*).

1730. ***L'Amerique Septentrionale dressee sur les Observations de Mrs. De L'Academie Royale des Sciences & quelques autres….par. G. De L'Isle,*** **Amsterdam.**

1838 - A representation of the whole earth, or of a part of it, on a flat surface (James Thomson, *An introduction to modern geography*, Belfast, p. 4).

c. 1885 - A representation of the surface of the earth or of any part of it, or of the whole or any part of the celestial sphere, usually drawn on paper or other material: A distinct and precise representation of anything (John Ogilvie, *The imperial dictionary of the English language*, London).

1922 - Simply a model of a portion of the earth's surface [ideal map] (Ll. Rodwell Jones, 'Commodity maps', *Geographical Teacher*, xi, p. 223).

c. 1950 - Any delineation of the surface of the earth, or of any part of it, drawn on paper or other material (*Collins graphic English dictionary*, London).

1989 - Holistic representations of spatial reality. The map is initially and primarily an intellectual abstraction of spatial reality but this must be subsequently communicated, i.e. modeled and coded, in a form that exploits the human and/or digital spatial processing capabilities (M.Visvalingham, reported in British Cartographic Society *Newsletter*, i).

1993 - A symbolised image of geographic reality, representing selected features or characteristics, resulting from the creative efforts of cartographers, and designed for use when spatial relationships are of special relevance (quoted in Michael Wood, 'Whither maps and map design', *Bulletin of the Society of Cartographers*, xxvii, p. 8).

1994 - A representation of the surface of the earth or any part of it (*Burlington dictionary* [Bridlington).

1995 - Two- or three-dimensional devices, allowing to give a spatial organization to phenomena, events, processes, things, etc in order to understand them (Christian Jacob).

Interestingly, the first mention of a "model" as part of a definition of a map is 1922 where a map – an ideal map - was defined as a model. Beginning with the 1989 example, definitions incorporate "new" types of maps that can be generated by computers. Definitions for maps as "holistic representations of spatial reality", "symbolised image of geographic reality…designed for use when spatial relationships are of special relevance", and "two- or three-dimensional devices" help to establish the relationship between models and maps. Furthermore, none of the 321 definitions of a map impose limiting factors for portrayal of the earth. A map as a "representation of the whole earth or part of it", as stated in many of Andrews' definitions, would logically include any portion of the earth's subsurface.

Based on the above definitions and considering the changes that computer technology is making in geologic mapping, we suggest the following usages for the words, "illustration", "model", and "map".

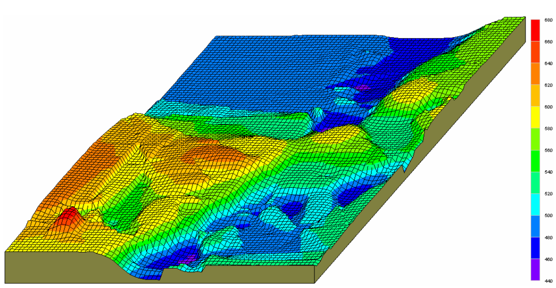
- First, the word "illustration" does not need any clarification in usage and should remain as defined by Meriam-Webster OnLine as, "a picture or diagram that helps make something clear or attractive". Therefore, all visualizations from maps and models are illustrations, but obviously, not all illustrations are maps or models.
- We suggest that the word "model" be used to describe (1) the digital files that comprise an interpreted geologic column, surface, cross section, or volume, and (2) any conceptualization or illustration of the geology that these digital files represent. "Modeling" would, therefore, include any of the processes involved in creating a model.
- We propose the word, "map" be used to describe: (1) any illustration of the surface or subsurface of the earth or any part thereof, and (2) the digital files that comprise a geologic model. Angular perspectives, chair slices, fence diagrams, and illustrations of interpreted well logs are all representations of the earth, and as such, are all maps.

Together, these definitions provide a modern clarification of the more traditional understanding of a map as any representation of the earth, while providing a compatible definition of a model that considers computer applications. The process of mapping still describes all the procedures and products involved with the interpretation of geologic data. While map and model can be synonymous, these definitions also allow us to refer to a geologic interpretation as a model, and any associated illustrations as maps.

It is important to realize that neither the original definitions nor our proposed definitions include any requirements that ensure the quality or usability of any map. There are no constraints placed on required cartographic elements (e.g. north arrow, posted scale), on the use of a single, consistent map scale, or on the accuracy of spatial relationships between map elements. We recognize that the use of these and other constraints help ensure that maps are useful. However, in agreement with the cited definitions, we feel strongly that these are not <u>required</u> characteristics of maps.

<u>What is the cause, relevance, and impact of this recent surge in shallow 3-D geologic modeling?</u> Three-dimensional geological models are not new to the field of geology. The oil industry has used them since the 1930s. However, 3-D geologic models of the near-surface – the upper hundred meters or so - particularly in glaciated areas, are relatively new. Accurately mapping and modeling the complexities of the materials left by glacial depositional and erosional processes, interspersed by long periods of soil formation, create daunting tasks for the geologists who are mapping, as well as attempting to explain the geology to colleagues and laymen. **P**olicy makers can be particularly perplexed if they try to implement land- and water- use decisions based on traditional 2-D maps. Artimo et al. (2003) explain that 3-D geological models are truly integrated solid models that represent the geometry, stratigraphy, sedimentology, and hydrostratigraphy of aquifer and non-aquifer units. When supported by a sedimentologic model, based on depositional and erosional processes, 3-D models can provide sophisticated and detailed geological information, and therefore the greatest potential benefits to users. The model, constructed by interpreting the data, provides the most complete depiction of the subsurface – as true a representation of reality as possible from the available data - and an internally consistent and directly integratable conceptual model of the materials and their physical properties that can be used directly by hydrogeologists for groundwater flow modeling.

The techniques for 3-D mapping of deep bedrock units for oil and other resources are applicable for near-surface 3-D mapping of glacial and other unconsolidated deposits. However, understanding and describing the variability and discontinuity of these sediments, both horizontally and vertically, requires considerably more detail and accuracy to understand and describe than ordinary bedrock mapping. Therefore, we have been forced to develop new techniques to (1) deal with large data sets, (2) describe the complexities of the near-surface geology, (3) portray the 3-D geology, and (4) provide an improved understanding of the deposits. All of this is necessary to solve real-world environmental and earth-resource problems. It is to this end that improved interaction is needed between those mapping the geology and those using the geologic information for, among other things, groundwater modeling.



2003. McKay and Berg. ***Computer-generated perspective view of the top of the lowermost Wisconsin Episode buried sand and gravel, middle Illinois River valley, Illinois,*** **Champaign, IL.**

According to Kempton (1980), establishment of the concept of "environmental geology" in the mid 1960s (Frye, 1967) was the single-most important reason for needing 3-D mapping for shallow deposits. The need became apparent as greater attention was paid to environmental and land-use issues, mainly centering upon groundwater contamination and resource availability. A demand was created for more precise information on the character and distribution of surficial geologic materials. The demand stimulated the development of new techniques to obtain and analyze subsurface data, and procedures, such as stack-unit mapping, were developed to better understand and portray geological complexities.

Prior to this time, most efforts to depict geologic units three dimensionally were generally indirect and relied on separate maps showing thickness and structure. Compounding the problem, at least in Illinois, was that before 1958 glacial deposits were not assigned to rock-stratigraphic units. Older geologic maps mainly portrayed the age of units and did not focus on materials. Also, they did not provide the type of information, mainly in the subsurface, that would be most useful for groundwater and land-use interpretations.

Over the last 10 years, advances in GIS and other computer-assisted modeling and visualization tools have resulted in new ways to portray and understand the subsurface (e.g., block diagrams, pull-apart models, interactive animations, etc.). The most profound contrast between maps produced in the pre-computer era from those produced now is that the digital nature of recent maps and models makes it possible for them to become “living” documents. Additionally, delivery of the latest map/model edition need not wait until another edition is printed. Rather, maps and models can be viewed and downloaded directly from the internet, thereby providing users with ready access to the latest versions. New hardware and software tools also have provided superior geologic models for use by groundwater hydrologists and hydrogeologists in developing their groundwater flow models.

New computer-assisted mapping tools are not necessarily innovations in research, and generally do not offer improvements in mapping accuracy or precision. However, these new tools and techniques are having a profound effect on: (1) how we think about and visualize geologic systems, (2) how we map, both in the field and in the office, and (3) how geologic maps and data are being used by geologists and the public (Lasemi and Berg, 2001).

We suggest that the introduction of detailed 3-D geologic mapping in hydrogeologic studies has been slowed by four main road blocks:

(1) obtaining 3-D geologic information is costly,
(2) until recently, there have been few software packages that provide sufficient 3-D modeling capabilities at affordable prices,
(3) many projects requiring groundwater flow investigations have not had sufficient time or money to obtain the detailed geologic interpretations they really needs, and
(4) while many hydrogeologists have recognized that better geologic data could improve their modeling, they typically have not been sufficiently trained to interpret the complex geologic sequences, nor qualified to generate the necessary high-resolution geologic models.

We suggest that these roadblocks can be overcome by education and the proper allocation of time and resources. This workshop on "Three-dimensional Geologic Mapping for Groundwater Applications" as well as the previous two workshops on the subject (Berg and Thorleifson, 2001 and Thorleifson and Berg, 2002) are intended specifically to address the need for education in the development and use of detailed, 3-D geologic maps. The goal of all three workshops has been for geologists to share information about methods for constructing 3-D geologic models specifically intended for use in groundwater flow models and to secure cooperation with groundwater professionals who understand the links between the latest geologic mapping techniques and their ability to work.

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Utilization of 3-D Geologic Modeling for a Large-scale Water Supply Project in Southwestern Finland

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The three-dimensional (3-D) geological model of the Virttaankangas aquifer in southwestern Finland (Artimo et al, 2003a; Artimo et al, 2003b) recently has been updated with new research data obtained during the last two years (Saraperä and Artimo, 2004). This 3-D model will constitute an important part of the studies conducted in the Virttaankangas area, which will be used for production of artificially infiltrated groundwater for the Turku region. The next step in the studies will involve the development of a 3-D groundwater flow model based on the data obtained from the 3-D geological model. The aim is to constantly develop and adjust the 3-D understanding of the aquifer, and to incorporate this data into the mentioned models. However, the further development of the 3-D models requires better control of the primary data. Therefore, a set of simple tailored GIS-tools were developed to facilitate and quicken the export of the primary data into the 3-D modeling software and the 3-D groundwater flow model.

In the water project for the Turku area, the 3-D geologic model is not only used to depict and understand the complexities of the Quaternary esker aquifer, but also as a tool to achieve the best available conceptual model for groundwater flow modeling. A feedback procedure is being implemented whereby results of groundwater flow modeling may require modifying the previously established 3-D geological model, such that the internal structures and architecture of the aquifer are modified to produce "a more accurate depiction" of the 3-D geology. Therefore, the 3-D geologic model would be updated first. The most significant fact is that the GIS system and the models are planned to be updated continuously, because the production of the artificially infiltrated groundwater will require these modeling tools both in the planning and in the actual groundwater production phases of the project. Therefore, the precise control of the growing amount of primary data and the ability to export the data to other software packages becomes essential (Figure 1). The time lag between the new observations that

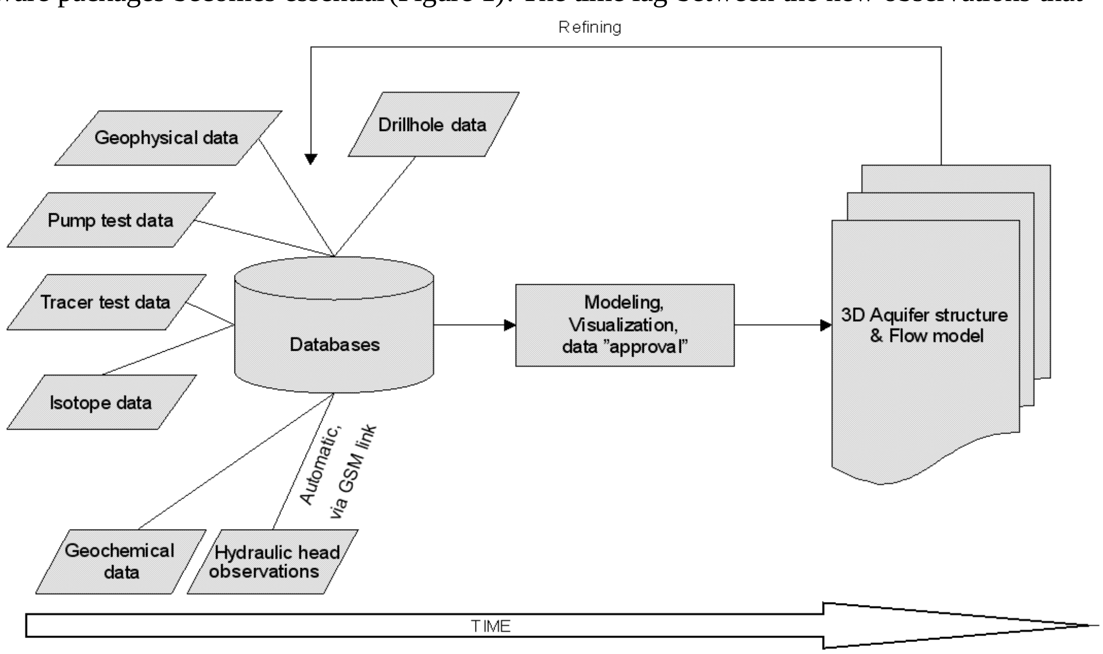

Figure 1. Virttaankangas data flow chart.

result in changes of the 3-D structures of the aquifer, and the updating of the 3-D geological and flow models is planned to be about 1-3 weeks. The average residence time of the artificially infiltrated groundwater in the aquifer is estimated to be about 3-6 months.

The ongoing development of both the GIS system and the 3-D geological and groundwater flow models will result in an integrated system including vast amounts of different data from drill holes, geophysical measurements (mostly gravimetric measurements, GPR soundings, and seismic soundings), hydrological measurements (including automatic hydraulic head measurements), and geochemical, pump test, tracer test, and isotopic investigations (carbon, oxygen, hydrogen). The 3-D geological model (Figure 2) will work as a tool to visualize these data, and the 3-D flow model will be used to simulate the flow system presuming that all the primary data have been taken into consideration in compiling of the model.

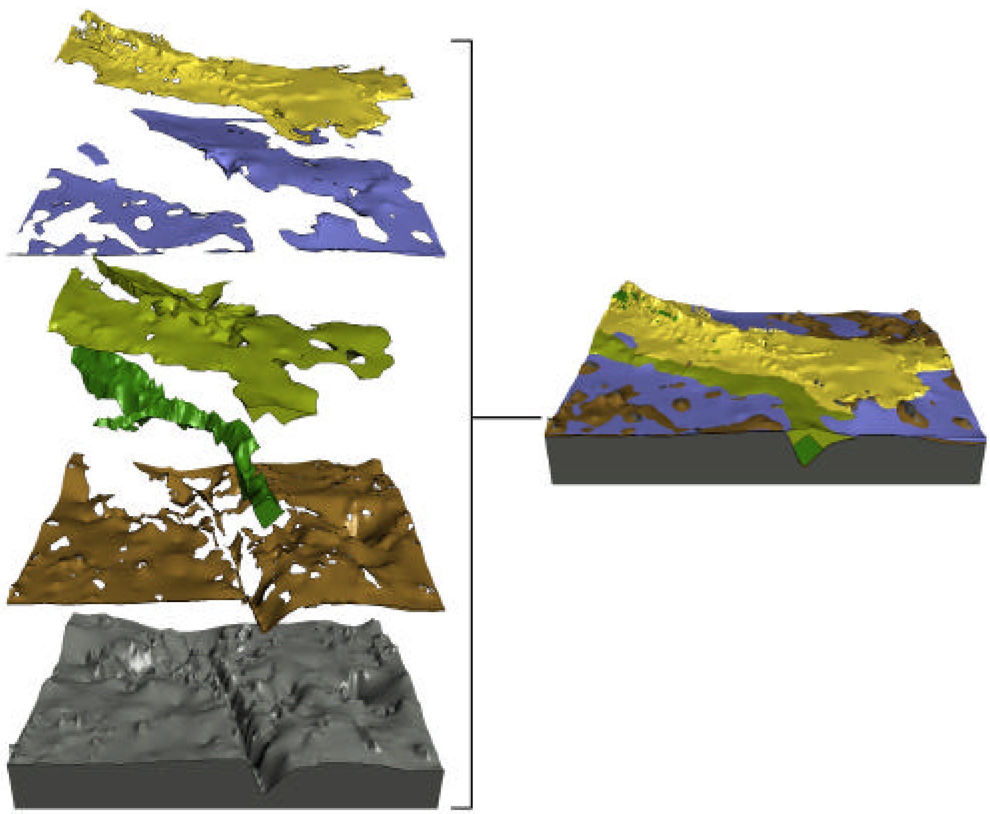

Figure 2. The latest version of the Virttaankangas 3-D hydrogeological model.

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Three-Dimensional Mapping of Quaternary Deposits in the Waterloo Region, Southwestern Ontario

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The Ontario Geological Survey (OGS) has embarked on a project of three-dimensional (3-D) mapping of Quaternary deposits within the Regional Municipality of Waterloo (RMOW). This project is being undertaken as part of a broader geoscience initiative designed to provide basic geoscience information for the protection and preservation of the provincial groundwater resource. The main objective of this project is to characterize, in three dimensions, the geometry and intrinsic properties of subsurface Quaternary deposits to (1) aid in studies involving groundwater extraction, protection, and remediation, (2) assist with the development of policies surrounding land use and nutrient management, and (3) better understand the interaction between ground and surface waters.

Three main areas of work are currently ongoing as part of this project. These can be summarized as: (1) data compilation and standardization; (2) acquisition of new geologic and geophysical data; and (3) data interpretation, synthesis and presentation. Our working database contains records from a variety of sources of varying data quality. These databases include:

1. borehole logs of monitoring and/or production wells acquired from the Water Services Division of the RMOW,
2. a geotechnical databank originally created by the Geological Survey of Canada (GSC) in the early 1970s which was subsequently updated and uploaded to an Access® database format in the late 1990s by the Department of Environmental Studies at the University of Waterloo,
3. a database of shallow (generally less than 10 m) sediment logs captured from hand written fieldnotes acquired by Dr. P.F. Karrow as part of his Quaternary mapping investigations within the region over the last 4 decades,
4. a similar database of shallow sediment exposure logs acquired by the OGS as part of field studies during the summers of 2002 and 2003,
5. a high resolution suite of borehole logs acquired from government reports, theses and unpublished consultants reports housed at the RMOW, and
6. a water wells database from the Ministry of the Environment (MOE).

Not surprisingly, most of these databases were structured differently and utilized terminology inconsistent with that proposed for 3-D mapping in southern Ontario. Terminology in each database was standardized in accordance with material codes developed for the seamless Quaternary geology map of southern Ontario. Each unique combination of terms was then translated to populate primary, secondary, and tertiary material attribute fields in the working database. The original sediment descriptions were retained in a separate field and are available for inspection during the interpretation phase. The MOE water wells database had over 850 unique combinations of materials that required translation. Well defined rules tempered by the interpretive experience of the OGS geologist were applied during the translation process. In instances where a translated bedrock unit had overburden materials below, the bedrock unit was reinterpreted and assigned an overburden descriptor. Once the databases were standardized, they were appended and filtered to remove data points with compromised locational attributes. Locational information was used in conjunction with the provincial digital elevation model to derive elevation values for each data point. Our working copy of the 3-D database for the Waterloo Region contains approximately 22,000 records and nearly 100,000 sediment layers (Figure 1). The database is continually updated as new, high quality records become available.

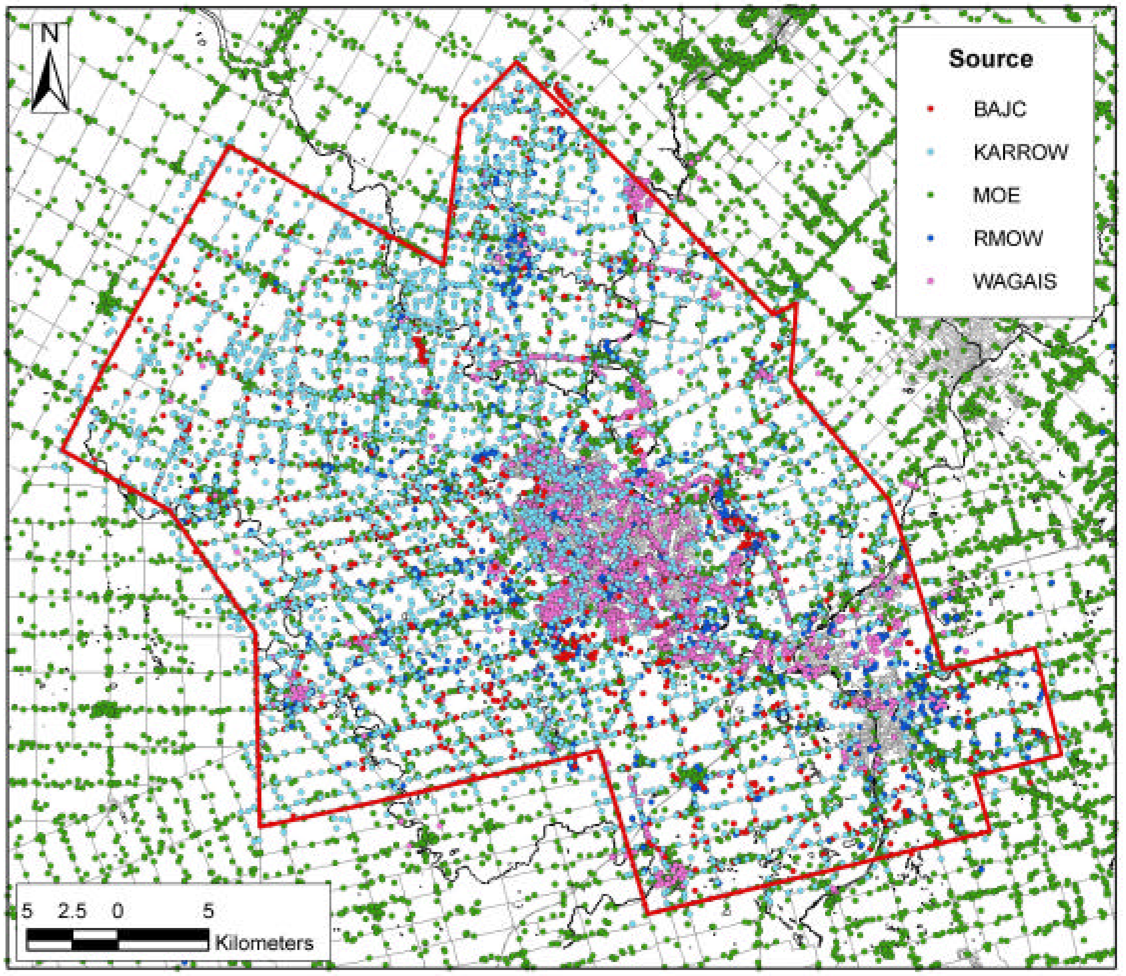

Figure 1. ArcGIS® plot of the Regional Municipality of Waterloo highlighting the location of subsurface information used for the creation of the 3-D geologic model.

The development of a conceptual geologic model for the interpretation of this data was undertaken following a review of all published information on the Quaternary geology of the Waterloo Region. Additional insights were gained by examining all available sediment exposures within the region, relogging of selected archived core, acquisition of seismic reflection and ground penetrating radar data, and continuous coring of strategically placed boreholes. The current geologic model contains 6 regionally significant stratigraphic units (Figure 2). These include: Upper Maryhill Till; Waterloo Moraine sediments; Lower Maryhill Till; Catfish Creek Till; Canning Drift; and older till and stratified sediments. The diachronous nature of these units has resulted in a much simpler, 2-layer model along the eastern edge of the region.

As part of our preliminary assessment of the subsurface stratigraphy of the Waterloo Region, we were able to quickly produce a first approximation of the elevation of the buried bedrock surface. Significant buried bedrock valleys were indicated and served as a basis for the placement of seismic reflection profiles. Seismic profiling was undertaken to confirm and refine the position of these buried bedrock valleys, as well as to shed some light on the physical properties, geometry, and contact relationships of subsurface units. The seismic data provide information on the subsurface with vertical and horizontal resolution in the order of metres. Locations for detailed common-midpoint (CMP) reflection profiles were chosen from the results of an initial survey of 19 test sites designed to evaluate data quality and estimate the depth to bedrock in various locations and geological settings within the region. On the basis of the test results, 9 sites were chosen for follow-up profiling, and to date approximately 12 km of seismic reflection profiles (P-wave) have been obtained using either an in-hole shotgun or MiniVib (TM) energy source. These surveys have identified strong reflections associated with sequences of thick, high-velocity tills, channel features within and on the surface of these units, and

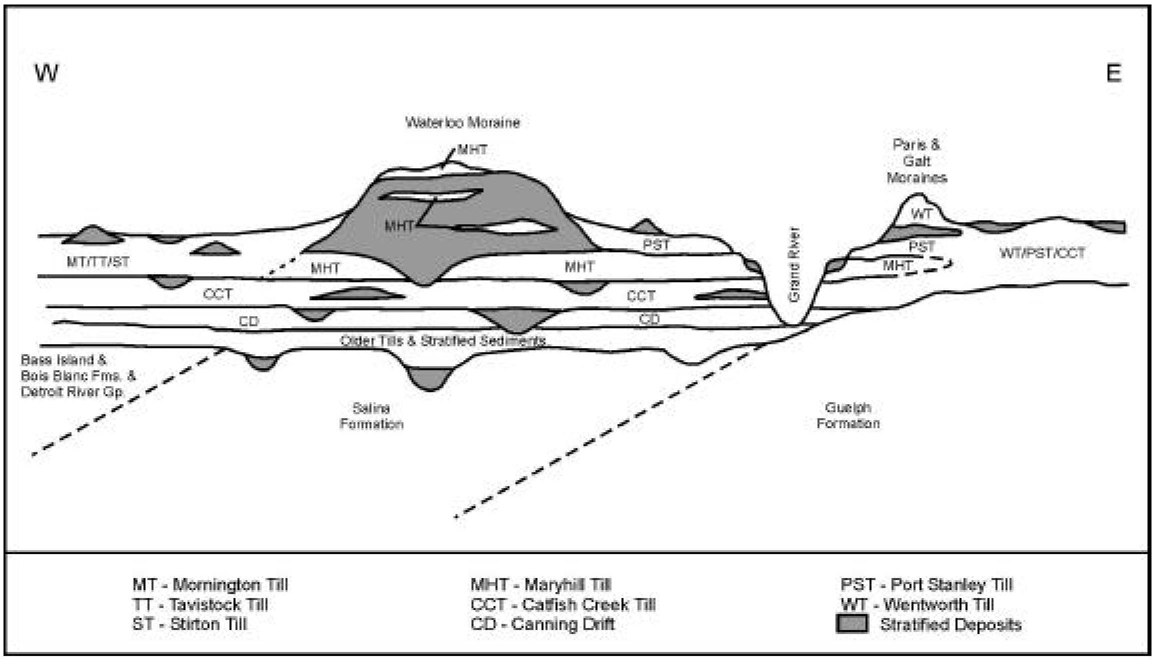

Figure 2. Conceptual geologic model for the Regional Municipality of Waterloo. Six lithostratigraphic units are recognized over the Waterloo Moraine.

channels or valleys on the bedrock surface. Test shear wave surveys (3.6 km at 3 sites) using the MiniVib (TM) in shear mode have also been obtained in areas where P-wave data are poor due to the presence of a thick, low-velocity surface layer.

An extensive program of ground penetrating radar (GPR) profiling was undertaken during the fall of 2002 and the summer of 2003 to assist with the development of depositional models for the near-surface, coarse-textured, stratified deposits of the region. Over 16 kilometers of GPR profiles were acquired at 14 sites. Sites were chosen on the basis of surface morphology. They consisted of hummocky terrain, ridges, gently undulating terrain, and plains. All GPR lines were surveyed twice using both 50 MHz and 100 MHz transmitters. One short transect line was also surveyed with 200 MHz transmitters. Generally, the higher the frequency of the source energy, the better the resolution of subsurface geology. However, penetration depths are compromised using the higher frequencies. Areas of hummocky terrain and ridges generally displayed variably-scaled channelized systems indicative of deposition in a glaciofluvial and/or subaquatic fan environment. Faults and chaotic bedding are infrequently observed. First order reflectors are generally flat-lying and commonly truncated along slopes and valley walls. Channelized deposits occur in the swales between ridges and knolls. Much of the apparent hummocky topography of the moraine is therefore interpreted as erosional in origin. Gently undulating to flat terranes generally display variable internal structures. Channelized reflectors on flat plains indicate deposition in shallow braided streams or deltaic environments. Flat-lying, parallel reflectors are interpreted to represent deposition in basinal glaciolacustrine settings.

There are presently in excess of 450 geophysically logged boreholes within the RMOW. This density of high quality geophysic al data is unparalleled within the province. A project is currently underway to standardize all of these records and to pick the main, geophysically-defined, lithologic units using OGS-developed material codes and to identify the main aquifers and aquitards within each borehole. This will be achieved by calibrating recently cored and geophysically logged boreholes within the region against geophysically logged boreholes lacking high quality sediment records. The geophysically-derived logs will be used during the modelling process to assist with regional correlations.

Data interpretation and synthesis is a labour intensive, iterative process that will require the use of high-powered GIS tools and 3-D viewing software. To date, a number of software programs have been utilized in the interpretation and synthesis process. The 3-D data is housed in an Access® database where it can be easily queried and updated. Preliminary interpretations of the data have been undertaken using ESRI products such as ArcGIS® and ArcScene®, as well as Viewlog®.

Viewlog® is being used in the interpretation process to pick formation tops along sections as well as to interpolate surfaces (Figure 3). Its strong link to Microsoft Access® allows for excellent query and live database update functionality. The OGS is currently evaluating higher-powered, 3-D modelling software to assist with the tasks of modelling more complex subsurface units, such as lenses and pinchouts and for the creation of block solid models for volumetric and hydrogeologic flow modelling. Following the construction of a 3-D geologic model, activities will shift and focus on the development of both technical and "user-friendly" derivative products that will assist with policy making decisions and resolution of land-use issues.

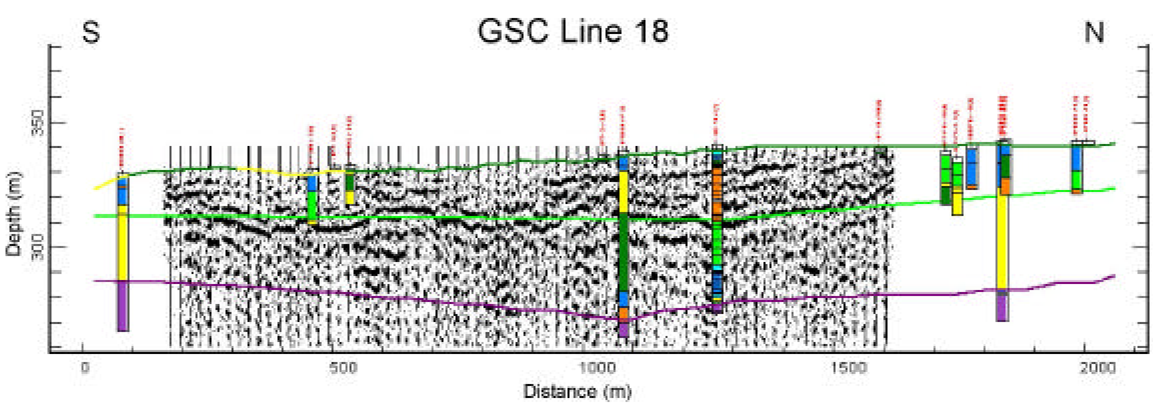

Figure 3. Viewlog® cross-section with p-wave seismic reflection profile "hung" in the background. The horizontal lines represent, from top to bottom, the ground surface, top of Catfish Creek Till, and bedrock surface.

Integrated Modelling of Geoscience Information to Support Sustainable Urban Planning, Greater Manchester Area, Northwest England

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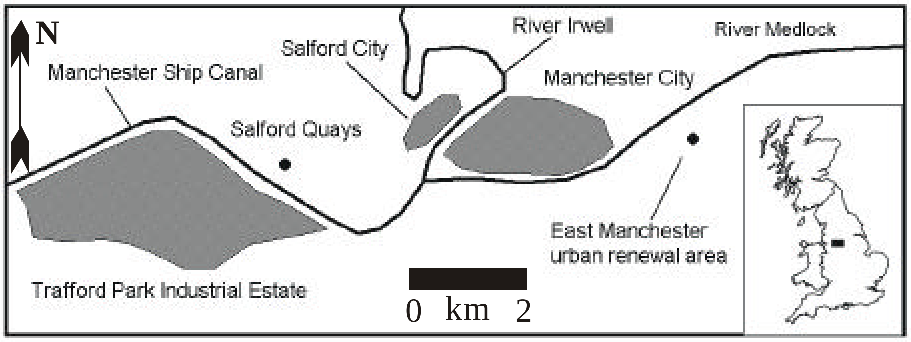
The provision of reliable and up-to-date geoscientific information for the urban environment has assumed increasing importance in recent years as legislative changes have forced developers, planning authorities and regulators to consider more fully the implications and impact on the environment of large-scale development initiatives. To comply with the principles of sustainable development, developers are increasingly required to demonstrate that proposals are based on the best possible scientific information and analysis of risk. Nowhere is this more relevant than in the context of urban regeneration, where planning policy guidance gives priority to re-use of previously developed (brownfield) land. In England, brownfield sites, suitable for re-development, cover an area equivalent to half the size of London.

To better understand the problems of bringing this land back into use, the quality of the land and any potential problems need to be investigated. Whilst site investigation studies may provide a local answer, there is generally little incentive for developers to integrate information and examine impacts beyond their own area of interest. By taking a more holistic view and combining knowledge of the near-surface geology with other geoscientific information, it is possible to predict geological scenarios that may better inform sustainable development objectives. Ongoing research in the conurbation of Greater Manchester, in northwest England (Figure 1), is working towards this objective through development of an integrated spatial model of the shallow subsurface.

The Manchester three-dimensional (3-D) model (Figure 2) covers a geographical area of 100 km^2 and is built around a framework of 6,500 site investigation boreholes. The 3-D configuration of the geological units in the subsurface is built up from serial cross-sections, drawn interactively by combining map-face data with downhole information. Correlated surfaces are gridded, and stacked to produce the final geological model. Attribution of the model with a range of parameters (geotechnical, hydrogeological, geochemical) allows rapid generation of a range of derived products.

The model has the potential to deliver information in formats relevant to a wide range of planning issues (ground stability, contaminated land, groundwater management) (Figure 3). Currently, the model is being used to provide the Environment Agency of England and Wales with a framework for understanding groundwater resource and protection issues beneath one of Europe's largest industrial parks.

The continued success of this approach will ultimately depend on engaging more fully with a range of users (consultants, planners) and demonstrating that there are real benefits (financial and environmental) in taking a more holistic approach to environmental assessment.

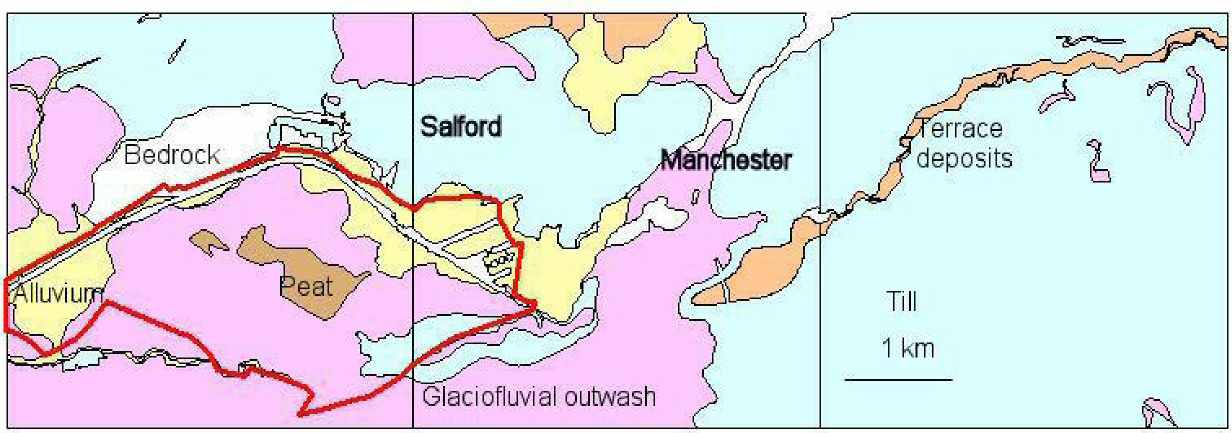


(a) Project area

(b) Trafford Park, Manchester

Issues:

- Groundwater management
- Aquifer protection



(c) 2-D map of superficial geology

Limitations:

- Difficult for the non-specialist to interpret
- Emphasis on top 2 m
- Difficult to produce derived (thematic) products

Figure 1. (a) Project area, (b) Trafford Park, Manchester issues, and (c) limitations of two-dimensional traditional geologic maps.

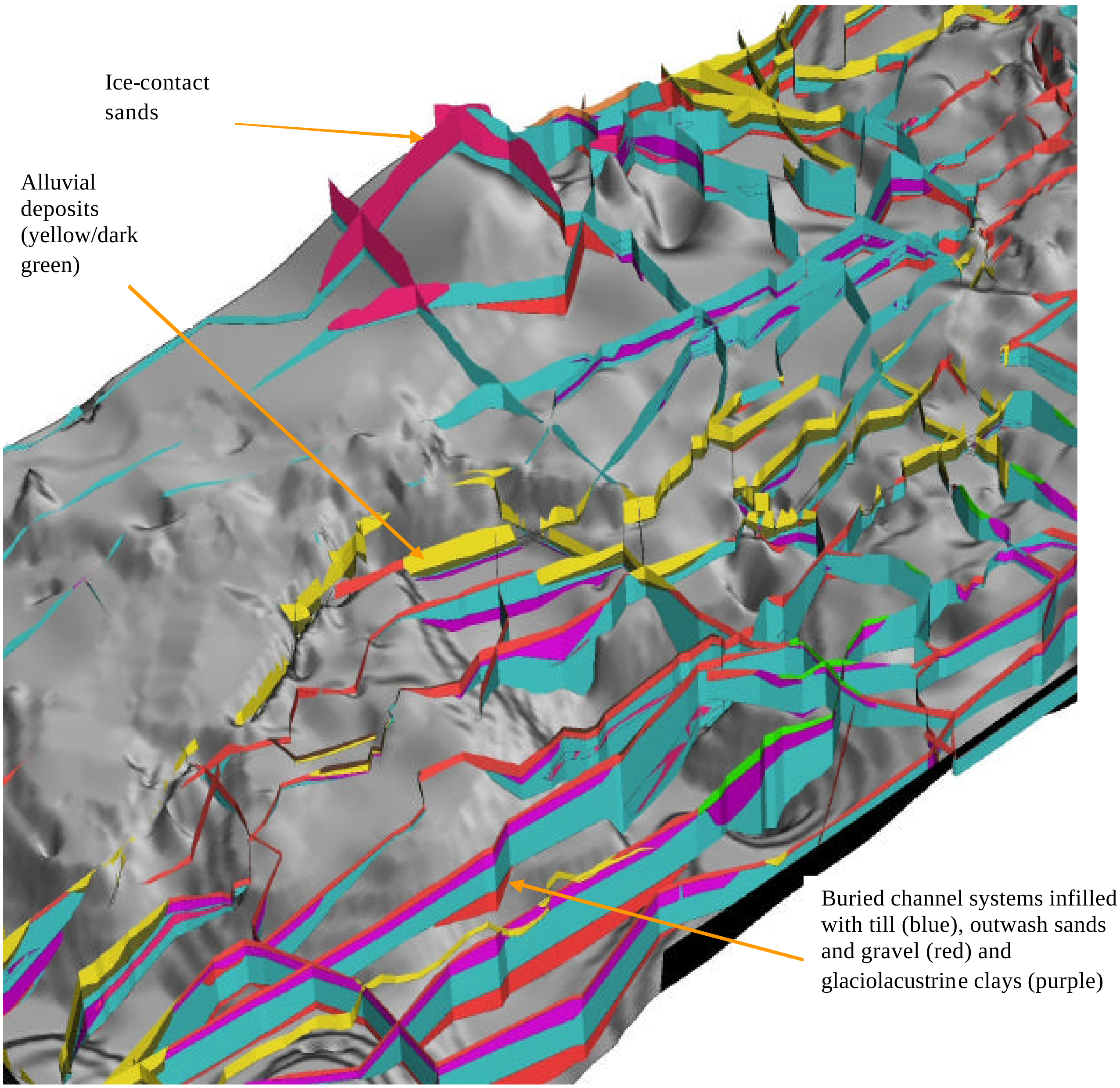
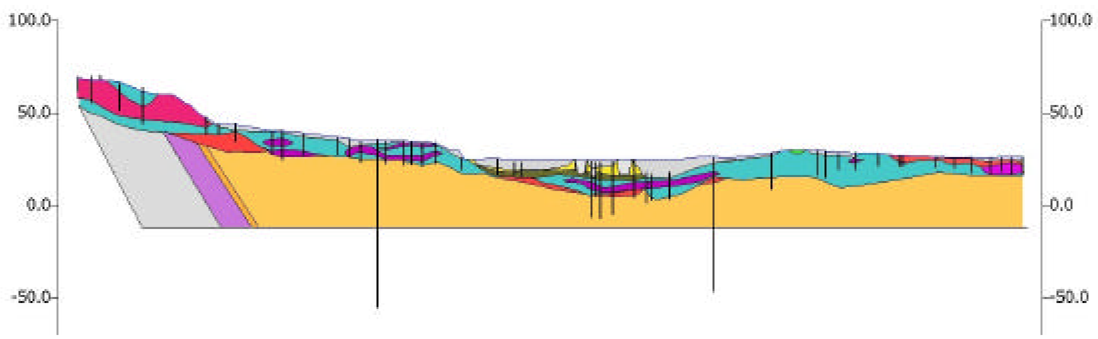
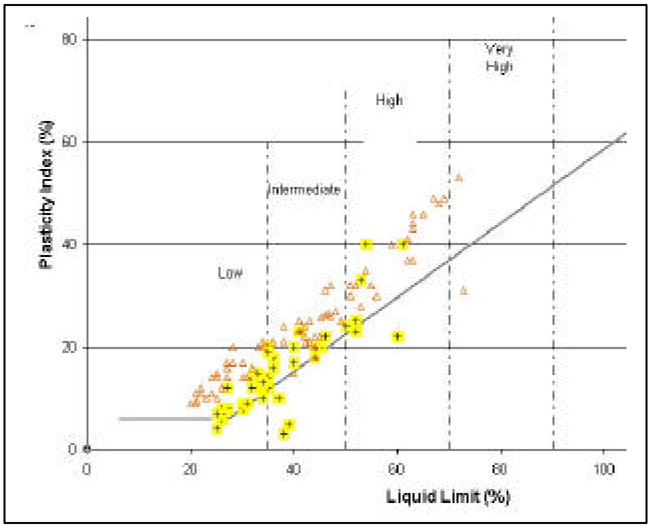


Figure 2. Three-dimensional model framework showing Quaternary deposits in multiple cross-sections lying on top of the Permo-Triassic sandstone aquifer (grey) in the Trafford Park area.

(a) Synthetic cross-sections along a user-defined transect (e.g., proposed pipeline route)



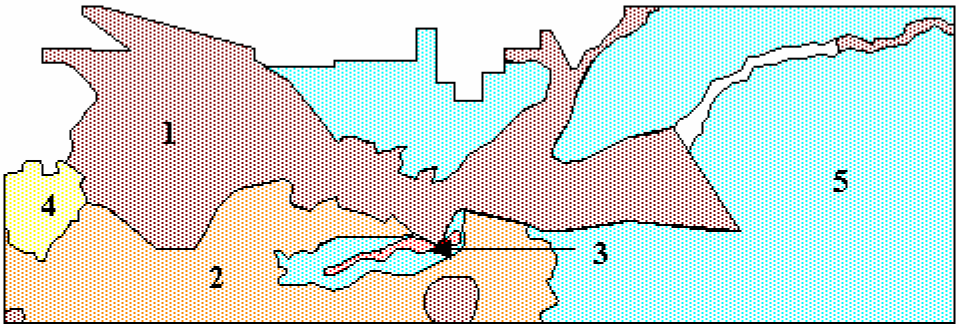
(b) Geotechnical properties of selected modelled units (e.g. for shrink-swell susceptibility)



Plasticity chart for alluvial silts (+) versus glaciolacustrine clays (?).

Under normal ground conditions, low and intermediate plasticity values generally indicate a low shrink-swell potential, whereas high and very high plasticity values indicate a high shrink-swell potential.

(c) Aquifer vulnerability



Hydrogeological domains map provides an assessment of recharge to the Permo -Triassic sandstone aquifer, and also an indication of groundwater vulnerability. (ranked 1-maximum recharge/vulnerability to 5 - minimum recharge/vulnerability)

Figure 3. Derivative products relevant to planning issues.

3-D Colour Schemes for Complex Glacial Aquifer/Aquitard Systems

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The Waterloo Moraine, which provides about 80% of the drinking water for the Regional Municipality of Waterloo, is a complex glacial system composed of highly intermingled material including gravel, sand, silt, clay, and bedrock. Over the last 10 years, we have conducted detailed studies of the Moraine in order to define the groundwater flow system and delineate the well capture zones that the Regional Municipality uses as a basis for designating wellhead protection areas (Martin and Frind, 1998; Frind et al, 2002). From our experience with this highly complex system, distinct units that can be unambiguously classified as either aquifers or aquitards are difficult to identify.

To adequately describe this complexity in three dimensions, we have developed a conceptual model that divides the Moraine into a number of layers (eight in this case). Each of these layers is nominally classified as "aquifer" or "aquitard", where an "aquifer" will contain mostly sand and gravel, but also some clay or silt, and an "aquitard" will contain mostly silt and clay, but also some sand and gravel. Each layer is represented in terms of continuous distributions of hydraulic conductivity K (m/s), translated into a continuous colour ramp as follows:

Material	K (m/s)	Colour range
Gravel	$10^{0} – 10^{-3}$	red – orange
Sand	$10^{-3} – 10^{-6}$	Orange – yellow
Silt	$10^{-6} – 10^{-9}$	Yellow – green
Clay	$10^{-9} – 10^{-12}$	green – blue

This system allows a gradual transition over the entire range of materials for each layer, using the full range of colours. Fissuring can be represented by superimposing a grid-like pattern onto the background colour. By showing the colour map for each layer, the complete 3-D system can be represented. This approach easily facilitates the realistic representation of complex glacial systems, such as the Waterloo Moraine, in the context of groundwater studies.

References

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Martin, P.J., and E.O. Frind. 1998. Modeling a Complex Multi-Aquifer System: The Waterloo Moraine: Ground Water, v. 36 (4), p. 679-690.

Cooperative Geological Mapping Strategies Across Canada: What Relevance for Groundwater?

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"Cooperative Geological Mapping Strategies Across Canada" (CGMS) was a 10-year vision statement written by the National Geological Surveys Committee (NGSC) that focused on the continuing need for reliable geoscience knowledge relating to mineral, energy, and groundwater resources, compatible with the Intergovernmental Geoscience Accord. The NGSC's vision statement, approved by all of Canada's Mines Ministers in 2000, identified geoscience knowledge as a key competitive advantage, essential to maintaining Canada as a pre-eminent global destination for exploration investment, which has been put at risk by decreased levels of effort by government agencies and industry. Hence the CGMS initiative presents itself as the effective vehicle for renewed government investment in public geoscience.

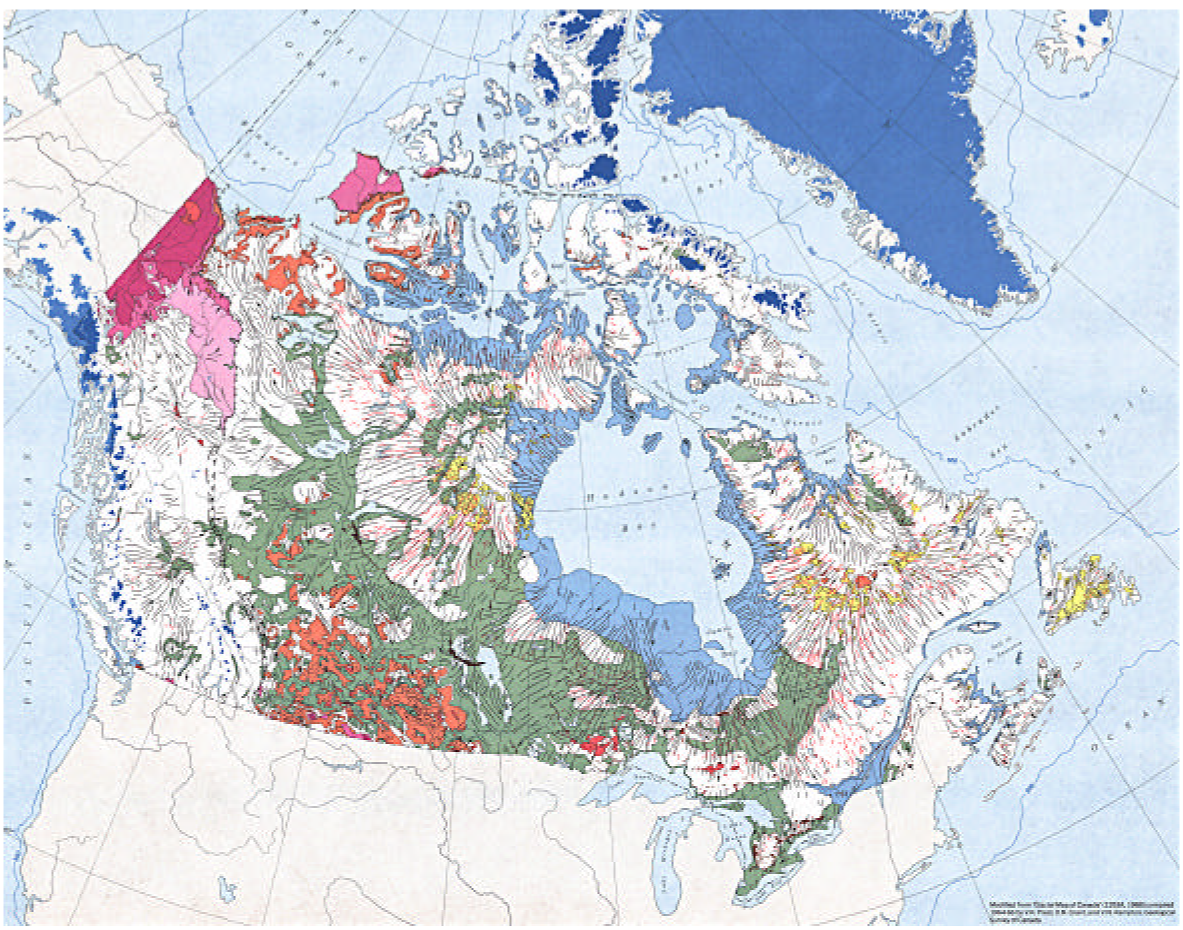
In Spring 2003, The Geological Survey of Canada met with each of the provincial and territorial Geological Survey organisations in order to better understand their perception of geoscience gaps and needs in their jurisdictions. These meetings highlighted the emergence of an inter-provincial/territorial mind-set with respect to CGMS that will promote cooperation across jurisdictional boundaries, facilitate priority setting at the broadly regional and national scales, and better guide the federal contribution to CGMS.

Public geoscience is a tool to address government issues and priorities, to contribute to the "Public Good". In the context of CGMS, this implies fostering the "Responsible Development of Natural Resources", and reducing the risk related to resource exploration and development by providing decision-makers, including industry, government, and society at large, with the sound scientific basis for determining how, where, and when resource development should take place. This could range from geological mapping to stimulate exploration in areas where resource potential is poorly understood, to geological mapping to enable decisions to be taken regarding the environmental impact of resource development.

Groundwater is already the subject of a key initiative: *"The Canadian Framework for Collaboration on Groundwater"*. CGMS can provide an important complement to the Groundwater Framework by focusing on public geoscience relating to groundwater as a resource that can impact on upstream and downstream land-use decision making. "Upstream" would include baseline studies prior to energy or mineral resource development, while "downstream" would include the potential impacts of such development on the environment. These issues could also include the availability of water required for the development of other resources, such as tar sands, as well as the sequestration of process waters that result from such development. The sequestration of carbon dioxide associated with enhanced oil recovery is a complex process that requires a comprehensive geoscience understanding of groundwater systems, as does saline mining to permit the underground storage of natural gas, a critical part of the energy economy in some densely populated parts of Canada. The extraction of industrial minerals, such as aggregate, and of non-traditional shallow gas both impact on shallow groundwater systems. Wise land-use decision making in all of these settings, by governments, industry, and society at large, requires the kind of public geoscience that can be provided under CGMS.

CGMS is a national initiative that will require a national workshop, and inter-provincial/territorial workshops represent an appropriate and necessary stepping-stone toward that end. A pilot inter-provincial/territorial workshop with federal participation has already been held in Ontario in March 2004, focusing on the Canadian Shield in central and eastern Canada. This will be followed at the end of May by other workshops that will focus on Cordilleran, Atlantic, and Northern Canada, and the Western Canada Sedimentary Basin from the prairies to the Arctic coast, and a national NGSC workshop in June. In parallel with this NGSC process, partnerships will be actively sought with other government departments, industry, and academia with a view to fundamentally restructuring the relationship between public geoscience and stakeholders Canada-wide. Already noteworthy in this regard, CGMS has been endorsed by Indian and Northern Affairs Canada in response to a recommendation by the minister's Industry-Government Oversight Committee.

If *"Strategies"* are indeed inter-provincial/territorial in nature, with active federal participation, access to the knowledge produced under their auspices should not be impeded by jurisdictional boundaries. The credibility of the CGMS initiative would be undermined without a delivery mechanism capable of serving the needs of the end-users. Collectively, members of the NGSC are currently developing such a delivery mechanism in the form of the Canadian Geoscience Knowledge Network (CGKN).



Three-Dimensional Geologic Mapping in Rapid-Growth Areas: A Case Study from Lake County, Northeastern Illinois

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In regions experiencing rapid suburban growth, the currently available information on the geology is often at a scale that is too small to aid decision-makers and a level of complexity that is not easily interpreted by non-geologists. Lake County, Illinois, is located in the northern portion of the Chicago metropolitan area and is part of a group of counties experiencing rapid development. The county borders on Lake Michigan, which is a source of water for much of the county's population (Figure 1). However, the most rapidly developing areas are predominantly outside of the Lake Michigan water allocation area, and it is here where information is most urgently needed about the near-surface geology and shallow aquifers. Better knowledge of the occurrence, geometry, and characteristics of the aquifers will allow their increased utilization.

Lake County has written its new regional development plan, so that as new geologic information becomes available it can quickly be integrated into the planning framework, and the county and municipalities can modify their plans as needed. The geologic information will provide a basis for revising zoning maps that govern the type of development permitted. Such revisions can then immediately impact density and type of housing, transportation network development, and other infrastructure allowed. Many current zoning laws are not sufficiently detailed to be able to control the types of development now being proposed.

Current information on the aquifers is based on limited data at small scales (Figures 2 and 3). Lake County and the Illinois State Geological Survey are working closely to develop large-scale, derivative, geology-based products to assist in county planning and development with respect to population growth and resource utilization. The initial step is to develop a detailed three-dimensional (3-D) model of the sediments that can be used as a framework for developing derivative products, particularly those that address the location and wise use of aquifers.

As part of the Central Great Lakes Geologic Mapping Coalition, we are developing 3-D stratigraphic models for each 1:24,000-scale quadrangle in Lake County. A larger, more regional perspective will be gained as models of adjacent areas are merged. Our first quadrangle for detailed 3-D mapping was the Antioch 7.5' Quadrangle. Here the drift ranges from about 150-300 feet thick and consists of tills and proglacial fluvial and lacustrine sediments of three late Wisconsin glacial events. Because the ice margin advanced and retreated across the quadrangle at least once during each event, the tills and ice-marginal facies (predominantly diamictons) are intertongued with the proglacial facies (predominantly fine silt and sand to coarse sand and gravel). The latter contain important drift aquifers. In the Antioch Quadrangle, more than 90% of all wells are screened in glacial drift.

Figure 4 shows the 3-D stratigraphic model of the Antioch Quadrangle. The stratigraphic units consist of 1) lithologically distinct till units (shown in greens), which consist predominantly of diamicton and resedimented proglacial facies (flows and lake sediments), and 2) coarse-grained sand and gravel facies (shown in yellows and golds). These units overlie Silurian bedrock (predominantly dolomite). The model was generated from about 275 borehole records. These records were selected from over 4000 drillers' logs (25 with natural gamma logs) and 10 stratigraphic borings (8 with natural gamma logs). We

Figure 1

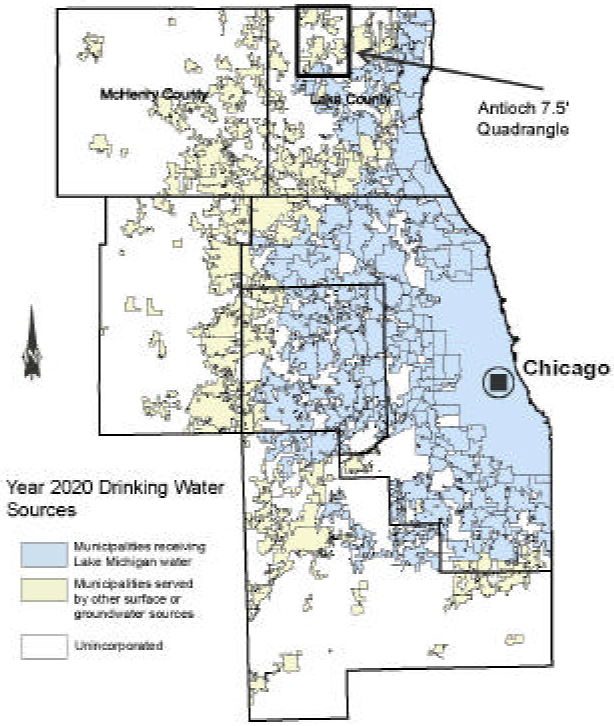


Figure 1 Location of the Antioch Quadrangle in relation to drinking water sources for the Greater Chicago Area (Northeastern Illinois Planning Commission, 2002).

Figure 2 Shallow (drift and upper bedrock) aquifer withdrawals in the Greater Chicago Area (Northeastern Illinois Water Supply Study, 2000).

Figure 3 Deep (bedrock) aquifer withdrawals in the Greater Chicago Area (Northeastern Illinois Water Supply Study, 2000).

Figure 2

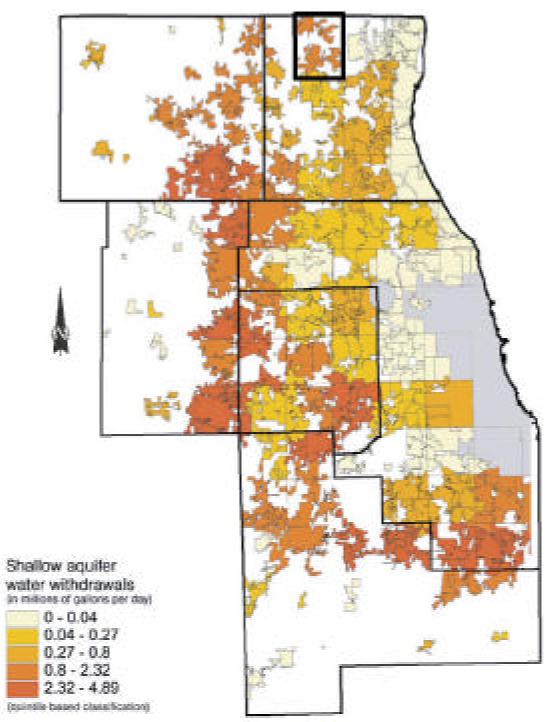
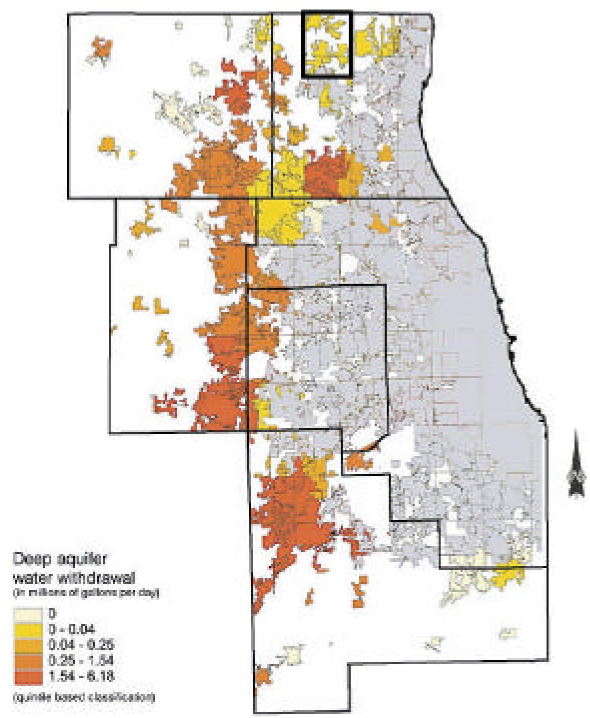


Figure 3



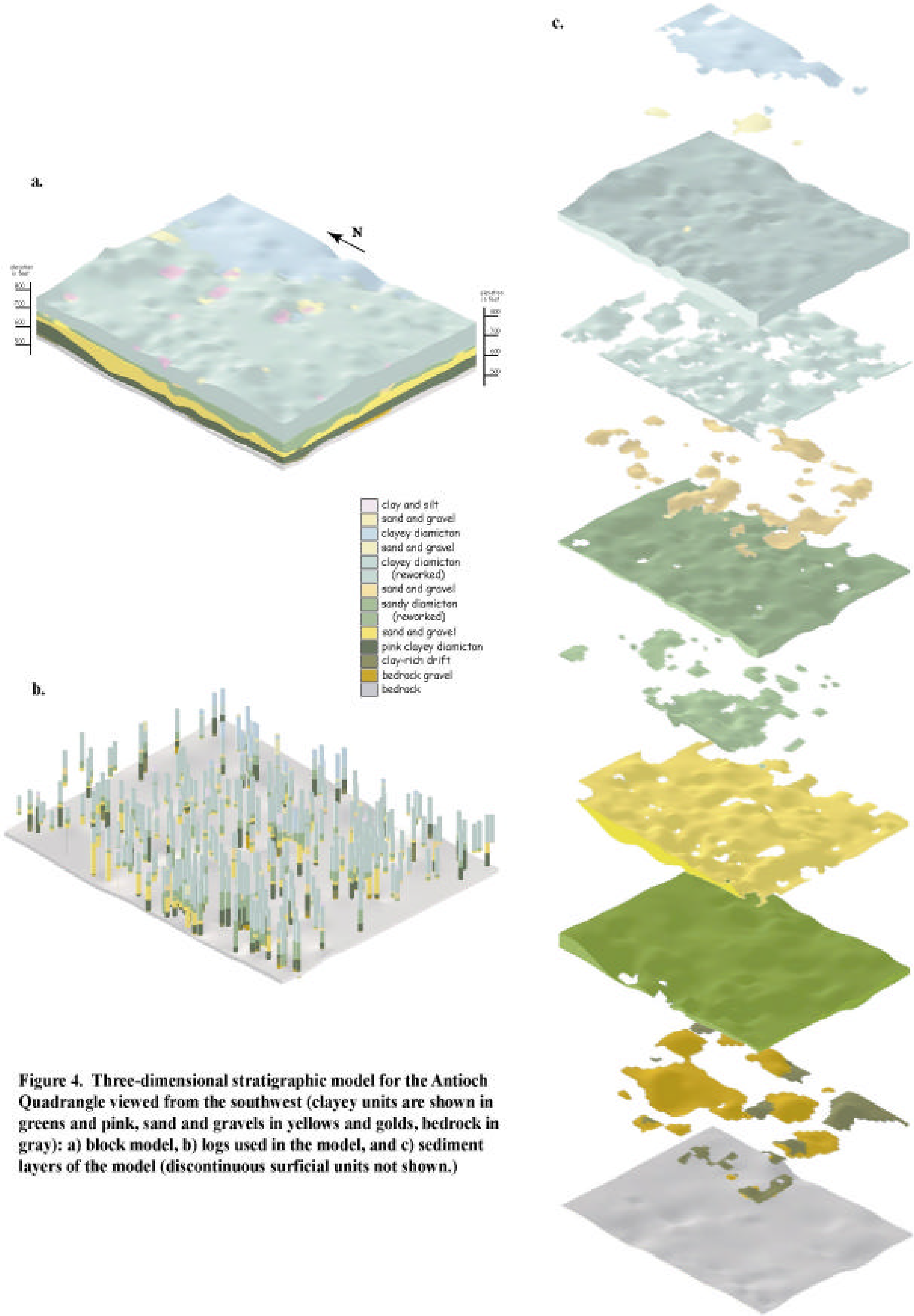


Figure 4. Three-dimensional stratigraphic model for the Antioch Quadrangle viewed from the southwest (clayey units are shown in greens and pink, sand and gravels in yellows and golds, bedrock in gray): a) block model, b) logs used in the model, and c) sediment layers of the model (discontinuous surficial units not shown.)

used RockWorks99 software to make stratigraphic picks and generate a datasheet for import into RockWorks2002, which we used to create the model. Hundreds of cross sections were drawn in RockWorks99 to check the picks. The locations of all data used in the model were verified using tax-parcel records, street address information, plat-books, and/or field checking.

We plotted the position of well screens for all 4000+ water wells on our model units to visually inspect which units are being tapped for water (Figure 5). This inspection is continuing and will likely result in further refinement of the model. We also constructed pie charts by section to illustrate spatial variation across the quadrangle with respect to which units are being used as aquifers (Figure 6). As we progress with our modeling, the detailed 3-D model will ultimately cover the majority of the county and will provide the framework for developing derivative products (e.g., isopach maps, engineering properties maps, hydrostratigraphic models) related to suburban development, resource extraction, aquifer capabilities, and recharge areas.

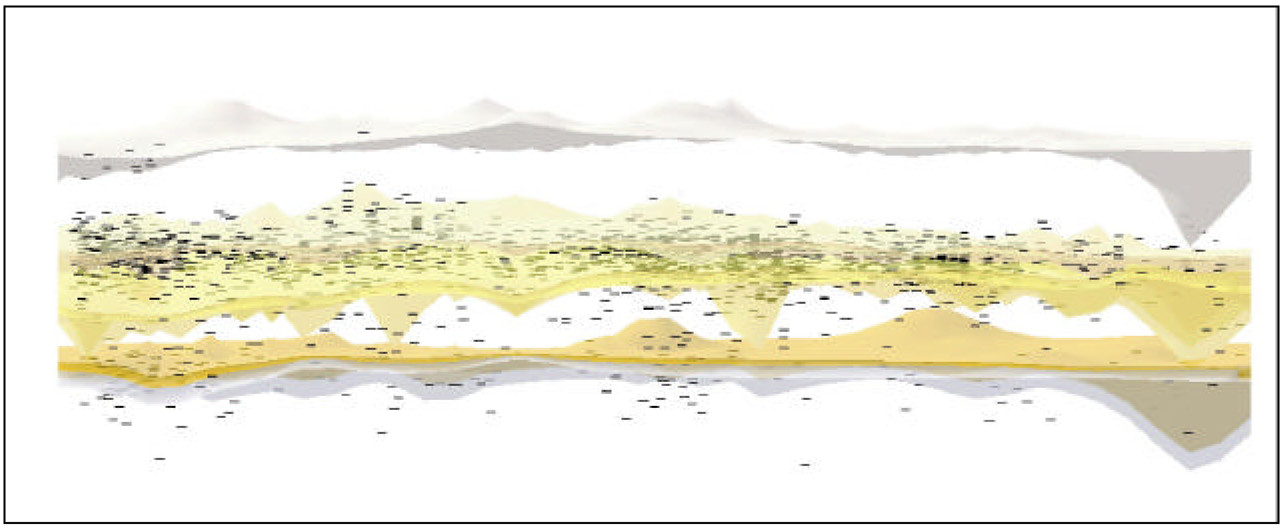


Figure 5. Positions of well screens in the Antioch Quadrangle with respect to the sand and gravel units (shown in yellows and golds), surface (shown in light tan), and top 20 feet of bedrock (shown in medium gray). View is from the south. Key shown in Figure 4.

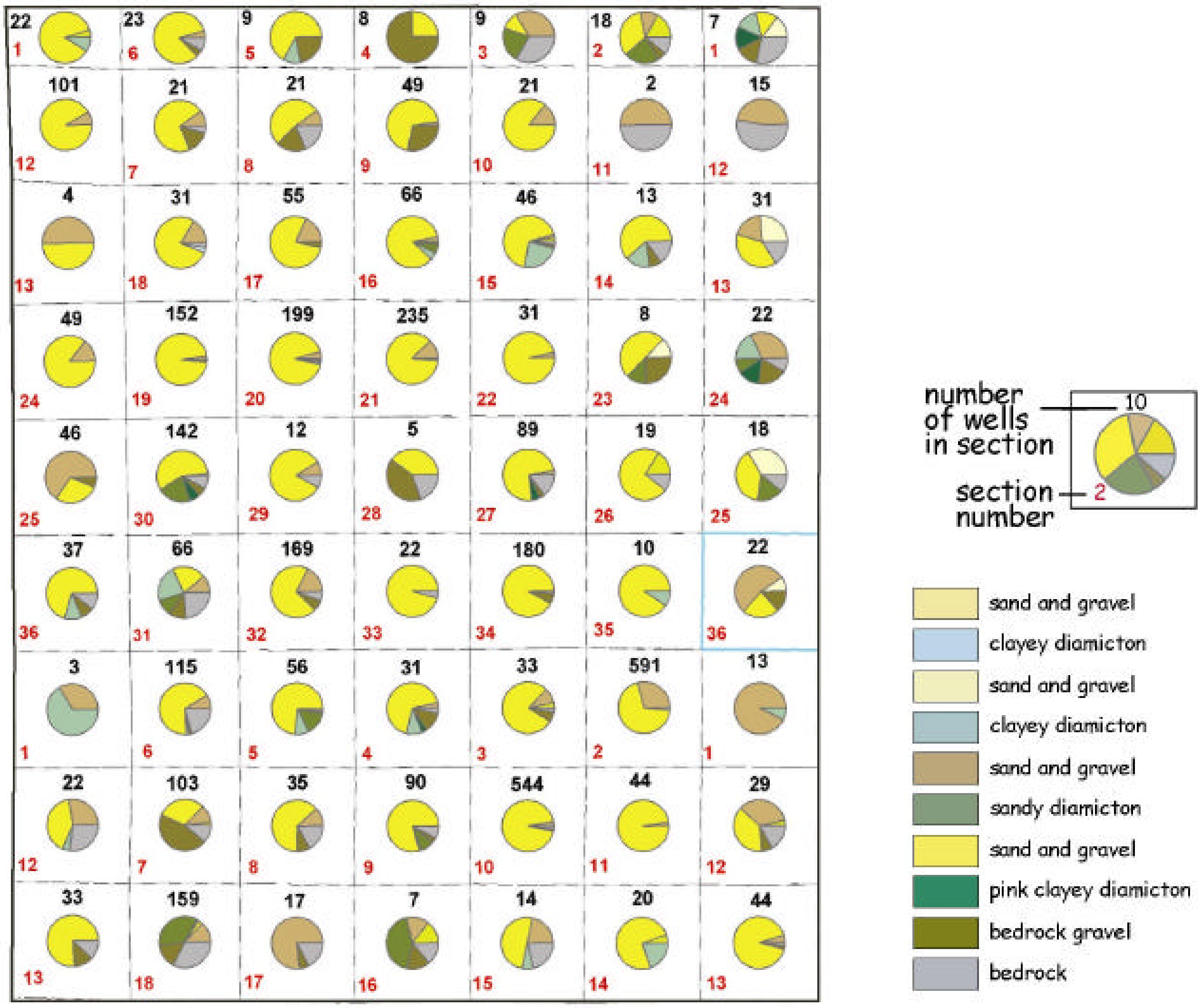


Figure 6. Pie charts for each square-mile section showing spatial variation in units being tapped for water across the Antioch Quadrangle.

Borehole Geophysical Logging in Unconsolidated Sediments – An Aid to 3-D Mapping

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Over the last two decades, several advances have been made in the development and application of slim-hole geophysical sondes for use in groundwater, engineering, and environmental applications. This equipment is commonly used to provide qualitative (but detailed) estimates of grain size, sediment type, porosity, density, pore-water salinity, as well as bulk and shear moduli, to supplement geological/geotechnical sampling in boreholes. The goal of this paper is to illustrate the enhanced information that geophysical logs provide about a borehole and the utility of geophysical logging in unconsolidated sediments as a tool for 3-D mapping.

Some of the earliest geophysical logs used in conjunction with water-well drilling were the natural gamma and single-point electrical resistivity logs; these are run in "open hole" conditions, and can be quite definitive for lithologic studies (Maathuis, 2001). As open holes are difficult to maintain in unconsolidated sediments, PVC-cased boreholes have become more common in conjunction with shallow geophysical logging and a considerable number of specific sondes have been developed for such applications. The Geological Survey of Canada (GSC) routinely operates a suite of slim hole (< 60mm diameter) sondes: natural gamma, inductive conductivity, magnetic susceptibility, gamma-gamma density, and temperature gradient. In addition, two downhole seismic arrays for compressional and shear wave velocity measurements are commonly run. Another significant tool (in use by other groups for porosity measurements) is the compensated neutron sonde. Emerging technologies at the GSC include the passive gamma-spectral sonde and the capacitive-coupled resistivity tool.

Geophysical properties of unconsolidated materials, using the various sondes mentioned above, are given by Hunter et al. (1998), Douma et al. (1999), and Pullan et al. (2002). In short, as a rule of thumb: natural gamma responds to grain size, with high count rates associated with clay materials; inductive conductivity measures the combined electrical conductivity of the pore-water and the matrix; magnetic susceptibility responds primarily to magnetite content; neutron absorption is inversely proportional to water content; the count-rate of the gamma-gamma tool is inversely proportional to density variation; a derived log, the spectral density ratio, compares the high- to low-energy portions of the spectral gamma-gamma log and is proportional to the average atomic number of the formation; temperature gradient is a function of thermal conductivity of materials with sharp vertical fluctuations in the curve associated with thermal disturbance from water flow; P- and S-wave velocities vary directly with bulk modulus and shear modulus respectively (function of compactness and porosity of the materials).

Although measurements from a single geophysical sonde can be used for stratigraphic characterization, a suite of geophysical logs is a significantly more powerful tool. Figure 1 shows a composite log suite from the Waterloo Moraine area in southern Ontario, which is used here to illustrate the additional information, at both the detailed and unit scales, that the geophysical logs can provide, even when a borehole has been continuously cored. The drillers' log shows that several tills were encountered in the hole, inter-layered with clay, silt, and gravel. From inspection of the changes in natural gamma, conductivity, and P-wave velocities, the till units can be subdivided based on interpreted changes in grain size, provenance, and elastic moduli. Commonly, abrupt changes in geophysical properties occur between units; such changes can serve to adjust interpreted depths in continuously cored holes and can be utilized to establish unit boundaries in boreholes with limited sampling. Note that though the lowest till unit in

Figure 1 (T4) would be interpreted as the most coarse-grained on the basis of the gamma, conductivity, and magnetic susceptibility logs, it also appears to have the lowest porosity as shown by the neutron, gamma-gamma density, and spectral

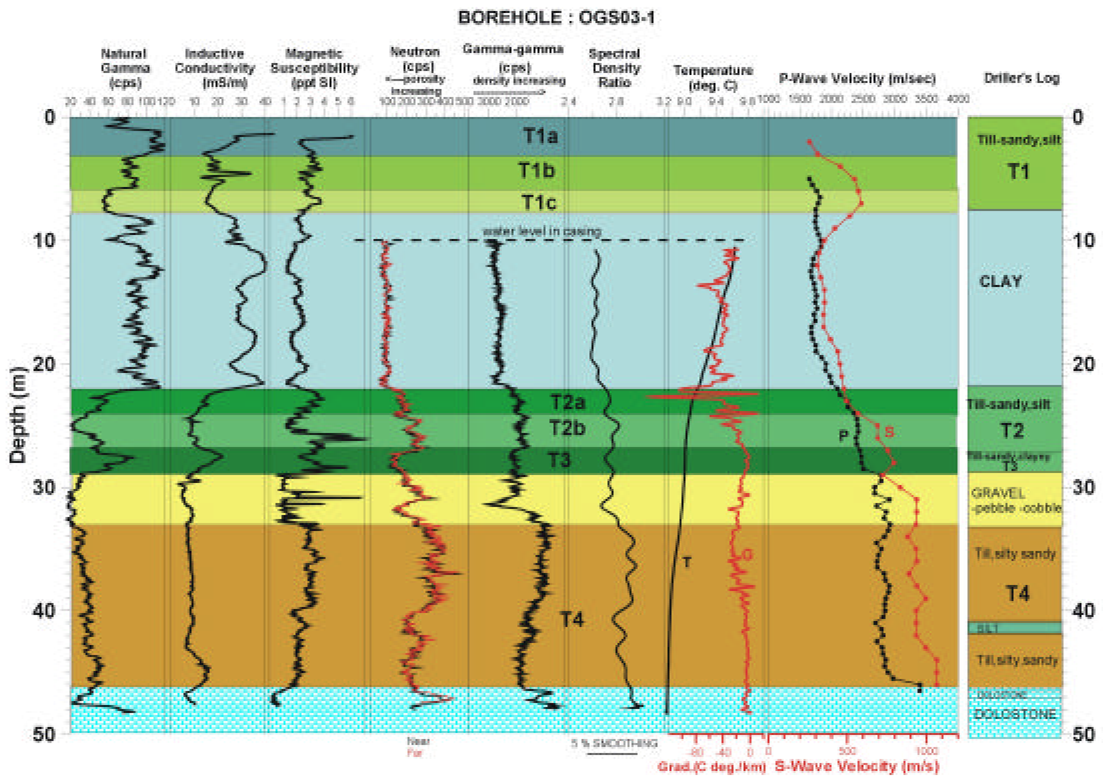

Figure 1. Geophysical log suite from a borehole in unconsolidated sediments near Waterloo, Ontario.

density ratio, and suggested by the P and S wave logs. This till has been identified as the Catfish Creek till (A. Bajc, Ontario Geological Survey, pers.comm.) and is known to be a regional aquitard.

Geophysical borehole logs can be important tools for regional stratigraphic correlation. An example using comparisons of anomalies within the electrical conductivity and magnetic susceptibility plots is shown in Figure 2. These data come from an area east of Ottawa, Ontario, where four boreholes spanning a total distance of ~60 km, were drilled within a Holocene basin consisting of Champlain Sea sediments. The fine-grained sediments (Leda clays) that make up most of the unconsolidated sequence were deposited in a marine environment, and some portions retain the original brackish-saline pore-water (e.g., boreholes A and D) yielding higher electrical conductivities. In other areas, modern (fresh) water is found in the pore spaces and the conductivities are relatively low (e.g., boreholes B and C). All boreholes, however, show two thin coarser-grained layers with lower conductivity than the surrounding material and distinct concentrations of magnetite; on some logs (not shown here) there are also indications of slightly higher densities and a slight increase in grain size. These anomalies are visible on the geophysical logs in many boreholes throughout the Ottawa area, and also from some boreholes as far away as Montreal. It is suggested that they represent widespread contemporaneous depositional events in the early history of the Champlain Sea.

Non-standard logs such as seismic velocity or gamma-gamma also show value in subsurface stratigraphic mapping. The P-wave downhole log can be used as a stratigraphic indicator in concert with other conventional logs, but is also extremely useful in providing vertical velocity control for high

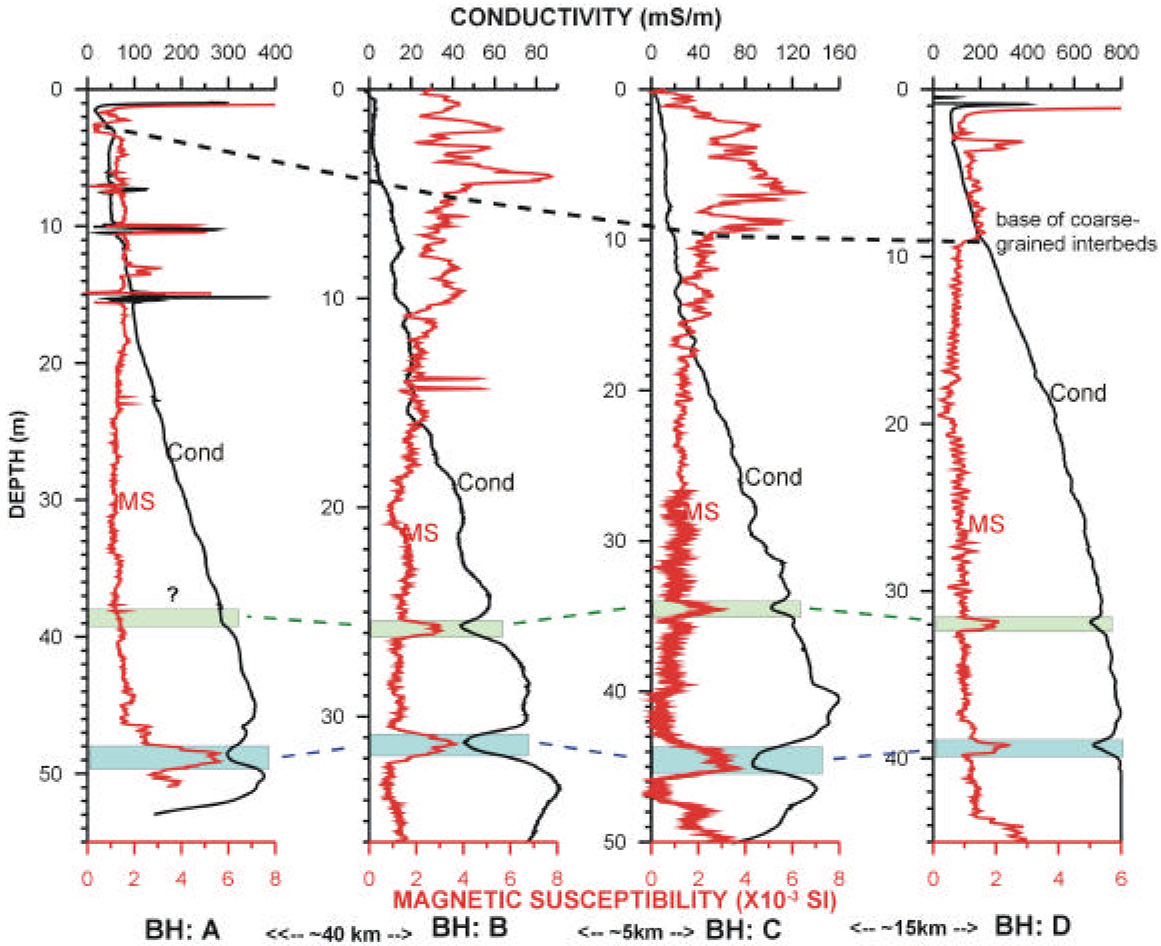

Figure 2. Magnetic Susceptibility and Inductive Conductivity logs from four widely-spaced boreholes within the Champlain Sea sediments in eastern Ontario showing regional marker beds.

resolution seismic surveys. As well, recent work is showing that seismic velocities can be used to provide total porosity estimates. Figure 3 shows an example of the use of velocity logs as a stratigraphic indicator from the Oak Ridges Moraine area near Toronto. The Newmarket Till is not well defined by most geophysical logs, since many of its geophysical characteristics are similar to formations above and below it. However, one distinguishing feature is its unusually high P-wave velocity (commonly > 2500 m/s), postulated to result from partial cementation of pore spaces.

Figure 3 shows a N-S section of P-wave downhole logs across the Oak Ridges Moraine area north of Toronto showing the interpreted thickness of the Newmarket Till. The presence or absence of the Newmarket Till and its role as an aquitard is very important in the development of the hydrogeological framework of the Toronto area; hence the P-wave downhole log is considered to be an important tool in such studies.

The GSC is establishing a number of "golden spike" boreholes (Sharpe et al., 2003) in various surficial geological areas across Canada. As well as being geophysical logged, these PVC-cased and preserved boreholes have been continuously cored, sampled, and geologically logged. Such "golden spikes" serve as reference data for surficial geological deposits in the area, and are also available as test sites for future developments in borehole or surface geophysical techniques.

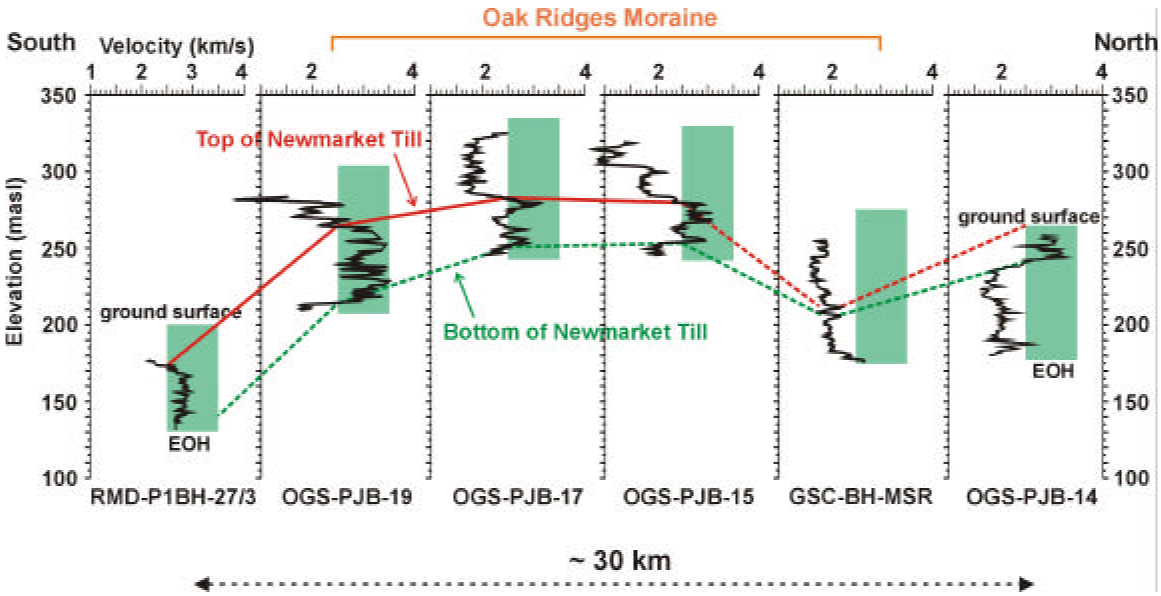

Figure 3. A suite of P-wave downhole logs across the Oak Ridges Moraine showing the regional correlation of high velocities associated with the Newmarket Till aquitard.

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Communicating the Vision?

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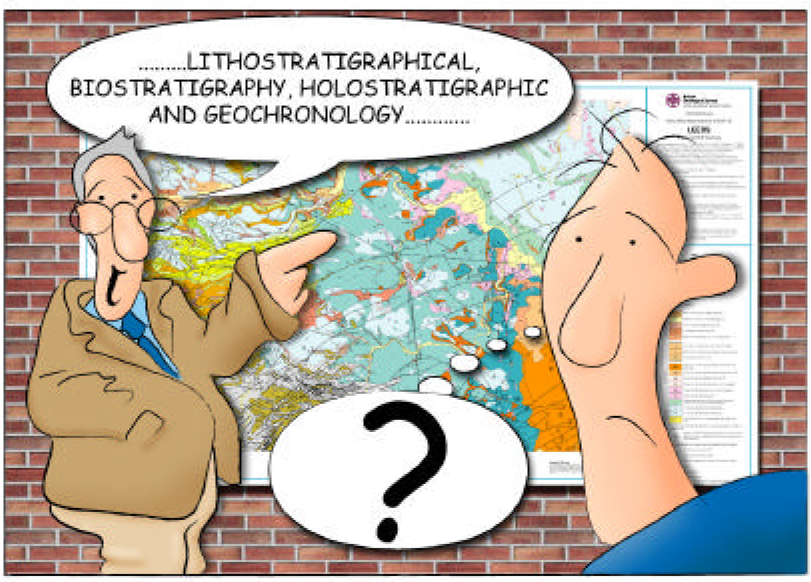
Vision? The title is intentionally ambiguous. One part of this abstract will look critically at how we geoscientists communicate our view of the earth and its processes and perhaps more importantly, communicate the value and *relevance* of our work, to those who need to know. The second part will examine, from the perspective of a small island, what lies ahead for Geological Surveys and the delivery of geoscience information.

The reality? At the beginning of the 21st century, at a time when "the environment" has the highest of profiles, geoscience should be occupying a prominent role. But it is not. It is a sad fact that the importance of geology to the environment, and to human health, property and assets is **not** well understood outside the geological profession. We geoscientists, and the geological surveys and research and academic institutions we work for must accept a substantial part of the responsibility for this lack of understanding and for the failure to persuade potential users to exploit our geoscience knowledge base. The output of our work continues to be dominated by complex, technical, and academic maps and reports. The quality of this science is not in question, but too often the science remains obscure, remote and inaccessible to the end-user. For too many of us the scientific paper or geological map is the end, and not the means to the end – there is little or no attempt to communicate the value of this science to those outside our profession. Is it surprising then, that the importance of geology to society and the environment is not obvious to the public, to governments and to commerce?



But wait a minute, I can hear you say, things have changed; we've got sophisticated new computers with GIS and 3-D modelling software, and we can devise all sorts of colourful coverages, dynamic databases and mutating models, and we can put them on the world wide web for all to appreciate! Fine, I will respond, but how convinced are you that those outside our profession can understand our message any better? A digital geological map or model remains what it is, a highly complex and technical product, and an awful lot less than 0.5% of society have the expertise or training to interpret it. If we genuinely want to be relevant then we have to find ways to communicate with those who inhabit the world beyond the sophisticated, but limited, circles of the geoscience cognoscenti.

The evidence? Having made some sweeping assertions, perhaps I ought to provide some evidence. For that I will focus on my own backyard. Examples from the United Kingdom (a relatively geologically stable country) show the majority of politicians and planners seemingly unaware of, for instance, the swelling and shrinking properties of clay, or the dissolution of gypsum. So they permit housing development that is inappropriate in terms of both location and design. Buildings, roads, and car parks have been constructed over unstable ground causing death, injury, and damage. The importance of including geoscience knowledge in the prediction of radon-affected areas (radon is the second biggest cause of lung cancer in the UK) is only just being fully appreciated. In the UK a lawyer would be deemed as professionally negligent if they did not obtain a report into possible coal mining beneath a property prior to purchase. But at the moment there is no compulsion to seek out information on similarly damaging natural underground voids and yet the case is equally compelling. The estimate of insured losses due to natural geological instability in Great Britain runs into 100s of millions of dollars per year. This, in a country where the industrial revolution was founded on coal and minerals, where William Smith was born, and where the Geological Survey has been in existence for 169 years!

In recent years that Survey, the British Geological Survey (BGS), has been trying to address this "communication problem". It is devoting an increasing proportion of its resources to doing science and developing products and services that attempt to meet the needs of a wider user base. Beware, another contentious statement is on its way - my belief is that this improved "customer focus" is also inextricably linked to the BGS funding situation. BGS has to compete with others for 50% of its income and our desire to want to be around for a few more years to continue to be able to do our survey and research work certainly focuses our minds on our clients' needs. The consequence has been that, in the last decade, we have witnessed an expansion in the range of products that try to meet the requirements of those who do have a real need to use geological information, but who do not possess a degree in geoscience. Most of these products have taken full advantage of the Information Technology revolution. They include site-specific reports that can be delivered via the web through simple entry of one's zip- or post-code; spreadsheets of hazard information for insurance companies (not a geological map in sight!); and last but not least, reports and maps that are explained in plain straightforward language (with no geo-jargon to be seen).

Please do not misunderstand me; I am not challenging the absolute necessity of high quality geological survey and research and the maps and models that result directly from it. But if we aspire to be relevant, then just delivering high quality science in this form means that the job is only half done. We have to reach out and get our message across. We have, as the Irish author W.B. Yeats once said, to think like wise men but communicate in the language of the people.

A view from a small island. Geological Surveys around the world are facing the same range of "challenges" (threats or opportunities depending on one's viewpoint) and looking hard at themselves and their role in society. Those comfortable times are long gone when Surveys could contemplate with certainty well funded, long-term field mapping programmes, or have the freedom to open up a new area of curiosity-driven research. Now we must contend with pressures arising from new and pervasive national and international government policy, greater expectations from industry and society, increasing competition from commerce, rapid developments in information technology, and last but not least, considerable uncertainty about our funding. Against this background Surveys are trying to develop strategies to ensure that they continue to be relevant - and thus continue to exist! But predicting how the next few years unfold is not easy. One thing is certain however; the data and information assets that Geological Surveys hold will play a key role in the coming years. The strategies for managing, developing, and delivering those information assets are thus critical.

In early 2002 BGS agreed to a corporate Information Strategy. That Strategy contained a vision of where BGS wanted to be in 5 years time. To some the vision appeared to just motherhood and apple pie – clichéd words that seem to be the hallmark of all vision statements - but the Strategy marked a fundamental shift. BGS had accepted that it was every bit as much a professional information organisation as it was a survey and research one. And as an information organisation it aspired to operate more maturely, to innovate and develop, and to reach out and communicate.

Realising the aspirations. Operating more maturely meant taking some things rather more seriously than the Survey had done to date; for instance:

- Quality – making the accuracy (and inaccuracy !) and precision of our data clear
- Consistency – developing, agreeing and using national and international standards for the geosciences
- Managing the data responsibly – the data we hold is just as important as the new research we want to do
- Coverage – national Geological Surveys should produce national datasets (and not a collection of disparate research projects)

We agreed we would resource and accelerate research at the interface of geoscience and information technology. Thus programmes on 3/4 dimensional modelling, digital field data capture, integrated digital workflows, and web services would be given priority and moved from developmental to operational mode as quickly as possible. Crucially, in order to realise these ambitions, we agreed we would follow a corporate, consistent, asset-based approach to information management. We would strive to make more and better quality information available in digital form and improve external on-line access to it. Thus, we need to improve internal systems and workflows and invest in IT infrastructure **and** enhance our Information Systems skill base. Last but not least, we would put significantly more resource into disseminating our work and its value, to the widest possible range of users.

Nobody said it would be easy. Such a strategy faces a range of questions/obstacles, most of which will be familiar to any person working in the geoscience information arena. How will we balance the funding needed for information management and delivery against geologicalsurvey/research aims? How would we change the culture on corporate data management and raise awareness of the strategic value of data (and thus the value of holding it corporately)? We needed to change the skills mix in the organisation and in particular, identifying staff who want to be involved in data management is a monumental task. Where would we find the resources to fund the IT infrastructure in order to keep pace with data volumes and sophistication? Could we find a better way of defining what the internal and external users really want? New products are expensive to develop and then roll out – yet another demand on a static/declining budget. Do we charge for data or not (here the conflicting UK Government and European Union policy and legislation on access to Public Sector data do not help!). And if we take our new, easily accessible products into the real world (i.e., outside the geoscience circle), won't we be sued when we are in error - liability is a big potential issue when people begin to use your data for real.

Operating outside the comfort zone may be painful, but it's rarely dull…………….

This abstract is based in part on an article recently submitted to the IUGS journal "Episodes".

Merging Conceptual Insight and Secondary Indicators into the Hydrogeologic Modelling Process: Example from the Oak Ridges Moraine, southern Ontario

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Construction of 3-D 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, more important, the continuity/discontinuity of complex hydrogeologic features. Three areas where aquifer interconnection is particularly critical include bedrock valley systems, aquitard breaches, and stream-aquifer interconnection. Without geometric continuity, realistic flow patterns cannot develop within the groundwater model.

Keefer (2002) discussed the importance of adding synthetic values into the gridding process, including imaginary wells and manual (hand-drawn) contouring. Logan (2001) discusses the challenges of incorporating partially penetrating well data (push-down conditions) into the model construction process. The objective of this paper is to address these issues and report the methodology developed to blend well picks, 3-D conceptual stratigraphic understanding (expert intuition), secondary hydrogeologic indicators, and a confidence-priority based surface checking rule system.

Central to this methodology is the process of capturing expert insight and conceptual understanding by blending 3-D horizon line drawing tools with on-section picking functions. The gridding algorithm still honours each well pick, but push-down conditions, pinch-outs and other complex conditions are represented by constraining the gridding process, between boreholes, with 3-D horizon lines. The majority of the 3-D drawing is performed on cross sections that are dynamically extruded, or pushed, through the model domain. Plan view hand-drawn contours can also be incorporated, but plan view contouring is a somewhat more indirect method for constraining complex features. Extruded sections, both parallel and perpendicular to the geologic features, can be used even if the feature is sinuous.

The objective of this approach is to automate everything *but* the interpretation. Database integration, flexible visualization, efficient layer picking tools, and a conceptual understanding of the key sedimentological processes are all critical inputs to the 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 system. This process can be considered as an extrapolation process to expand between and beyond hard or reliable data points.

This approach has been used to construct a sub regional flow model of the Oak Ridges Moraine (ORM) in southern Ontario, Canada. The project began with the construction of a 5-layer MODFLOW model of the entire ORM, using the extensive stratigraphic framework and digital model surfaces developed by the Geological Survey of Canada (GSC) (Russell et al., 2002). Following the calibration of the 5-layer GSC model, the central third of the GSC study area was selected for refinement using the process outlined in this paper. The goals of the refinement from 5 to 8 layers were to better represent the deep Laurentian River bedrock valley systems, fining upwards patterns infilling sub glacial erosional valleys, and further subdivide the lower sediments within the major wellfields. Secondary data indicators, including well screen position, water levels and water found comments, were also incorporated into the refinement process.

Data. A solid database foundation (and comprehensive data model) was required for both the primary lithologic data and secondary information (well screens, water levels, etc.). A single relational database containing over 140,000 wells, 600,000 lithologic descriptions, 2 million water level readings, plus millions of surface water and climate data was assembled. The database structure was based on the Earthfx Data Model, and standardized data entry, reporting, and database validation were performed with the Sitefx Groundwater Data Management System. In addition, over 1,500 hydrogeologic reports and 2,400 large format maps and drawings were scanned. The entire database system and report library is hosted online using the VIEWLOG/Webserver product, which provides interactive maps, well logs, cross sections, and hydrographs.

Water well driller's logs form the majority of the borehole information, supplemented by high quality data from the GSC (Sharpe et al., 2003) and an additional 12,000 geotechnical boreholes. The reliability of individual MOE water well driller's logs is frequently suspect. However, as a group, the logs provide significant, yet biased, subsurface information. This bias is because most drillers are hired simply to "find water", so they frequently stop drilling as soon as they breach the top of a significant aquifer. As a result, the logs are primarily a record of aquitard materials, with only the bottom most screened sand or gravel unit representative of the significant aquifer. So, despite the apparently large number of wells, there is still limited information on the deep valley systems, and data quality is highly variable.

The success of the interpretation task was highly dependent on the *integrated, interactive* visual presentation of a large volume of data, and the efficient *capture* of the conceptual insights. Interactivity and display flexibility were critical, allowing the interpreter to view fine details and identify subtle patterns, yet continue to understand the broader context. The VIEWLOG 3D Borehole GIS software was used for all visualization; synthesis and interpretation tasks (Figure 1). The software directly connects to the relational database (Figure 1, A) to allow for dynamic filtering and queries. The software provides an integrated set of GIS mapping functions (B, F, and G), dynamic cross sectioning (C), real-time 3-D fly-through (D), and borehole data display, editing and picking functions (E).

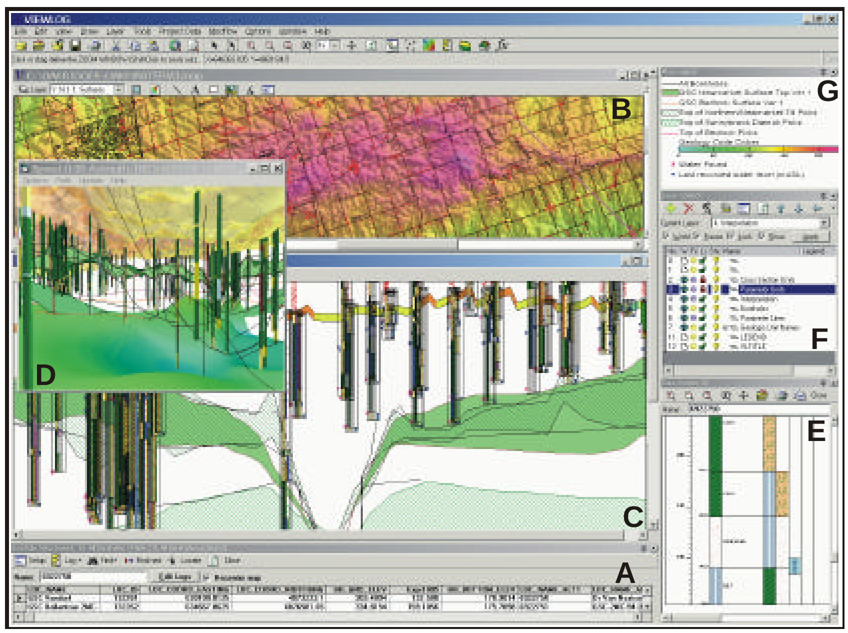

Figure 1. On-screen interpretation required the visual integration of large volumes and types of information.

A total of over 67,000 borehole unit boundary picks were made by the interpretation team. An additional 12,000 3-D polyline vertex points were made on sections that were dynamically pushed through the complex geologic features and valley systems. Polylines represent lines of hydrostratigraphic contact or plan view manual elevation contours. Well screens proved particularly valuable as an effective indicator of aquifer position. Bedrock valleys were represented as continuous aquifer systems (Figure 2). Sub-glacial tunnel channels were interpreted as breaches in the Newmarket

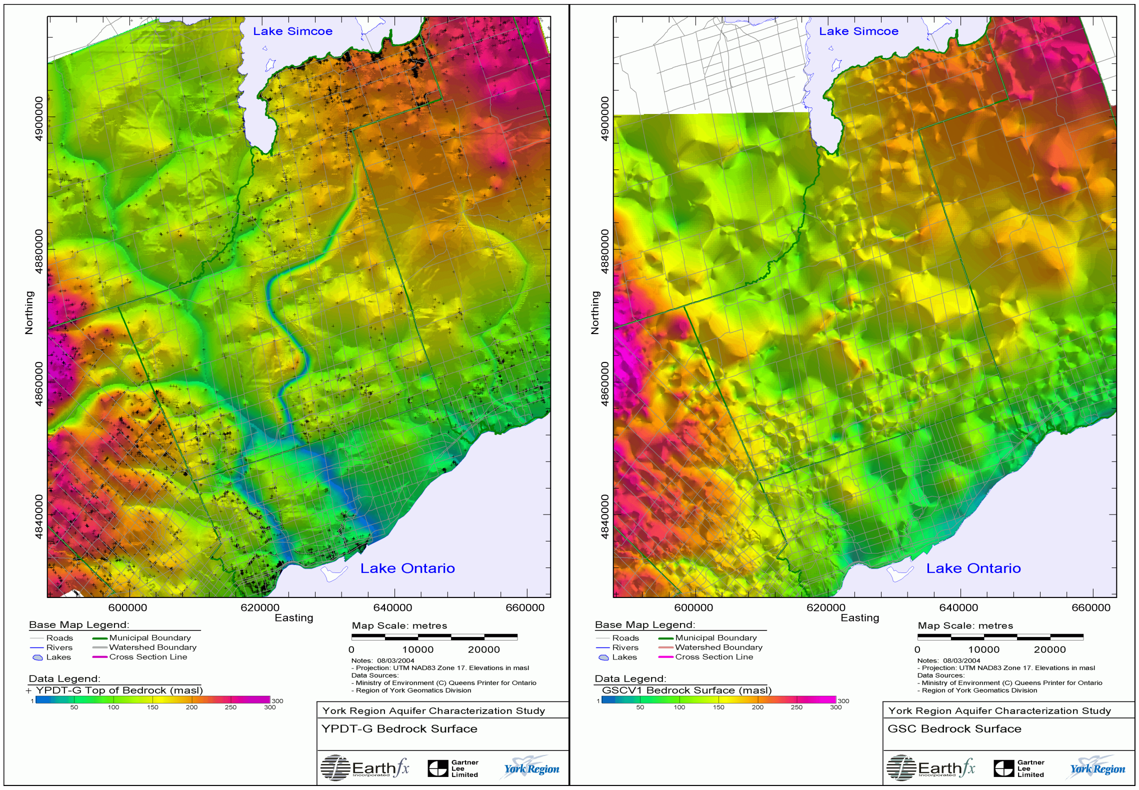

Figure 2. Comparison between constrained gridding bedrock surface (left) with the same surface gridded using kriging and push-down approach.

aquitard, yet were also modeled with an upper silt zone representative of the fining upwards sediments postulated in the GSC's conceptual models.

Results. The hydrostratigraphic units were input into a MODFLOW model covering the sub-regional ORM core model area (84 x 106 km). A cell size of 100 m was selected to represent detailed stream-aquifer interaction, and over 4,400 Strahler classified stream reaches were represented in the model. The MODFLOW model grid has 840 rows, 1,056 columns, and eight layers, for a total of approximately 7.1 million cells.

The calibrated flow model results clearly demonstrate the importance of aquifer continuity and geometry. Sensitivity analysis simulations with uniform aquifer properties demonstrate that aquifer geometry explains many of the regional water level patterns. The influence of deep bedrock valleys on the spatial distribution of groundwater discharge to streams can also been seen. Model calibration indicates that the erosional valleys or tunnel channels are not open windows interconnecting the upper and intermediate aquifer systems, but that the silt infilling in the channels is likely about one order of magnitude more permeable than the tight Newmarket Aquitard.

Conclusion/Summary. This interpretation methodology has proven effective in dealing with the complex geology and variable data quality encountered in the ORM study area. The constrained gridding process produces conceptually accurate surfaces with fewer illogical "bullseyes". Drawing in three dimensions is difficult, but the dynamic cross section approach has proven effective. Maintaining consistency between sections can be a challenge, but perpendicular tie-lines can be used. An integrated combination of plan view, cross section, and 3-D visualization tools are needed. Cross sections provide a precise "reference frame" drawing environment (Figure 3), while real-time 3-D fly-through (Figure 4) is more suited to qualitative error checking and not precise 3-D drawing.

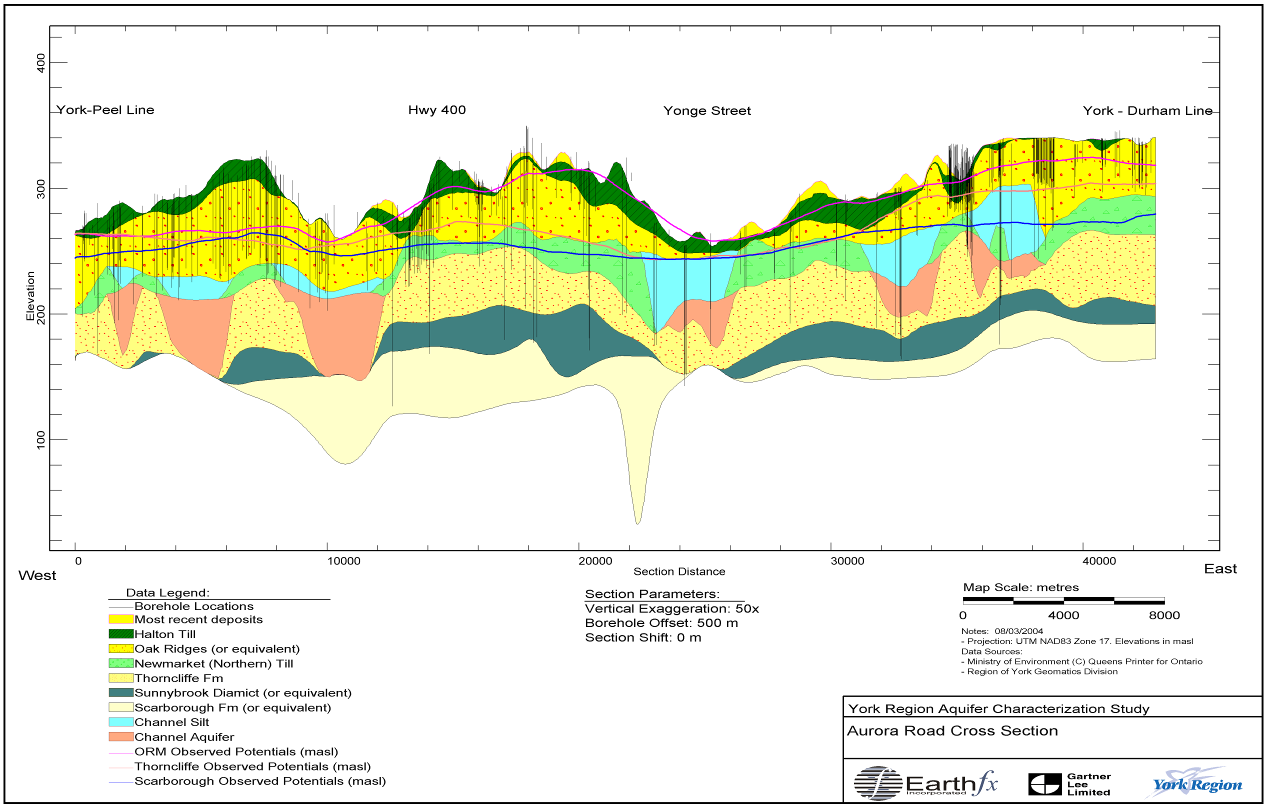

Figure 3. East-west cross section under the moraine perpendicular to tunnel channels.

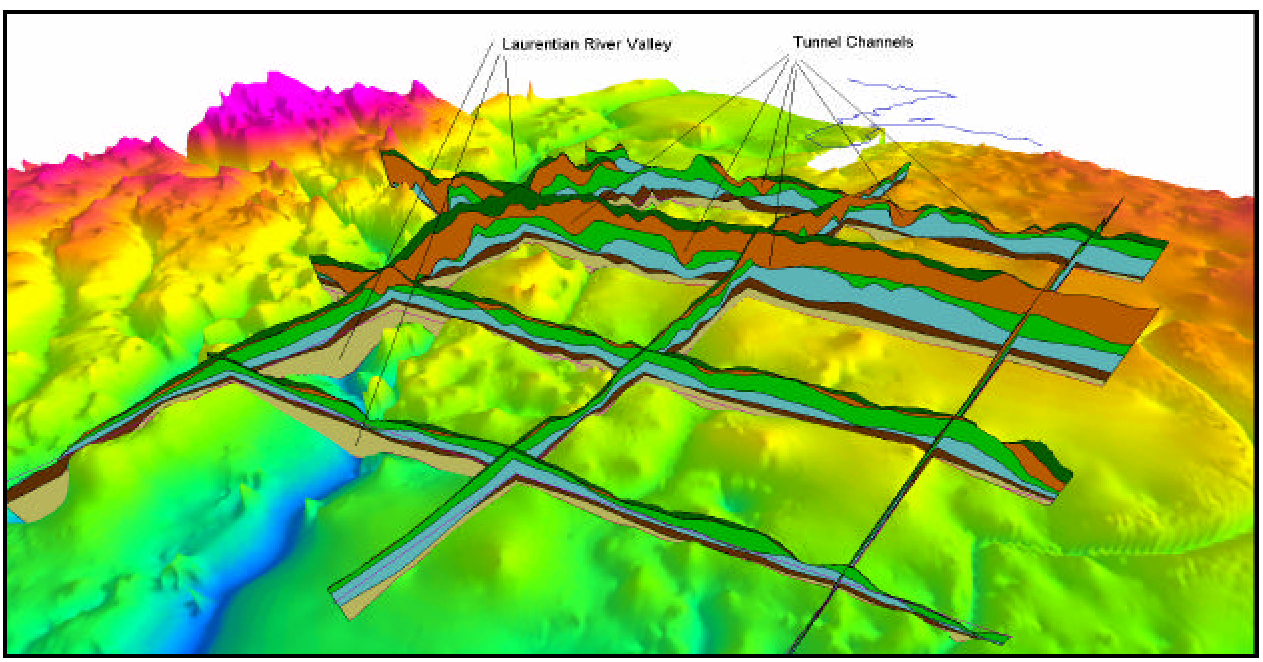

Figure 4. Bedrock surface and fence diagram of overburden layers. View from Toronto looking northwest. Width of 3-D viewport is approximately 150 km.

The methodology shows that it is possible to move beyond a simple layer-cake system, even on a regional scale. Complex larger scale features, such as the tunnel channels and infill sequences, can be accurately represented; however, good conceptual models are essential to guide the interpretation process. Data gaps (lack of deep boreholes), and data quality issues are universal problems, and our view is that constrained gridding with good conceptual models and secondary data should become the preferred model construction approach.

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Addressing Data Management Challenges in 3-D Geologic Mapping Projects

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Three-dimensional geologic mapping projects create the need to manage and interpret thousands of individual geologic unit descriptions, the resultant interpretations of deposit distributions, and a range of mapping products. To address these problems effectively, we have developed a database structure that allows for

- multiple interpretations for individual unit descriptions,
- independent selection of top and bottom surface picks,
- evaluation of data point uncertainty,
- evaluation of interpretation uncertainty,
- integration of non-observed picks,
- elimination of many data entry errors,
- effective management of data location and elevation values,
- permanent association between specific data values and all resultant mapping products, and
- effective tracking of the many decisions, products, and changes related to the data, long after the project is completed.

This database structure was designed to work with any relational database management software. Many aspects could be implemented using spreadsheet software also. The initial database design used Microsoft Access. A replicated design allowed multiple users to view and edit the data simultaneously. Local copies, or replicas, of the database were installed on each person's hard drive. A central, master copy was maintained on a server. The replicas were synchronized periodically with the master copy, and the software automatically recorded and managed changes. This paper focuses on the generic design and implementation aspects of the database structure.

One of the basic types of information in geologic mapping projects is the description of individual geologic units. The interpretations made from these descriptive units typically form the basic mappable data elements. For any given project, multiple interpretations typically are associated with each descriptive unit. There are many types of interpretations, including generalized lithologic, stratigraphic, lithogenetic, and hydrofacies interpretations. Multiple interpretations are generally needed for individual unit descriptions if more that one geologist is reviewing descriptive logs, if alternate interpretations of a unit are being considered, or if both generalized and detailed interpretations are needed within a complex sequence of deposits.

One of our primary design goals for this database structure was to ensure that the structure did not impose significant limits on how interpretations could be made or managed. To provide the necessary database flexibility, the basic structure of the interpretations was examined. We considered different classification systems in which each interpretative value was a category within a classification system. To include this information in the database, we formalized the notion of an interpretive system (classification system) composed of interpretive units (categories) (Figures 1 and 2). For example, a lithostratigraphic interpretive system for Quaternary deposits in Kane County, Illinois might contain a limited number of interpretive units, including those corresponding to

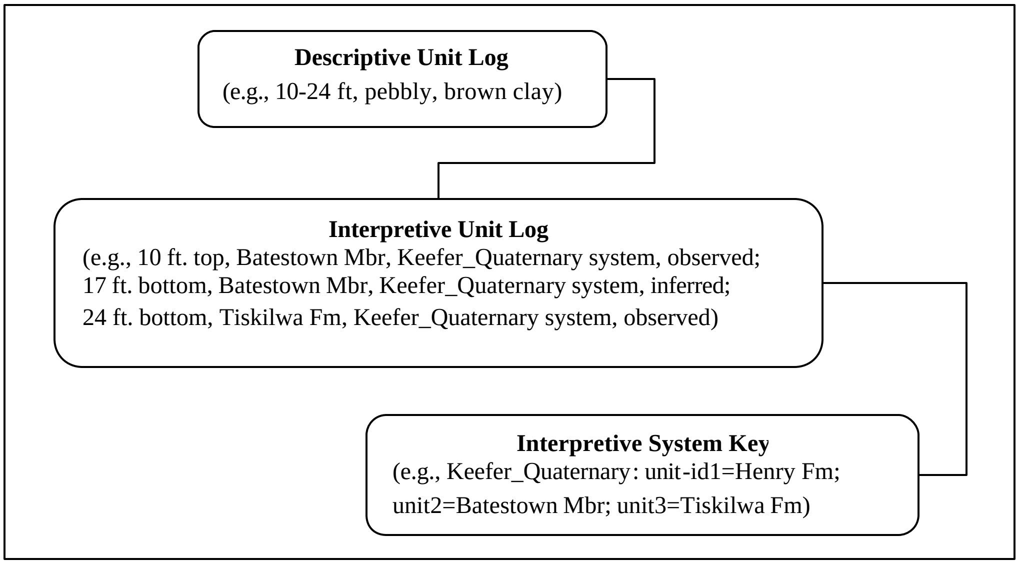

Figure 1. Schematic of relationships guiding the use of interpretive systems to define observed and inferred interpretive picks assigned to individual descriptive units.

formally defined formations, members, facies, and tongues. Flexibility of the data structure was increased by allowing each investigator to define his or her own interpretive systems and to use those systems to make interpretive picks.

To illustrate this capability, both the first and second authors could define lithostratigraphic interpretive <u>systems</u> composed of identical interpretive <u>units</u>. Because the systems are uniquely named and managed, the Tiskilwa Formation picks made using the Keefer_Quaternary interpretive system, for example, would not have to agree with Tiskilwa Formation picks made using the Davis_Quaternary system, even for the same well log. This strategy for managing interpretations allows complete flexibility

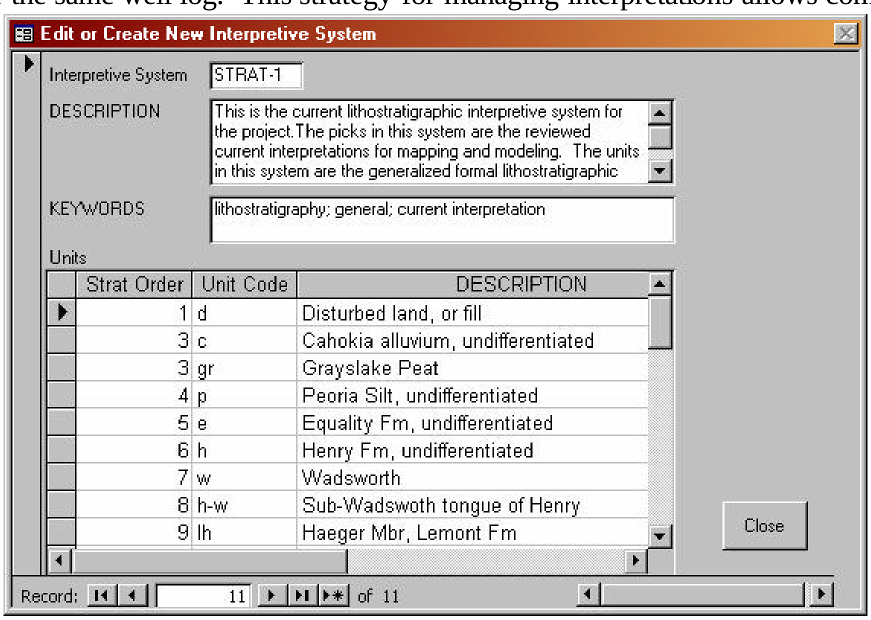

Figure 2. Form interface to the interpretive system data. This form allows editing of existing interpretive systems and units and the creation of new interpretive systems.

in both the definition of specific interpretive units within a given system and also in the number and type of interpretive systems that are defined and applied to a dataset.

Another advantage is the flexibility to allow for picks of both generalized and detailed lithostratigraphic units within a single interpretive system, for example, Keefer_Quaternary. As an illustration, this system might include the following interpretive units: Lemont_Undifferentiated, Lemont_Yorkville, Lemont_Batestown, Lemont_Yorkville_A, Lemont_Yorkville_B, and Lemont_Yorkville_C. The Lemont_Undifferentiated unit would be needed to interpret poor quality well logs that lack observed changes, or contacts, within a thick clayey sequence. Detailed controlled borehole descriptions might support delineation of the Lemont_Batestown and Lemont_Yorkville units. A well-described outcrop might also allow for delineation of the Lemont_Yorkville facies A, B, and C. Limitations in the detail that could be shown in the final map, however, might require a second, more generalized set of picks for the outcrop descriptions (i.e., the more generalized picks of the undifferentiated, Lemont_Yorkville unit.)

Two important attributes were assigned to each record in the <u>interpretive log</u>: (1) independence of top and bottom picks, and (2) recognition of observed and inferred picks. Independence of top and bottom picks is needed to address logs or outcrops where only one contact of a unit is clearly observable. The recognition of observed and inferred picks was added to accommodate sequences where two units of similar texture are adjacent and the driller's log records only one thick unit. In these situations, the inferred picks can be made based on local trends of the surface or on nearby observed contacts. For example, one descriptive log might show a change in materials at a depth of 109 feet that could be interpreted as the contact between the Yorkville and Tiskilwa diamictons (Figure 3). In this situation, the contact would be considered an observed contact. However, an alternate interpretation of this same log

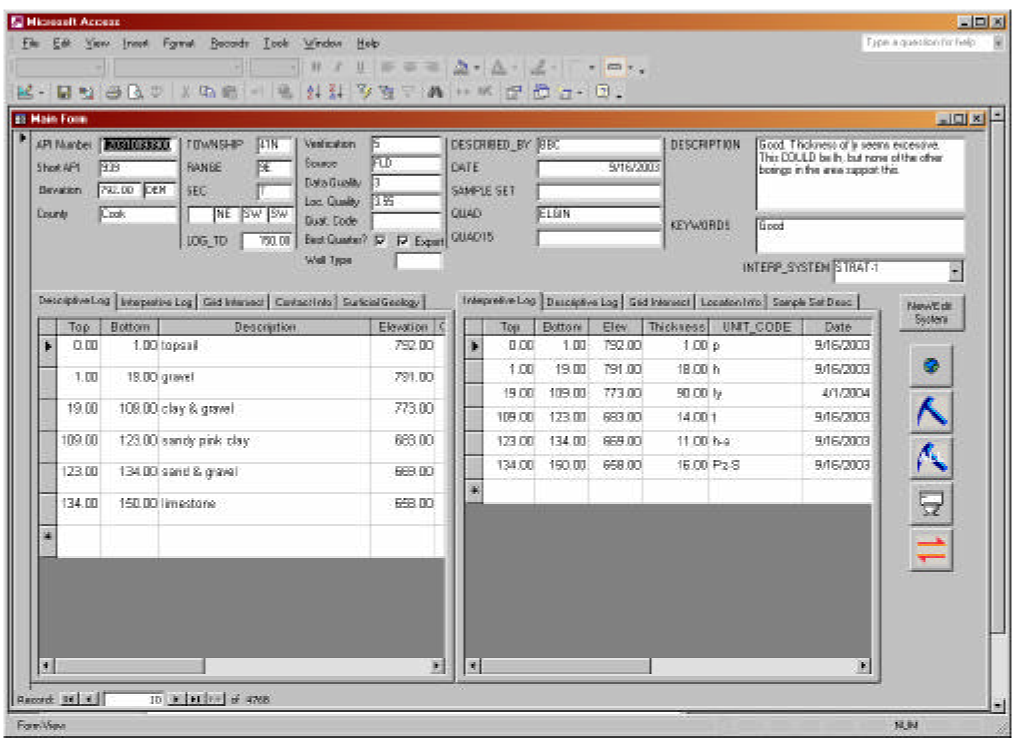

Figure 3. The main interface for working with data point header data, descriptive logs, and interpretive logs. Buttons and tabs for accessing other data forms are included. A recorded break within a continuous sequence of clayey materials is interpreted as the observed contact between two lithostratigraphic units, the Yorkville (ly) and the Tiskilwa (t) diamictons.

could have the Yorkville diamicton overlying the Batestown diamicton with the Tiskilwa diamicton occurring below. Using nearby well control, the contact between the Yorkville and Batestown in this second scenario might be inferred to be at a depth of 89 feet, and the top of the Tiskilwa might be left at the observed 109-foot depth.

Mapping efforts generally rely heavily on data of variable quality. Outcrop descriptions and water well logs tend toward opposite extremes. Evaluations of uncertainty or confidence can be expressed for the entire log or for each contact. Our data structure currently provides three fields to help express the confidence or quality of individual logs. One field is provided for describing the uncertainty of each interpretive surface pick.

Computer-assisted surface interpolation and contouring programs often make morphologically unrealistic surfaces from noisy or irregularly distributed mapping data sets. To help constrain these surface maps, it is sometimes necessary to add non-observed data points in areas where the data are sparse or particularly variable. These non-observed data, often called synthetic data, are used to ensure that resulting maps match conceptual models of the unit distributions. To manage these synthetic points, we allowed for their inclusion in the database and ensured that they were easily identifiable. The inclusion of both observed and synthetic data allows map users to understand which portions of the maps are supported by observed data and which are supported by conceptual models of the units.

To help reduce data entry errors that occur from keying errors and inconsistent terminology, the database was designed using lookup tables whenever possible.

Our experiences and with recent technological changes emphasized the importance of allowing multiple location and elevation values (Figure 4). Our system maintains location and elevation values

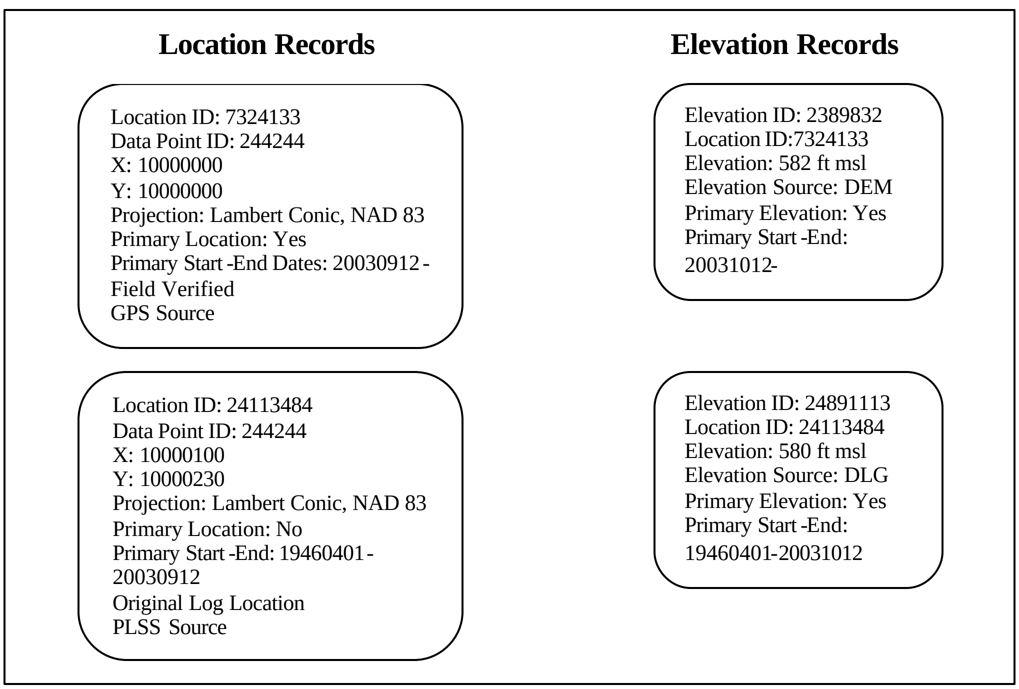

Figure 4. Example location and elevation records illustrating multiple locations per data point, the association of elevations to locations, the use of start-end dates for primary location/elevation, and the use of primary elevation flags for each location/elevation.

in their own tables. Location values are associated with individual data points via the main data point identification number. Each location record includes comments or descriptions that record the source and date of the location value. Only one location is identified as the current, primary location, and an unlimited number of alternate location values can be maintained. Time/date stamps and the primary location flag are also used to associate data location records with interpretation records and, hence, map products. Elevation values, in this data structure, are associated with specific location values, not data points directly. As with locations, the preferred elevation value is clearly identified. Alternate elevations are maintained as separate records, and information on the source, date, and additional comments are preserved (Figure 4). This system allows the management of separate locations and elevations based on different base maps (e.g., DLG vs DOQ). For example, if a data point has the location validated by DLG for one project, because the DLG is the selected base for that project, this information can be recorded. If this same datum is used on another project that uses a DOQ base map, the corrected location and elevation can be easily added and used without deleting the previous records.

The potential for large numbers of records, changing interpretations, resultant changes in the mapped distribution of deposits, and a variety of mapping products can create an information management nightmare. Time/date stamps, a separate product table, system-level user identification numbers, and multiple comment fields ensure that

- interpretations are easily associated with specific map products,
- alternate locations and elevations are permanently associated with specific interpretations and map products,
- objectives of each interpretive system are clearly defined,
- distinctions in interpretive units within each interpretive system are clearly defined,
- data uncertainties are expressed,
- datum-specific notes are recorded,
- all other data-specific concerns and documentation are managed and maintained within the database structure.

A Stratigraphic Database Approach to 3-D Modelling in the Oak Ridges Moraine Area, Southern Ontario

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The Quaternary strata of the ~11, 000 km^2 Oak Ridges Moraine (ORM) study area contain viable groundwater reservoirs for residents and industry of the highly populated greater Toronto area. Quantification of the regional hydrogeology, a goal of the ORM study, provides a basis to effectively plan for the protection and sustainable use of these valuable groundwater resources. In addition to measured hydraulic parameters, quantitative hydrogeological modelling requires a model of the 3-D stratigraphic geometry. The Quaternary stratigraphy of the ORM study area is a challenging architecture to model due to the large area, diverse geological history, and relatively sparse data coverage. Widely varying erosional and depositional regimes, ranging from highly erosional channel cutting sub-glacial outbreak floods to low-energy glaciolacustrine deposition, have formed a complex arrangement of aquifer and aquitard units (Barnett et al., 1998). For 3-D modelling, the strata were sub-divided into 5 main stratigraphic units and were defined by constructing surfaces for the following units (stratigraphically from oldest to youngest): bedrock, lower sediment, Newmarket Till, Oak Ridges Moraine and channel sediment, and Halton Till. The younger glaciolacustrine sediment and alluvium unit is fully exposed and therefore defined as the residual volume between the Halton Till surface and the topographic DEM. This document illustrates the 3-D stratigraphic model-building process developed for the ORM study.

Two similar yet contrasting methods are commonly used for producing 3-D stratigraphic models: i) the cross-section/fence diagram method and ii) the stratigraphic database method. In the cross-section/fence diagram method, swaths of boreholes in cross-sections are interpreted and stratigraphic contact lines are extrapolated. These contacts are digitized and stored spatially in section. Interpolated surfaces and volumes are then produced using a series of digital cross-sections (e.g., Alms et al., 1996; Thorleifson et al., 2002). The stratigraphic database method also involves interpreting stratigraphic contacts but, with this technique, contact depths are determined in individual boreholes with no extrapolation in between (Hughes, 1993). Stratigraphic contact depths are stored in a relational database table from which queried datasets are subsequently used to interpolate unit surfaces and derived volumes. For the ORM study, it was decided that the stratigraphic database method would be used in order to produce a regional, data-driven model free of any manually edited sub-surface extrapolations. Contact depths were determined mainly from observed/reported textural descriptions, and physical and geophysical properties in the borehole record. Spatial context was derived from nearby field observations and other sub-surface data and utilized to assist borehole interpretation.

Significant effort was required to standardize textural descriptions and integrate large numbers of borehole data from a variety of sources. New, high-quality boreholes and seismic data plus reliable archival boreholes were interpreted and coded by geologists guided by field knowledge of unit thicknesses and spatial relationships, conceptual model-based process knowledge, and stratigraphic sequence. Over 60,000 less reliable Ontario Ministry of the Environment (MOE) water wells were systematically location verified, de-clustered, and then stratigraphically coded by an automated expert system (Logan et al., in press). The automated coding was constrained by both the conceptual model and a training framework of preliminary stratigraphic surfaces interpolated from coded, high-quality data (Figure 1). MOE water wells and high-quality data were then combined to assemble datasets used to interpolate final stratigraphic surfaces. Extracted datasets were also combined with DEM-controlled, surface map unit contacts for added data support. Due to the complex geology in the ORM study area, surface mapping had a large impact on the 3-D model. The non-uniform deposition and erosion patterns that have occurred in this study area have resulted in a sedimentary basin in which portions of all

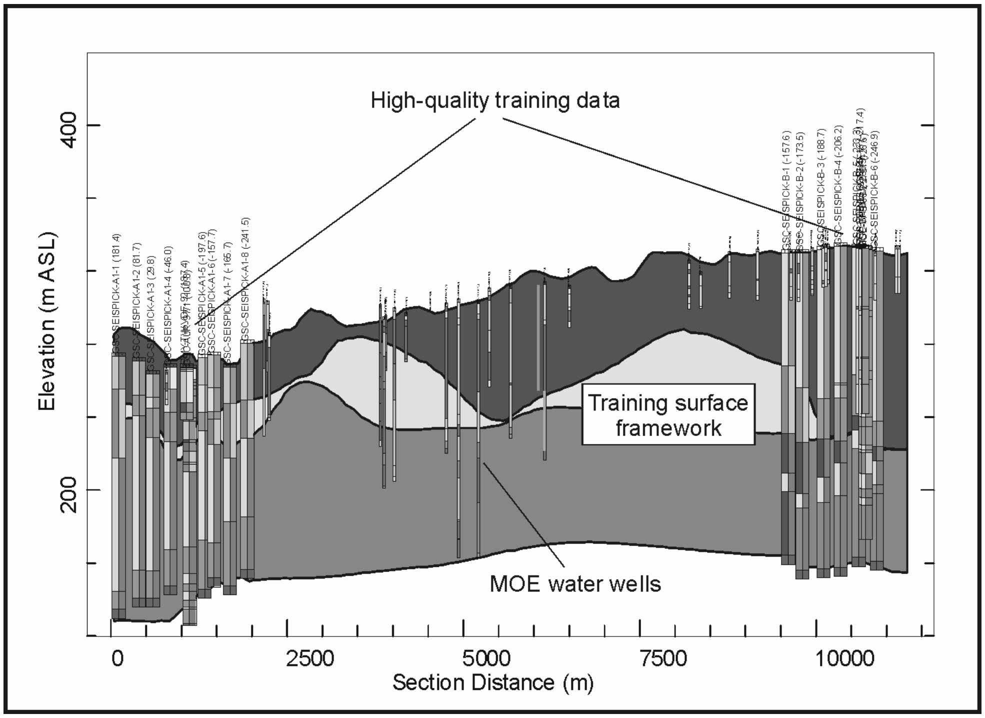

Figure 1. Training framework constructed from high-quality data is used to help constrain the automated coding of MOE water wells using an expert system.

modelled stratigraphic units are exposed to varying degrees, and thus all are partially defined by the topographic relief of mapped unit areas. These areas, representing fully exposed and observable portions of stratigraphic surfaces, were clipped from the DEM and combined with their corresponding interpolated surfaces.

The ORM study 3-D model was designed to be a regional level product that would allow a clear assessment of data quality and coverage, and also to provide a framework for more detailed hydrogeological studies. The model can be described as a geologically constrained, data-driven model, i.e., the geological understanding that forms the basis for the ORM study governs the 3-D model in a broad sense (e.g., stratigraphic unit age relationships and geological mapping controls), but the actual placement and shape of units and buried features (e.g., tunnel channels) were left to interpolations of observed contact points. The stratigraphic database derived model, while yielding an objective data-driven result, may, however, portray some unit configurations and relationships unrealistically due to deficiencies in data coverage. For example in the ORM study, sparse data often result in sub-linear trends of thin or absent Newmarket Till that may indicate the course of buried channels. These potential channel candidates are likely more connected and less undulating than the current 3-D model would suggest based on the shape of exposed channels found in the northern Newmarket Till uplands (Figure 2). Where user requirements dictate, the geometry of selected channel candidates can be subsequently altered to appear more realistic by adding extrapolated control lines based on more detailed geological investigation and/or additional new data (Kassenaar et al., this volume). The revised model can then be used to produce a quantitative flow-modelling scenario.

A useful aspect of the stratigraphic database is the ease by which it is updated and queried for surface interpolations. New data, data coding corrections, or conceptual model-based rule changes are easily integrated for re-modelling, enabling controlled experimentation and iterative model checking (Logan et al., in press). Numerous, unpublished model iterations have been produced, and version 1 of

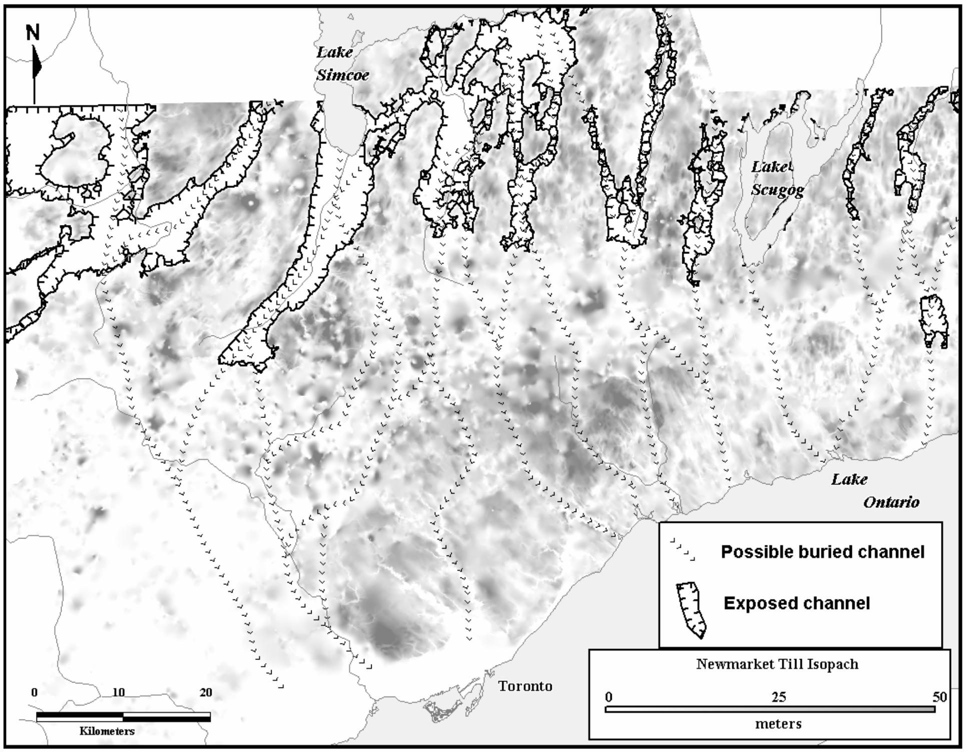

Figure 2. Linear trends of thin or missing Newmarket Till may indicate buried channels.

the ORM study 3-D model has been released (Logan et al., 2002). With the addition of ~5,000 water wells, 181 high-quality boreholes and ~13 km of seismic profile data as well as some data corrections and expert system coding refinements, release of version 2 is planned in 2004.

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Geologic Framework of Two Contrasting Nearshore Areas of Michigan, and New Hypotheses for Relationships Among Geology, Ground-water Flow, Water Quality, and Ecology

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Introduction. Development of 3-D geologic models for the Great Lakes is necessary to improve understanding of ground-water flow regimes and their effects on nearshore water quality and ecology (Haack et al, unpub. data). Improved understanding of the hydrogeologic framework is needed to address the significance of ground water to the Great Lakes (Grannemann et al, 2000) and their water balance (Neff and Killian, 2003). Such research needs to include development and testing of geologic models (Sharpe et al, 2002) that help predict variability of hydrogeologic properties within and linkage between Quaternary sediments and bedrock. Here we discuss the hydrogeologic settings and salient information gaps for two contrasting areas of Michigan, and we offer new hypotheses about geologic controls on the ground-water flow system, water quality, and ecology of the nearshore environment of the Great Lakes. The two areas are Monroe County along Lake Erie in southeastern Michigan, and the Grand Traverse Bay region along Lake Michigan in the northwestern Lower Peninsula (Figure 1). The Quaternary geology and geomorphology of the two areas differ markedly. Monroe County is characterized by low relief and has relatively thin sediments of low permeability (Mozola, 1970; Reeves et al, 2004). In contrast, the Grand Traverse Bay region has relatively high relief glacial geomorphology (Lundstrom et al, 2003) formed by thick glacial sediments of generally high permeability.

Methods. The data and methods that we used were not uniform within the two study areas, nor between them. The data and methods used reflect the varying availability of data, the natural settings, societal infrastructure, and project objectives for the two areas. Water-well data (drillers logs from the Michigan Department of Environmental Quality, 2003) were available for both areas, though the concentration and quality of data are spatially variable. The depth and altitude for the top of bedrock is better constrained in Monroe County because most water wells there penetrate relatively thin Quaternary sediments of low permeability to obtain water supplies from bedrock. In contrast, most wells in the Grand Traverse region obtain water within Quaternary aquifers and do not reach bedrock. For this area, we used available oil and gas well logs to constrain Quaternary sediment thickness and bedrock geology. Monroe County coastal sites comprise the pilot study area of the USGS Great Lakes nearshore integrated science group. In the first year of this pilot study, we obtained preliminary results on nearshore hydrology (particularly hydraulic potential), water quality, biology, and geologic setting of two sites along Lake Erie to investigate the effects of quarry dewatering (Haack et al, unpub. data). Results from the Grand Traverse Bay region mainly reflect new surficial geologic mapping during the past year (Lundstrom et al, 2003), as part of the Central Great Lakes Geologic Mapping Coalition effort (Berg et al, 2000). As part of this work, exposures (mostly at gravel pits) were examined during field reconnaissance of the landscape to help characterize map units. Contacts and drumlin long axes were located using GSMCAD (Williams, 2003) on 65 1:24,000 7.5-minute topographic quadrangles that cover the area, supplemented by use of a PG-2 plotter for analysis of aerial photographs. We combined available DEM data (10 meter data for most of the nearshore area and 30 meter data for some of the inland area) with bathymetric data for Lake Michigan (Holcombe et al, 1996).

Monroe County. The geologic framework of the county mostly consists of clay-rich Quaternary sediments that overlie the subcropping bedrock aquifer comprised of a gently northwest-dipping Silurian and Devonian sequence of predominantly carbonate rocks (Figures 1 and 2). Northeast-trending bands of subcropping bedrock that decrease in age northwestward are the result of preglacial and subglacial

Figure 1.

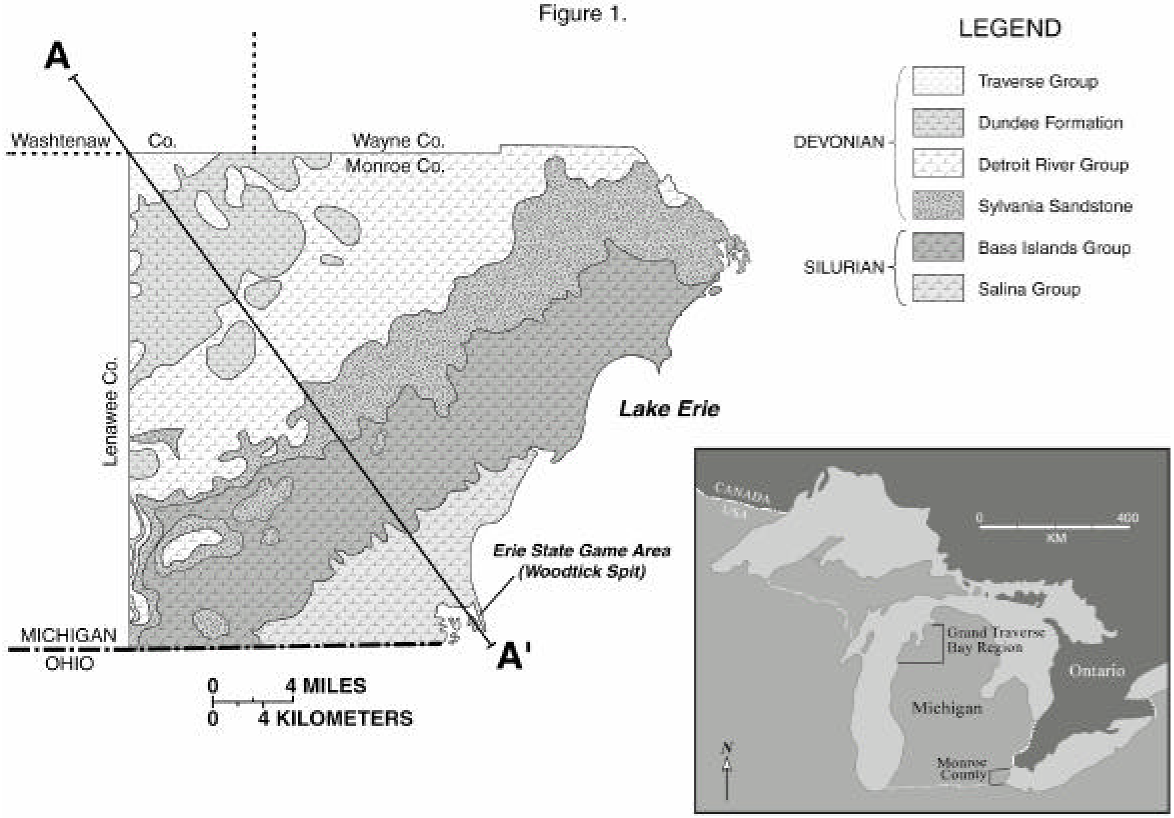

Figure 2a.

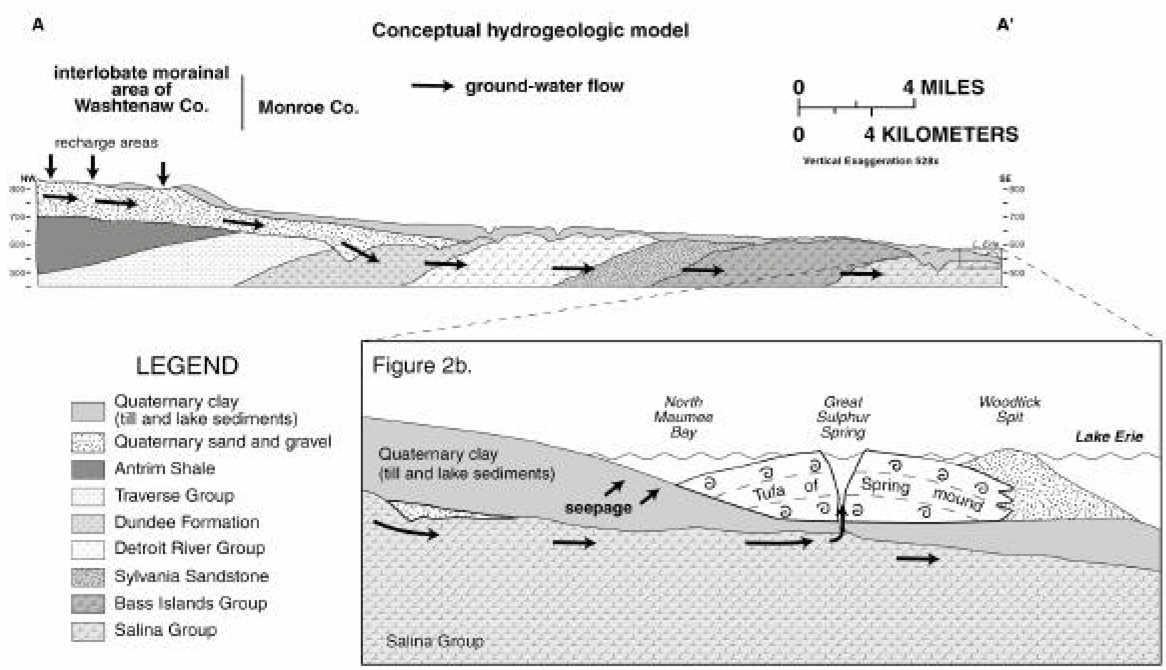

Figure 1. Bedrock geologic map of Monroe County (Quaternary sediment cover not shown).
Figure 2a. Hydrogeologic cross section showing hypothesized ground-water flow.
Figure 2b. Inset of geomorphic and hypothesized stratigraphic relations of the nearshore zone of Erie State Game Area.

erosion superimposed on strata that dip gently northwest toward the center of the Michigan Basin (Dorr and Eschman, 1970). The subcropping stratigraphic sequence includes the Silurian Salina and Bass Islands Groups, and the Devonian Detroit River Group, Dundee Limestone, and Traverse Group. In this area, these strata are predominantly carbonates and dolomites, interbedded with less extensive evaporitic shales and sandstone. Northwestward, toward the depocenter of the Michigan Basin, some of the dolomitic strata of the Salina and Detroit River Groups grade to thick evaporite deposits (Landes, 1945). The carbonates and evaporitic rock types are subject to dissolution by groundwater. In similar settings elsewhere along the margin of the Michigan Basin, as in Macomb and St. Clair Counties and in the Mackinac Straits region, stratigraphic and structural relations indicate dissolution of the Salina Group. The overlying Traverse Group and Dundee Limestone also have formed karst features in northeast Michigan (Dorr and Eschman, 1970). In western Monroe County, sinkhole morphology is probable evidence of active dissolution of Silurian and Devonian carbonate aquifers in postglacial time. North and west of Monroe County, these carbonate strata are overlain by relatively impermeable shales of Devonian and Mississippian age, including the Antrim, Bedford, and Coldwater Shales. (Figures 1 and 2) Just west of the coastal Erie State Game Area (ESGA), water-well records indicate an aligned set of closed depressions in the bedrock topography that is not reflected in the surface topography. The bedrock topography buried by Quaternary sediments may indicate a collapsed karstic passage that transmits ground water toward the Erie State Game Area.

Quaternary sediments of Monroe County form a low-relief plain. Hydrogeologic investigations (Mozola, 1970; Nicholas et al, 1996; Reeves et al, 2004) and water-well records (Michigan Department of Environmental Quality, 2003) indicate that most of the Quaternary deposits are fine-grained, clay-rich material that include glacial till and glaciolacustrine sediment. These low-permeability sediments act as confining beds to ground-water flow between the underlying bedrock aquifers and the surface. For most of the county, Quaternary sediment thickness ranges from about 3-17 m. However, in the northwest corner of the county, a thickness of up to 50 m is transitional to a greater thickness of Quaternary sediment in adjoining parts of Lenawee and Washtenaw Counties. These relatively thick sediments are associated with an interlobate moraine belt that includes the Defiance and Fort Wayne moraines (Dorr and Eschman, 1970). Though clay-rich till also covers the surface of portions of these moraines, glaciofluvial sand and gravel underlie the clay-rich surfaces of the moraines. The sand and gravel may form permeable surficial recharge areas northwest of Monroe County. However, the extent of these recharge areas is unknown (Reeves et al, 2004). (Regionally, the bedrock aquifer is thought to be recharged predominantly in south-central Ohio and Indiana. From the recharge area, ground water moves northward until it meets saline water in the Michigan Basin and then discharges either to surface-water in Indiana and northern Ohio or to Lake Erie (Bugliosi, 1999)). The sand-and-gravel units continue under surficial clay units and are contiguous with confined aquifers in northwestern Monroe County. Additional hydrogeologically-isolated belts of sand-rich surficial sediments occur in portions of Monroe County; these sediments are mainly beach and nearshore deposits of prehistoric high-lake levels during late glacial and postglacial time. At the Erie State Game Area, a prominent coastal spit, the Woodtick Peninsula (Spit), formed during the late Holocene. The spit forms a barrier that protects a coastal marsh area on its west side. In the center of the marsh, emergent land surrounds a major natural spring, the Great Sulphur Spring (Figure 2b). The rim of the pond and the emergent land around the spring is a tufa composed of calcareous cemented floral and faunal remains that presently thrive in the spring-pond. The water chemistry of the spring indicates that it discharges from the subcropping Silurian bedrock aquifer of the Salina Group (Haack et al, unpub. data). The Salina carbonates are part of an aquifer that is contiguous in an upflow direction (Nicholas et al, 1996) with similar, overlying Silurian/Devonian strata.

Grand Traverse Bay region. In contrast to Monroe County, the six-county region around Grand Traverse Bay (GTB) of northern Lake Michigan is characterized by greater topographic relief and greater permeability, thickness, and complexity of the Quaternary sediments, which include common glaciofluvial and deltaic sand and gravel instead of the clay-rich sediments of Monroe County. Within 10 to 40 km of the GTB coastline, the landscape is characterized by an anastomosed network of large subglacial (tunnel) valleys (Figure 3) which are incised into drumlinized uplands composed of loamy till

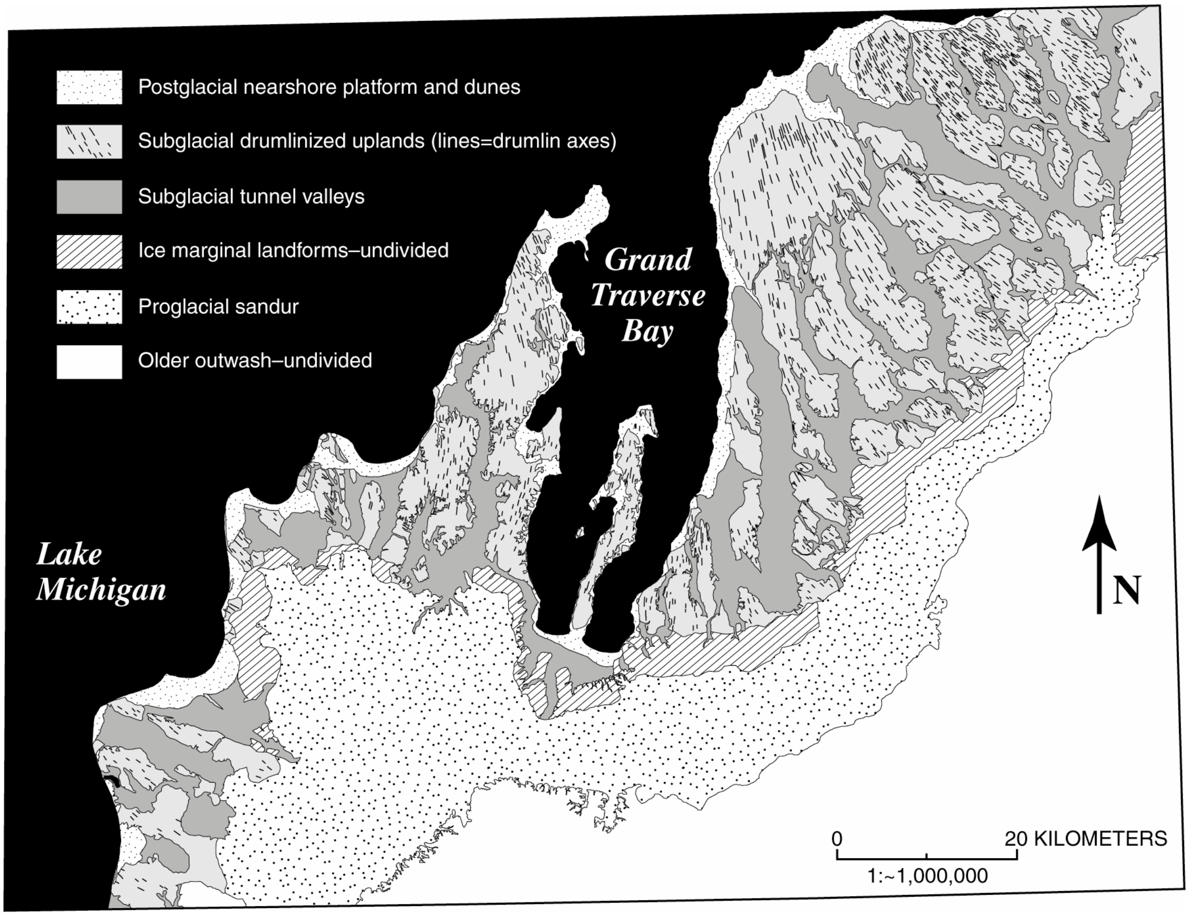

Figure 3. Glacial geomorphic map of the Grand Traverse Bay region (simplified from Lundstrom et al, 2003).

over bedded sand and gravel. Locally, the tunnel valleys are partially occupied by deep inland lakes and extensive wetlands that include groundwater discharge areas. The tunnel valleys also occur offshore to form prominent bathymetric features of northern Lake Michigan, including the arms of Grand Traverse Bay. The bedrock of this area is somewhat similar to that of southeastern Michigan, including a sequence of Devonian limestone, the Traverse Group, which is locally exposed in the coastal regions of Charlevoix and Antrim Counties. The limestones dip southeastward away from the coast and toward the Michigan Basin depocenter. The Traverse Group is overlain by younger impermeable shales (Antrim, Ellsworth, Sunbury, Coldwater), where they occur southeastward of their erosional limit beneath Quaternary sediments. Southeastward from the coast, surface elevations rise to more than 250 m above Lake Michigan and Quaternary sediment thickness increases to greater than 200 m. In these high areas, extensive glaciofluvial sand-and-gravel aquifers (sandur, outwash, Figure 3) are at the surface just beyond the southern limit of the tunnel valleys and other subglacial terrain. Similar to their prominent expression in surface topography, tunnel valleys are also incised into bedrock, especially where the bedrock surface occurs beneath relatively thin Quaternary deposits near the coast. Bathymetry of Grand Traverse Bay and of deep linear lakes necessitates that tunnel valleys have been locally eroded below the base of the impermeable bedrock shales and into the underlying carbonate aquifers of the Traverse Group. However, the thickness and stratigraphy of Quaternary sediments under these water bodies is largely unknown. Landward, the nature of bedrock topography beneath tunnel valleys is less well constrained than near the coast, but a transect of drillholes in southern Charlevoix County provides evidence for coincident bedrock valleys and surficial tunnel valleys. The lithology and hydrogeologic properties of Quaternary sediments of the tunnel valleys is not characterized at depth, but surficial exposures indicate a wide variety of sediments: glacial sand and gravel of high permeability, melt-out till of low permeability, and postglacial alluvium, organic deposits, marl and other lacustrine sediments. Tunnel valleys include extensive areas of ground-water discharge to wetlands, lakes, rivers, and coastal embayments, as well as permeable Quaternary sediments that affect ground-water flow from upland recharge areas toward Lake Michigan. Geologic drilling and geophysical investigations are needed to characterize these features. Because the geologic expression of tunnel valleys was not considered by Boutt et al (2001), their modeled groundwater flux for the Grand Traverse Bay region could have been significantly underestimated. The Finger Lakes of central New York State are somewhat similar to the tunnel valleys of the GTB region. Seismic reflection studies (Mullins and Eyles, 1996) have shown thick Quaternary sediment fills beneath the elongate Finger Lakes, and the basal sediment typically includes permeable sand and gravel that form aquifers.

Hypotheses. In Monroe County, biogenic tufa formation by nearshore ecosystems dependent on large, sustained regional ground-water discharge from a karstic bedrock aquifer has resulted in deposition of a large spring mound at Erie State Game Area (Figure 2b). Groundwater discharge and tufa mound formation are linked to rising lake levels of Lake Erie during late Holocene time. The east flank of the spring mound forms a shoal against which longshore drift and sedimentation has formed the spit of the Woodtick Peninsula. The spit probably has accreted vertically and perhaps laterally during spring mound growth and rising lake level. The spring area may be localized where a buried karstic bedrock valley intersects and/or has developed within a more permeable or thin window through the Quaternary sediments and into the nearshore zone of western Lake Erie.

Because recharge of groundwater into bedrock aquifers through the confining beds of Quaternary sediments in Monroe County is very limited, sufficient recharge to balance discharge in the nearshore region would probably require recharge outside of Monroe County as suggested by Bugliosi (1999) and as shown in Figure 2a. The chemistry of the discharging spring water also indicates a remote water source. For the moraine belts to supply recharge, lateral flow of ground water southeastward above the confining beds of Devonian and Mississipian shales and below confining beds of Quaternary tills is required to recharge Silurian and Devonian carbonate bedrock aquifers beyond the subcropping erosional limit of the bedrock shales.

Ground-water discharge in nearshore environments of the Grand Traverse Bay region is also significant to water quality and aquatic ecology, but the effects are different than those in Monroe County and are largely affected by the different glacial geology of this region. Here, the calcium bicarbonate dominated water chemistry is probably controlled by the abundance of regionally derived Paleozoic limestone clasts in the glaciofluvial aquifers. The chemistry of discharging ground water favors biogenic carbonate precipitation, which commonly occurs in rivers, wetlands, and nearshore settings, thus forming additional varied and unique substrates and integral ecosystem components. Most streams are groundwater-fed and provide habitat for cold-water fish assemblages, including trout species. There are several factors that make it likely that the magnitude of ground-water recharge in northern Michigan and resulting ground-water flux toward the nearshore setting of the Grand Traverse region should be significantly greater than in southeast Michigan. These factors include cooler climate, greater lake-effect snowfall, greater effective moisture, larger hydraulic gradients, and more permeable sediments favoring greater infiltration and flow.

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Investigating the Characteristics and Three-Dimensional Distribution of Quaternary Sediments Infilling Parts of the Dundas Valley, Hamilton, Ontario

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Introduction. Southern Ontario is underlain by an eroded Paleozoic bedrock surface dissected by numerous bedrock valleys. These valleys are infilled with variable thicknesses of Quaternary sediment that record paleoenvironmental change during the Late Quaternary and also host productive aquifers. The Dundas Valley of the Hamilton-Wentworth region forms a prominent west-east re-entrant in the Niagara Escarpment extending from Copetown in the west to Lake Ontario in the east. The modern valley is underlain by a buried bedrock valley estimated to be infilled with up to 180m of Quaternary sediment including glacial, lacustrine, and fluvial deposits. There are few exposures through these valley infill deposits and their subsurface characteristics and distribution are poorly understood.

The Dundas Valley underlies a densely populated and heavily urbanized region and there are serious concerns with regard to contamination of groundwater from a number of sources including industrial and municipal waste disposal sites and buried storage tanks. Groundwater from aquifers in the Dundas Valley supply surface water bodies such as Cootes Paradise and Hamilton Harbour (Figure 1); the harbour is identified as one of 43 Areas of Concern (AOC's) in the Great Lakes region. This study focuses on a small area within the Dundas Valley that forms part of the McMaster University campus (Figure 1). This area was selected because of the availability of subsurface data and the need to understand sediment characteristics and aquifer geometries below the campus which hosts a nuclear reactor and lies close to a severely contaminated industrial site.

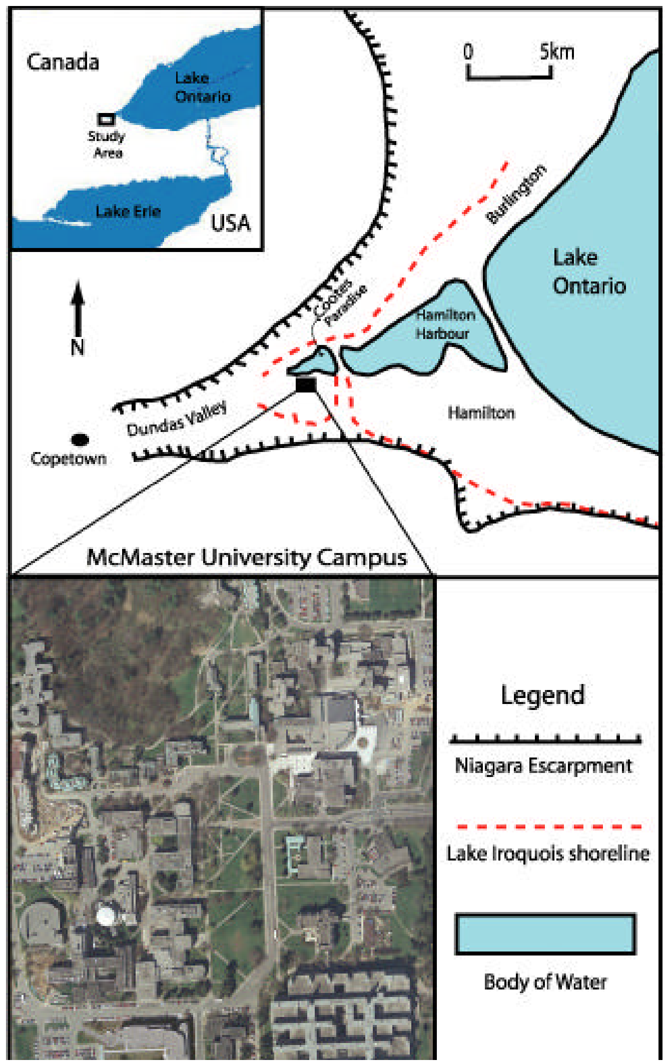

Figure 1. Location of the McMaster University campus and Dundas Valley in Southern Ontario. Air photo from City of Hamilton, GIS Services.

Regional glacial stratigraphy. Although the Quaternary sediment infill of the Dundas Valley is very poorly understood, regional stratigraphic studies (Karrow, 1987) suggest that it may contain pre-

Wisconsin deposits in the deepest parts, overlain by thick glacial and glaciolacustrine deposits that record ice margin fluctuations and changing environmental conditions during the Wisconsin. Near surface deposits in the lower part of the valley record the formation and drainage of Lake Iroquois, a high level (45m above present lake level) post-glacial lake that formed in the Ontario basin, and the development of extensive bay mouth bars that isolated Cootes Paradise and Hamilton Harbour from the open lake (Figure 1). Post-glacial fluvial deposits also form a surficial cover in parts of the valley (Karrow, 1987).

Methodology. This study utilizes subsurface data available from construction reports, waterwell and borehole records to create a series of images showing the three-dimensional subsurface geology of the McMaster University campus and adjacent areas of the Westdale Terrace (Figures 1, 2, and 3). The

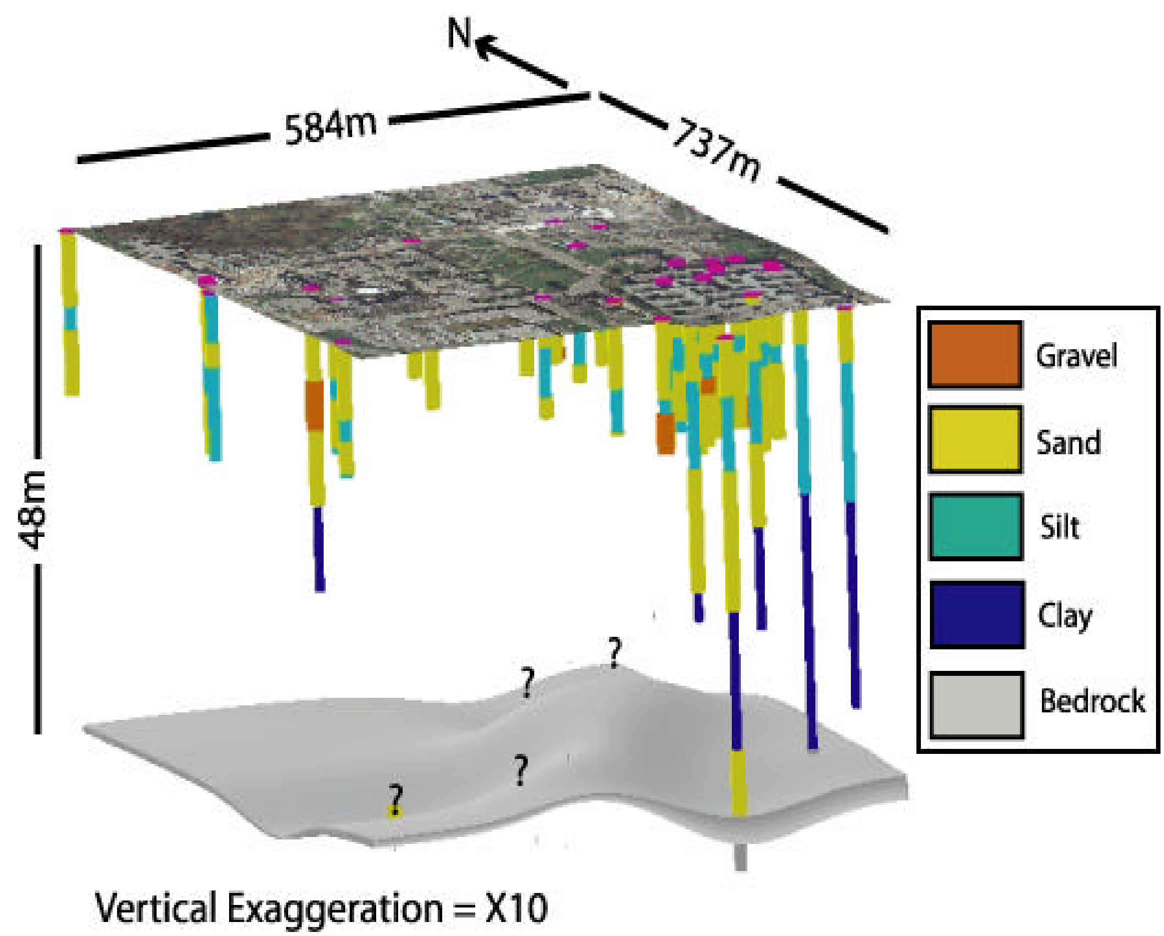

Figure 2. Three-dimensional borehole plot of the McMaster campus showing borehole locations and stratigraphy. "?" shows the position of 4 wells with bedrock elevation data only (data from Karrow, 1964).

original borehole and construction reports were of variable quality and data from several boreholes were eliminated because their descriptions did not correlate well with adjacent wells or they were too shallow. Forty-three boreholes were used to map the subsurface geology of the 0.43km^2 area (Figure 2). Unfortunately, only 6 of these boreholes penetrated bedrock, 4 of which were reported on a local bedrock topography map (Karrow, 1964). Borehole locations were established using a georeferenced digital topographic map of the campus area and subsurface stratigraphic units were identified through careful lithologic correlation between boreholes; many closed sections were constructed to check the accuracy of correlations between individual stratigraphic units. Data were entered into an excel spreadsheet and reformatted for entry into RockWorks2002 software which created borehole correlations, fence diagrams, and a 3-D block diagram, shown with individual sediment horizons vertically separated in Figure 3.

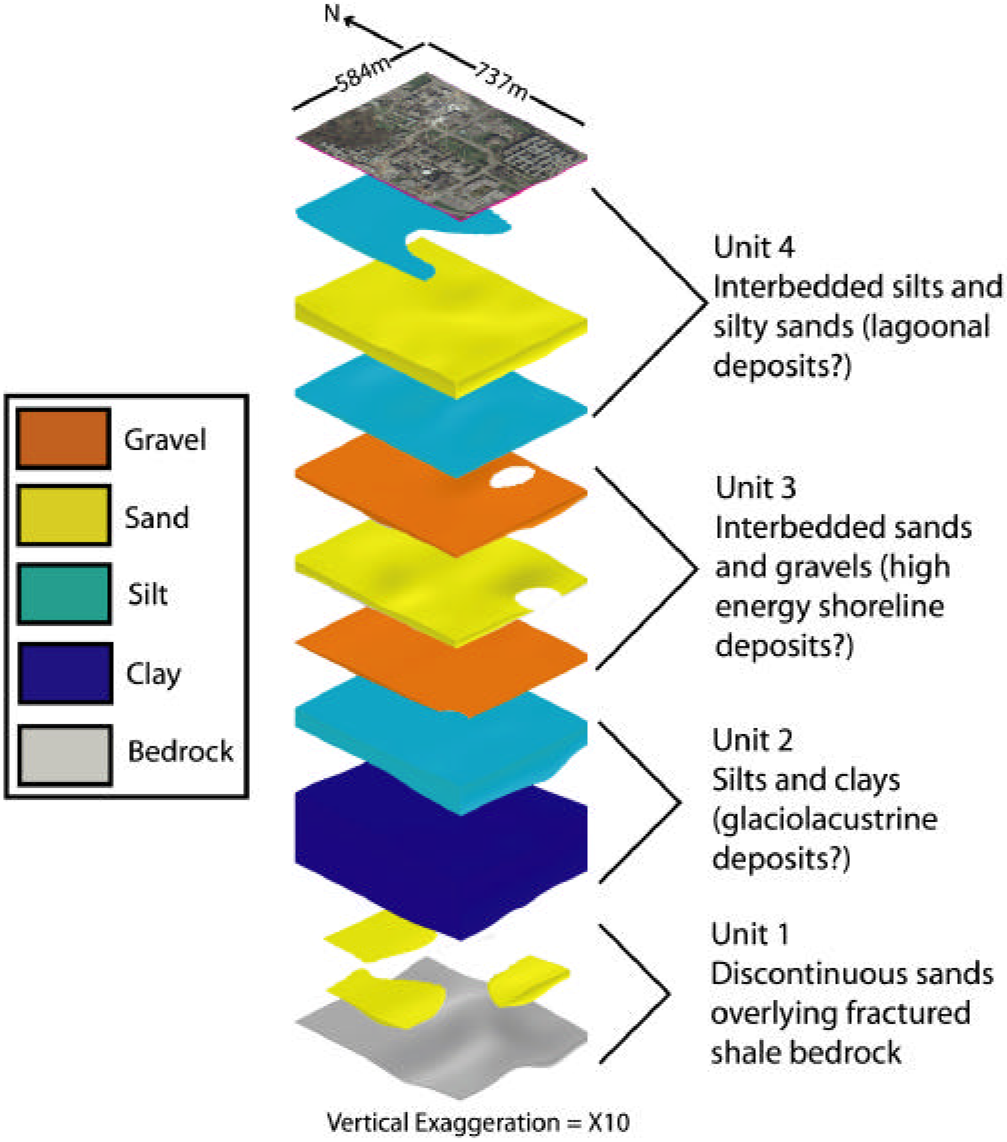

Figure 3. Three-dimensional stratigraphy of the McMaster University campus illustrated as stacked individual sediment horizons. Individual horizons have been grouped into units with similar lithological and permeability characteristics (Units 1-4). Unit 3 forms a significant aquifer below campus.

<u>**Subsurface stratigraphy and depositional environments**</u>**.** Bedrock lies at a depth of between 40 and 50m below the McMaster campus and consists of fine-grained red and grey shales of the Queenston Formation. Bedrock topography is poorly constrained due to the paucity of deep boreholes, but has at least 12m of relief and probably slopes northward into deeper parts of the Dundas Valley (Figure 2). The erosional topography on the bedrock surface was likely created by a combination of both fluvial and glacial processes (Edgecombe, 1999).

Unit 1: Sediments immediately overlying bedrock include discontinuous sands (Unit 1) overlain by clays and silty clays (Unit 2, Figure 3). The sands are silt-rich and contain occasional gravels or red shale clasts and, together with fractured shale on the upper bedrock surface, may form a localized aquifer. These sands probably originated as fluvial deposits.

Unit 2: Grey silty clays overlie either bedrock or sands of Unit 1 and form an 11 to 23m thick unit that contains scattered clasts and occasional pockets of silty, coarse sand. Silty clays are overlain by grey clayey silts (Figure 3) and, together with underlying clays, form an extensive lower aquitard. Lower silts and clays record either glaciolacustrine depositional conditions or subglacial reworking of previously deposited lacustrine sediments. These deposits may have formed during the final stages of late Wisconsin glacial occupation of the Lake Ontario basin or during the early stages of development of postglacial Lake Iroquois approximately 12,000 y.b.p.

Unit 3: Fine-grained deposits of Unit 2 are overlain by a distinctive unit of sands and gravels that forms a continuous aquifer beneath the campus (Unit 3, Figure 3). This 4.5 to 6m thick unit consists of interbedded gravels and fine to medium grained sands; gravels have sharp basal contacts and appear to fill broad channels cut into underlying silts or sands. These coarse-grained sediments formed under relatively high energy conditions, and were probably associated with shoreline environments of post-glacial Lake Iroquois or fluvial systems feeding into the lake.

Unit 4: The uppermost sedimentary unit mapped below the McMaster campus is approximately 8m thick and consists of interbedded silts and silty sands with occasional clay layers (Unit 4, Figure 3); silts tend to become finer-grained and more clay-rich toward the north (towards Cootes Paradise). These deposits probably record deposition in low energy lagoonal environments created at the western end of Lake Iroquois by the growth of shoreline bars.

This study, although restricted in extent, provides preliminary data on the sedimentary infill of part of the Dundas Valley and may be used in the initial development of a three-dimensional stratigraphic model of the broader Dundas Valley. Better understanding of the sedimentary infill of the valley allows more accurate reconstructions of late Quaternary paleoenvironmental change in the region and the identification and delineation of major aquifers and aquitards.

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Three-dimensional Geological Mapping and Groundwater Flow Modeling in the City of Pickering, Ontario; Application to Urban Environmental Issues

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Deposition of glacial sediments during the last glaciation between 70,000 and 12,000 years ago left a complex aquifer system in south central Ontario. The heterogeneous nature of subsurface geology along with sporadic and site-specific research in hydrogeology has resulted in limited understanding of regional groundwater flow. The objective of this study was to develop an improved understanding of the geology and hydrogeology of 340 km^2 of a rapidly urbanizing watershed in the City of Pickering, Ontario Figure 1).

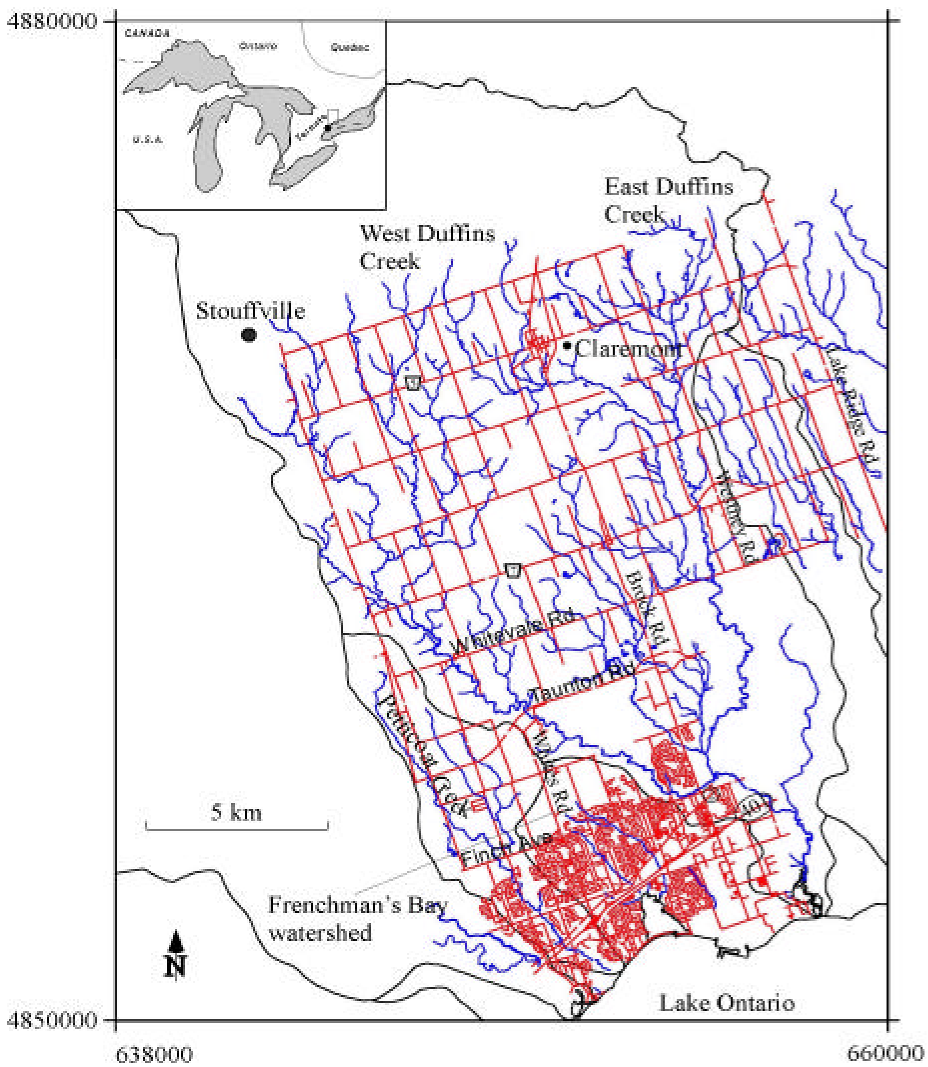

Figure 1. Map of Study area showing location of the Frenchman's Bay, Duffins Creek and Petticoat Creek drainage basins.

Geologic information from 260 cored boreholes was supplemented with more than 3,400 water well records and used to develop a three-dimensional (3-D) conceptual model representing the hydrostratigraphy and groundwater flow patterns in the Frenchman's Bay, Duffins Creek, and Petticoat Creek watersheds (Figure 2). The 3-D hydrostratigraphic model was developed through a GIS query

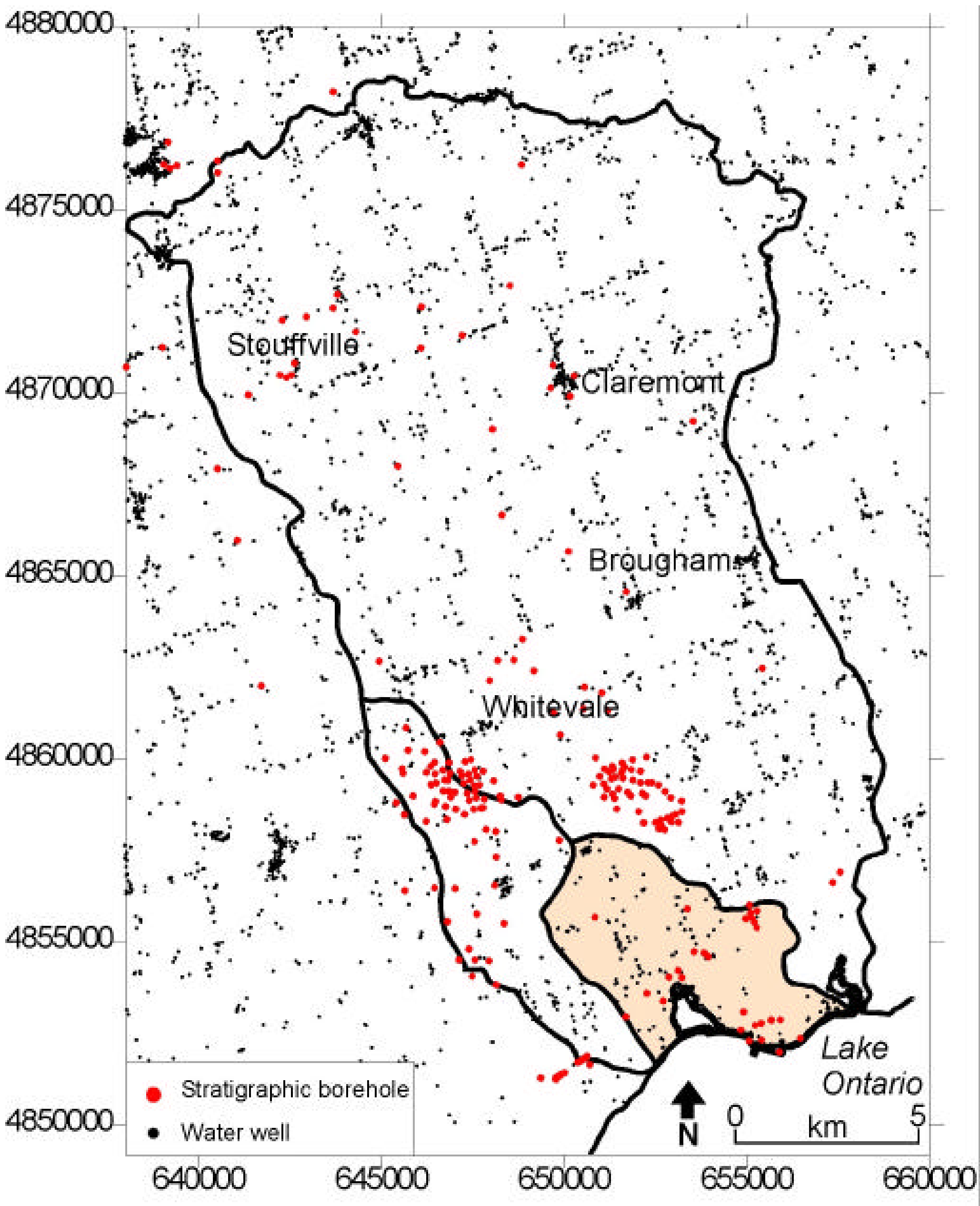

Figure 2. Distribution of boreholes in Study area.

of water well data and contoured geologic surfaces. Aquifers were identified as zones which are screened at similar elevations separated by layers of low permeability. The hydrostratigraphy of the glacial deposits was depicted as six uneven and discontinuous layers comprising three aquifer systems separated by three less permeable layers (Figures 3 and 4). Layers from the resultant conceptual model were imported into FEFLOW, a finite element numerical model, for steady state calibration and quantification of the groundwater flow system. The methodology for developing this 3-D hydrostratigraphic model can be applied to other glaciated basins where numerical modeling of complex aquifer systems can be a valuable tool for better understanding the groundwater flow and predicting future impacts on groundwater quantity and quality.

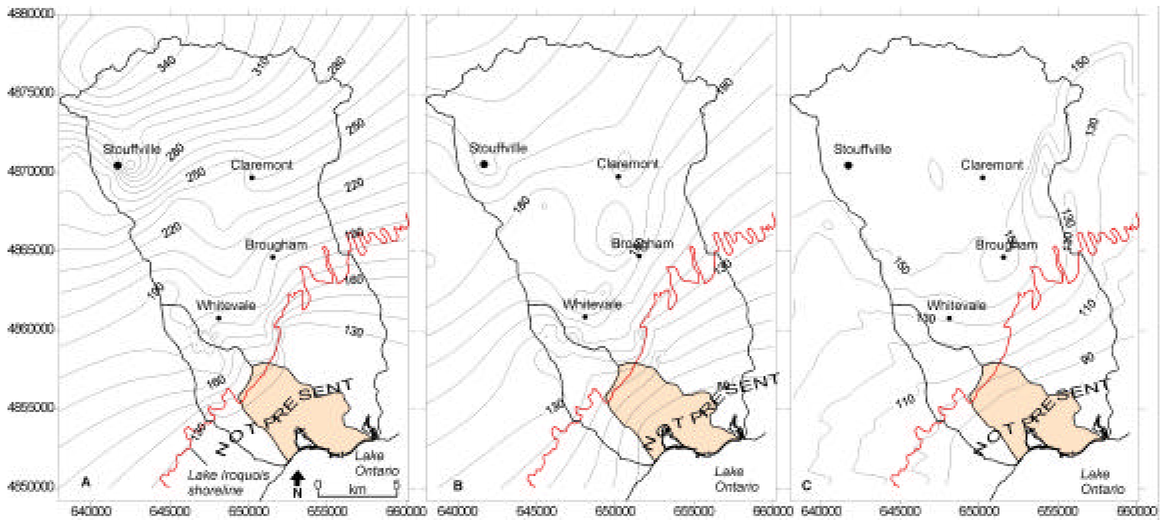

Figure 3. Contoured upper surface of A. Upper Aquifer (ORM/Interstadial deposits), B. Middle Aquifer (Thorncliffe Formation), C. Lower Aquifer (Scarborough Formation). Contour interval 10 m.

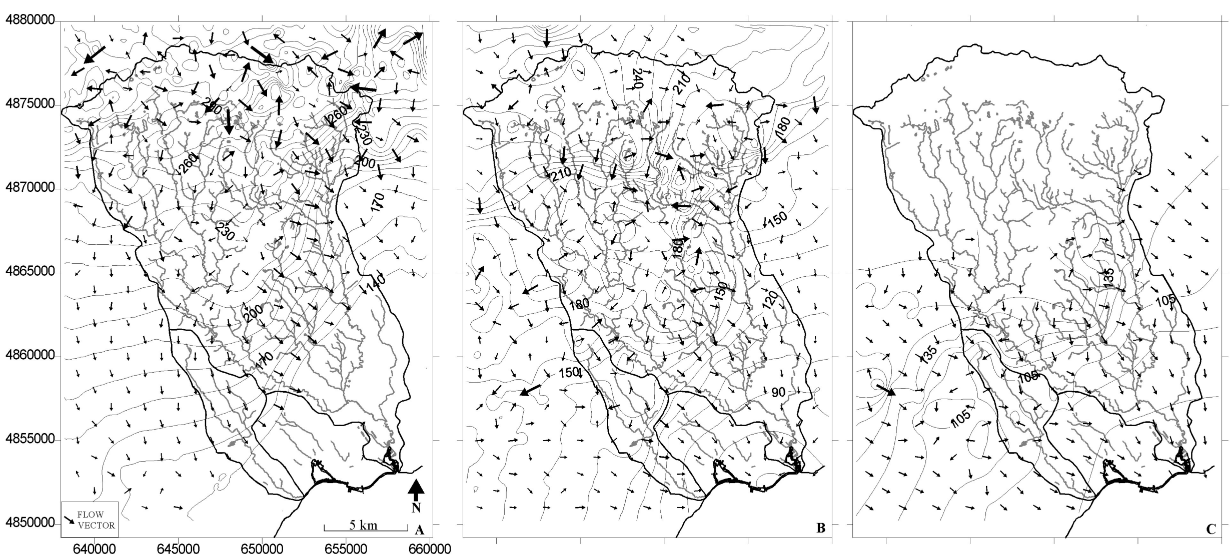

Figure 4. Contoured hydraulic heads and groundwater flow directions for A. Upper aquifer, B. Middle aquifer, C. Lower Aquifer. Arrow size is proportional to magnitude of gradient. Contour interval 10 m.

A 3-Dimensional, Transient Simulation of Ground-water Drawdown and Recovery from Coalbed Methane Development in Multiple Coal Seams in Southwest Montana

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Methane production from coal beds accounts for almost 8% of the total methane production in the United States (Van Voast, 2003) and is a relatively new, but important industry in the Powder River Basin in southeast Montana and northeast Wyoming (Figure 1). Coalbed methane is formed in the coal by either biogenic or thermogenic processes. If the coalbed is buried deeply, generally greater than 30m, and there is sufficient hydrostatic pressure, the methane will remain adsorbed on cleat surfaces and in micro-pores in coal (Rice,1993; Rightmire et al, 1984). The gas is held in place by weak attractive forces between the coal and the gas and by hydrostatic pressure from ground water in the coal. To produce the gas, water is pumped from wells completed in the coal, the hydrostatic pressure is reduced, and the gas is desorbed. The gas and water move to the well as a two-phase fluid. The water enters the pump and is discharged through the water line and the gas flows up the well casing to be extracted by a low-pressure compressor.

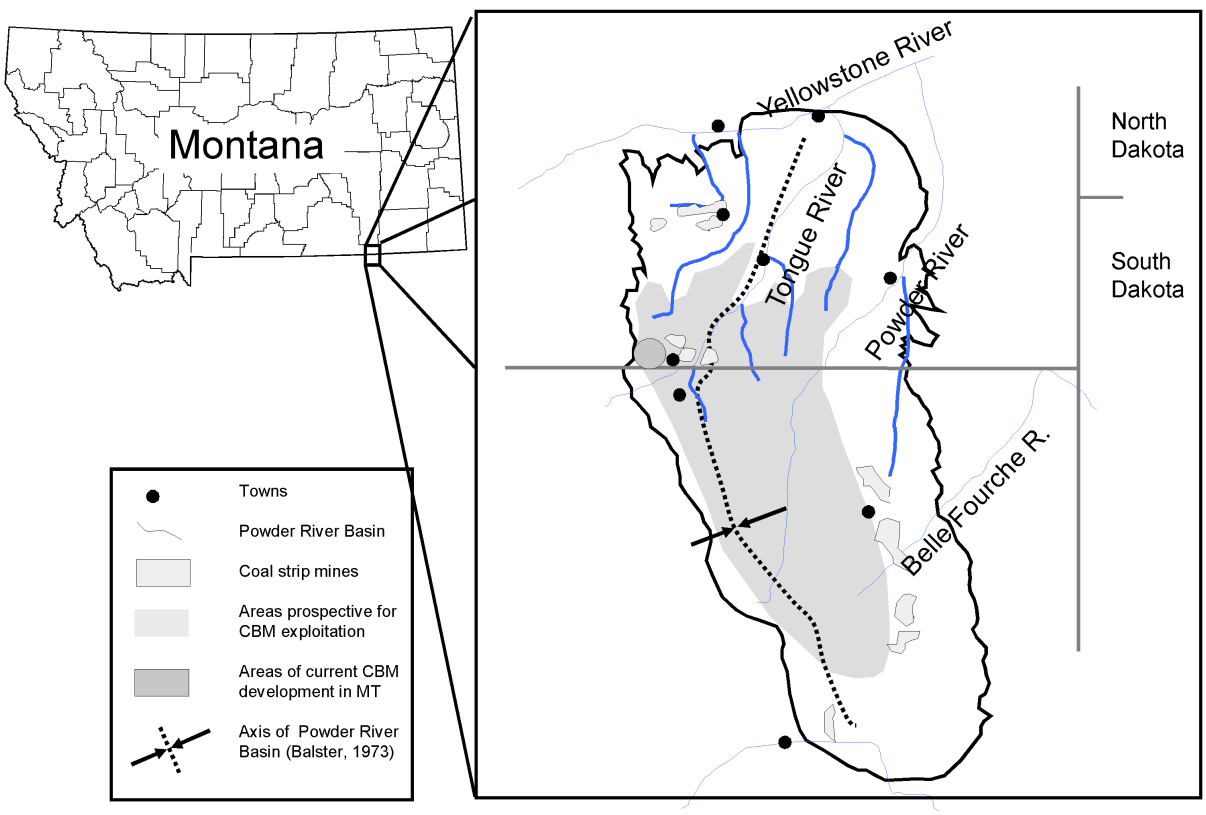

Figure 1. The Powder River Basin in southeast Montana and northeast Wyoming.

Additional efficiency in reducing water pressure in the coalbeds is achieved by completing wells in grid patterns called pods. Pods typically cover an area of about 3.2 km^2 and consists of 10 to 15 wells completed in each coal seam, or about one production well per 0.32 km^2 per producing coal seam. In some areas, as many as four coal seams are targeted, and pods may consist of as many as 40 or 50 wells. In southeastern Montana, coal seams hold two valuable energy resources (mineable coal and coalbed methane), but also ground water that is vital to a large agricultural economy. Proper, equitable management of these resources necessitates development of hydrologic impact predictions. The effects of long-term, sustained well-yields over areas of coalbeds that may exceed townships in size are undocumented in Montana. Computer-generated ground-water flow modeling was used to demonstrate potential drawdown, discharge rates, and recovery of a 100 km^2 coalbed methane production field. The MODFLOW program (McDonald and Harbaugh, 1988) and a pre/post processor, Ground Water Vistas (Rumbaugh and Rumbaugh, 1998) were used to develop a 3-dimensional ground-water flow model of the Hanging Woman Creek area in southeast Montana. Hydrologic characteristics for this area are similar to other areas of the Powder River Basin. There are at least three roughly parallel coalbeds capable of producing methane dipping at a nearly uniform gradient of 0.004 toward the southwest. The coalbeds are separated by as much as 50 meters of interburden sandstones and claystones. Several normal faults in the study area have displacements greater than the thickness of the coalbeds and thus, affect well placement, discharge rate, and the drawdown pattern. The model grid was set up for 0.16 km^2 spacing in the central area to allow 0.32 km^2 well spacing commonly used in coalbed methane development. The grid spacing was 402 meters for columns and rows in the central area of the model; the spacing was increased toward the edges of the model for a maximum column width of 2,200 meters and a maximum row width of 10,000 meters. Six layers were used to simulate the three principle coalbeds, the overburden and stream beds, and the interburden between coalbeds. The elevation and thickness of each layer was based on isopach maps presented by Culbertson and Klett (1979a and 1979b); layers were offset to reflect the larger faults in the central area of the model. The final version of the model consisted of 31,200 active cells for a 30-year simulation. To simulate progressive development, production, and decomissioning, coalbed methane development was simulated in three phases: 10 years of pumping in the south half of the field, then 10 years of pumping in both the south and north halves, and finally, 10 years of pumping only in the north half of the field. Each well field was over-pumped at a rate 1.5 to 2 times the final rate during the first year to induce rapid drawdown. Including start-up and long-term pumping rates, water produced during the modeled periods ranges from 11 to 76 liters per minute per well. The model simulated a total production of 10,000,000 to 30,000,000 cubic meters of water per year from 576 wells and 1,082 wells, respectively. The cumulative water production, after 20 years of pumping from all wells in the model was 4.9 billion cubic meters.

In the 20-year life of the production fields, pumping produced about 6 meters of drawdown at a distance of 3.2 kilometers (Figure 2). The maximum drawdown in the deeper coalbeds was 135 to 165 meters; 9 meters of drawdown was produced at a distance of about 3.2 kilometers and 1.5 meters of drawdown was produced at a distance of about 6.4 meters. Twenty-five years after pumping is stopped, water levels in the shallowest coalbed recovered about 70%. Figure 3 presents model-generated hydrographs for wells in the shallowest of the three coalbeds.

The limitations of a computer-generated model are reflected in the assumptions made in the construction of the model. In this case, the coalbeds and interburden were assumed to have uniform thickness, aquifer parameters were assumed to be uniform, and regional recharge/discharge relationships were assumed to be constant. The well locations and pumping schedule used here, with large blocks of wells coming on-line at the same time, may not reflect the best design with respect to pipeline placement and discharge control. Development would be expected to begin in the south and move north, however, this may not be the case. The modeled scenario does not take into account mineral ownership or other factors that affect development plans. The model evaluated an isolated production field, whereas development in Wyoming indicates that new fields typically are developed adjacent to other fields or mines to take advantage of

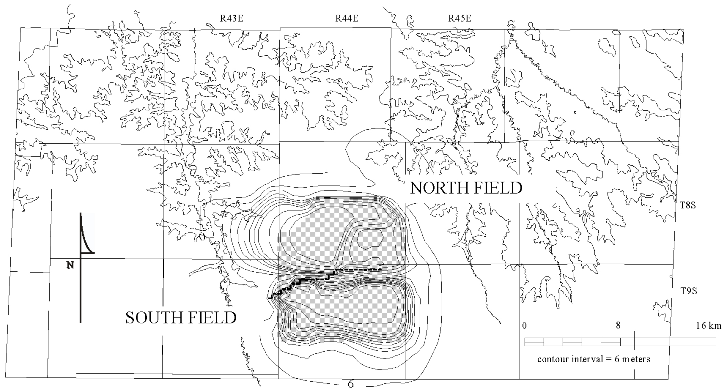

Figure 2. At the end of 20 years, wells in the Anderson coalbed north of the fault (heavy line) have been pumped at an average of 40 Liters per minute for 10 years and wells south of the fault have been pumped for 20 years. A drawdown of about 6 meters has reached about 3.2 kilometers south of the well field.

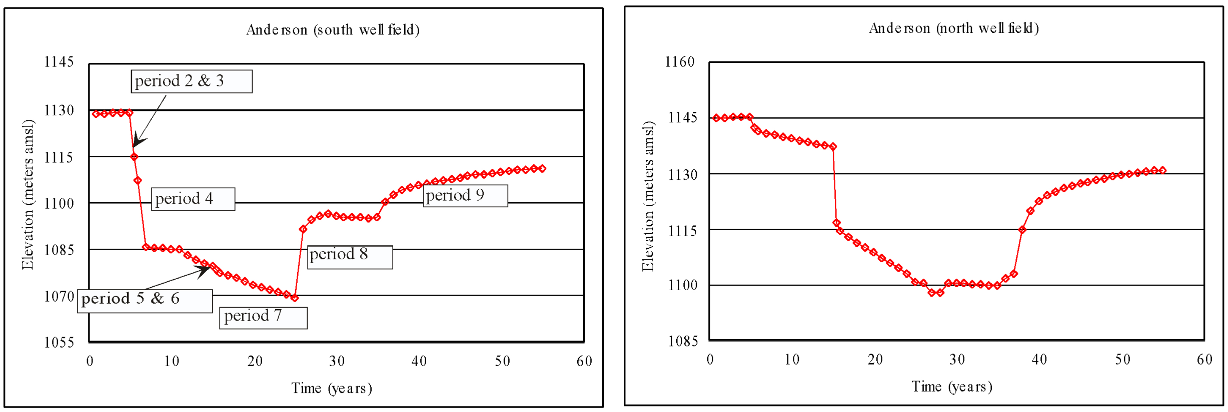

Figure 3. The Anderson coalbed is represented by Layer 2 of the model. The well-field hydrographs show the effect of over-pumping to induce rapid drawdown. The stress periods are indicated on the first hydrograph.

existing drawdown. All of these factors affect well placement and timing, and therefore will alter the anticipated impacts to ground-water systems. Limitations of the model code prevent an evaluation of such phenomena as fluid density changes due to de-gassing, aquifer compression due to long-term pumping, and bio-film growth and decay due to chemistry changes, which may also affect pumping rates and drawdown. Similarly, the code used in this simulation considers only porous media and ignores fracture-dominated flow that may exist in areas of faulting. Faults in coalbeds have been shown to be no-flow boundaries (Van Voast and Reiten, 1988). In this model, faults are simulated by offsetting the layers, and cells near the fault are assigned a horizontal-flow barrier.

Within the limitations described, the model does provide a means to demonstrate, though not predict, some of the hydrologic conditions that may be encountered in coalbed methane development. The regional ground-water gradient, which tends to reflect structural gradients, exerts a measurable control on the shape of the zone of influence. The presence of faulting within a well field, which is common, will strongly determine pumping rates.

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Three-Dimensional Groundwater Flow Modelling in the Quaternary Succession Near Cold Lake in East-Central Alberta

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Introduction. Groundwater from the Quaternary succession is an important source of water for both domestic and industrial use in the Cold Lake – Beaver River (CLBR) drainage basin in east-central Alberta (Figure. 1). Growing demands on groundwater by expanding thermal in-situ heavy oil extraction projects in the basin, coupled with an extended period of drought, has increased the need for a regional groundwater numerical model to help assess groundwater flow and manage its use in the basin. Two major steps were necessary to complete the study: a) a detailed hydrogeological characterization of the Quaternary succession, and b) the development of a numerical groundwater flow model. One example for the practical usage of the calibrated numerical model is the transition curve analysis for various pumping scenarios in different aquifers and locations in relation to surface water bodies. Herein, transient numerical simulations are used to establish the transition from water produced from elastic storage to water produced from induced infiltration from surface water, and to determine the source of the latter (induced recharge, decreased leakage to lakes and rivers). This analysis can help to evaluate the time frames of various pumping scenarios with respect to "water mining", and to establish which surface water bodies are most susceptible to groundwater extraction and therefore should be monitored.

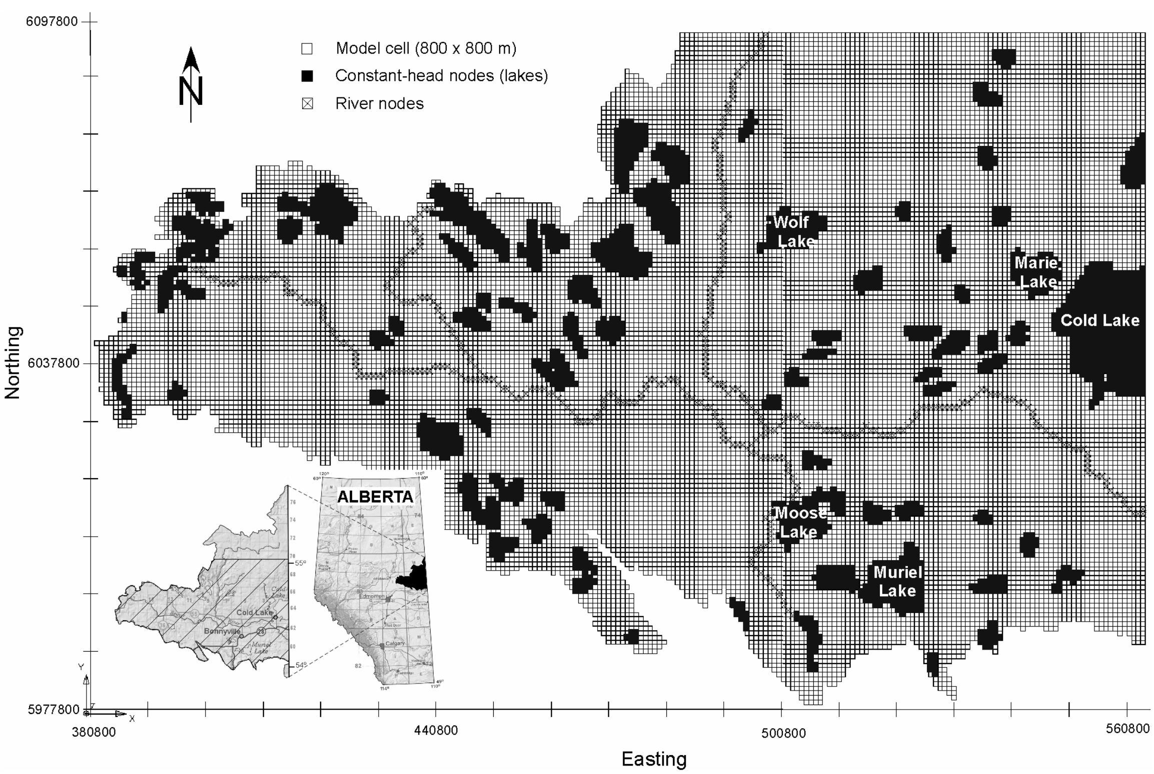

Figure 1. Location of the Cold Lake – Beaver River Basin study area, showing grid discretization and boundary conditions.

Hydrostratigraphy. Channel incisions in the bedrock topography by pre-glacial and glacial river systems have created depositional basins in which up to 250 m of drift have accumulated. The hydrostratigraphy of the Quaternary units in this drift sequence is characterized by a succession of sand and gravel aquifers that are separated by, or embedded within, thick glacial tills representing at least four major glacial events. Confinement of some Quaternary units to bedrock channels, combined with stratigraphic superposition resulting from fluvial down-cutting and successive stacking, have produced a complex hydrostratigraphy with a combination of confined, leaky, and unconfined aquifers. For the development of a numerical groundwater flow model, the hydrostratigraphy was simplified to a 12-layer (Figure 2), glacial-drift aquifer system. The mapping of the top structure of the aquifer and aquitard layers was performed using three-dimensional mapping software.

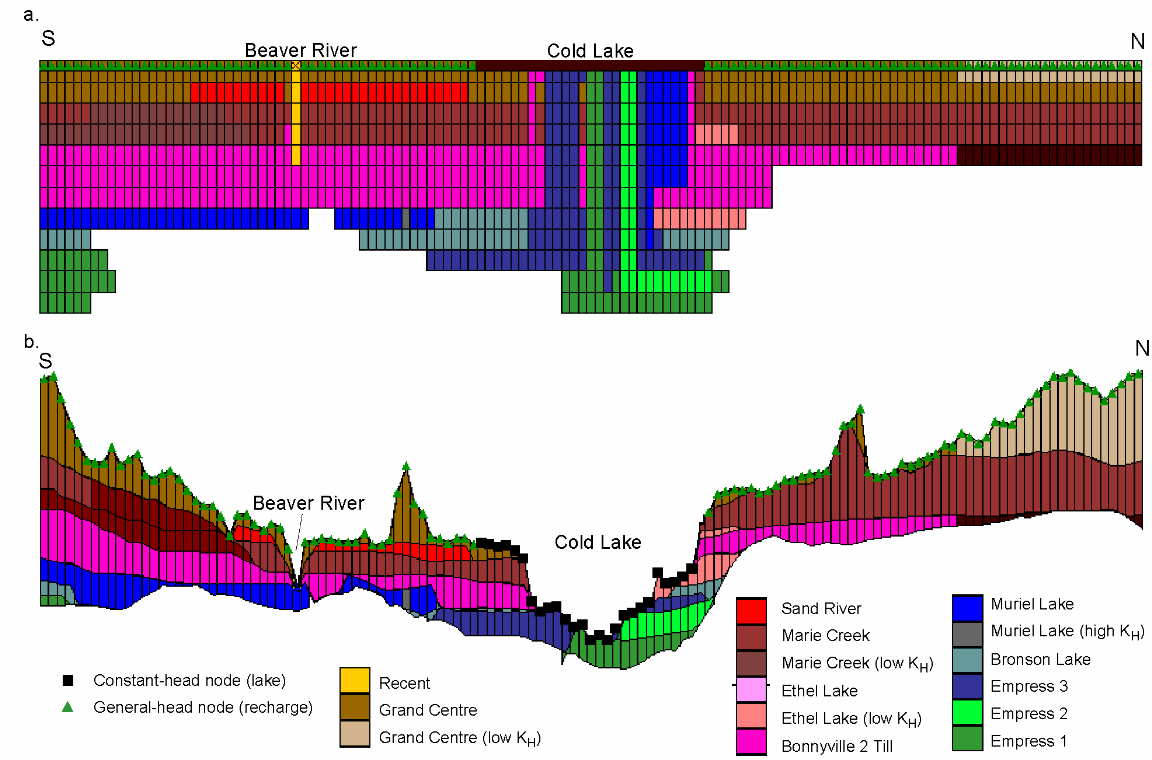

Figure 2. South - north cross section through the eastern part of the model area in a) ortho view and b) true-layer view.

Numerical Model. Groundwater flow in the CLBR basin was modeled numerically with the Groundwater Modelling System (GMS 4.0), which employs the modeling package MODFLOW. MODFLOW is a finite difference model developed by the United States Geological Survey (USGS), and is a well-established and globally used groundwater modelling software. The surface-elevation grids of the hydrostratigraphic units were directly mapped to a three-dimensional model grid in the groundwater modeling software using a "true layer" approach. The model grid consists of 233 columns and 150 rows, and the cell dimensions are 800 by 800 m (Figure 1). The total number of grid cells is 454,350, of which 186,866 are active cells within the study area of the CLBR drainage basin (~ 11000 km^2). Each hydrostratigraphic unit was assigned material properties in the form of hydrogeological parameters (horizontal hydraulic conductivity, vertical anisotropy, and specific storage). In the "true layer" approach, the various hydrostratigraphic units have to be present continuously. Therefore, in places where a unit is absent, the respective layer has to become "very thin" (2 - 20 cm) and these thin cells are assigned material properties of the under- or overlying unit. All outer lateral boundaries in the model are defined as “no-flow” boundaries because they either represent flow divides or areas of flow parallel to the boundary. The exceptions are areas where channel aquifers extend beyond the limits of the surface drainage basin. In these areas, either “general-head” or “constant-head” nodes model the potential in- and outflows. The base of the Quaternary succession is formed by low-permeability shales and is modeled as a “no flow” boundary. Recharge rates in the CLBR Basin are not well known and therefore, instead of assigning recharge fluxes, recharge is simulated through a general-head type boundary at the top layer. Wetlands cover large parts of the CLBR Basin, which indicates that the water table is at or near the ground surface and head values were specified to the respective ground surface elevation. Only the major rivers in the study area were simulated with river nodes in the top layer of the model. Water levels in most lakes in the CLBR Basin only vary within a few meters. Therefore, lakes are simulated in the model by assigning constant hydraulic heads according to the respective lake level. The model was calibrated to static water level measurements in water wells (steady-state) and hydrographs in wells in the vicinity of sites performing long-term (15 years) pumping associated with oil sands development.

Results. Steady-state water balances calculated by the calibrated model suggest that the majority of water entering the groundwater system is derived from recharge due to infiltration from wetlands or precipitation (~232,000 m^3/d or 8 mm/year), while minor amounts of water are provided by leakage from recharging lakes (~30,000 m^3/d). Discharge of groundwater occurs through the major rivers (~141,000 m^3/d), secondary drainage (~30,000 m^3/d) and lakes (~87,000 m^3/d), while approximately 4000 m^3/d leave the drainage basin through flow in channels extending beyond its boundaries. The simulated hydraulic head distribution is very sensitive to the hydraulic rock properties of the aquitards and the lowermost post-channel aquifer. Apparently, the hydraulic parameters of shallow till aquitards control vertical flow of recharge-derived water into the deeper hydrostratigraphic units. The hydraulic conductivity in the lowermost post-channel aquifer, due to its large extent, contiguity, and hydraulic connection to rivers and lakes, governs the lateral flow and drainage into the discharge features. With respect to the modeling of groundwater – surface water interaction, a key step forward has been the incorporation of lake-bottom bathymetry into the digital elevation model to map aquifer outcrops on the bottoms of lakes.

Transition curve analyses for potential pumping scenarios in the CLBR Basin show that, depending on aquifer depth and location in the groundwater flow system, the time between groundwater mining from aquifer storage and produced water being balanced by induced infiltration ranges between approximately 10 days to 3 years (Figures 3 and 4).

Conclusions. Due to the complexity of the Quaternary hydrostratigraphy and interaction between groundwater flow and surface water bodies in the CLBR Basin, impacts of groundwater extraction can only be accurately evaluated using a regional numerical flow model. A proper geological characterization of the subsurface, and the adequate representation of fluid sources and sinks are essential for developing a well-calibrated numerical model and managing water resources in the Cold Lake – Beaver River drainage basin.

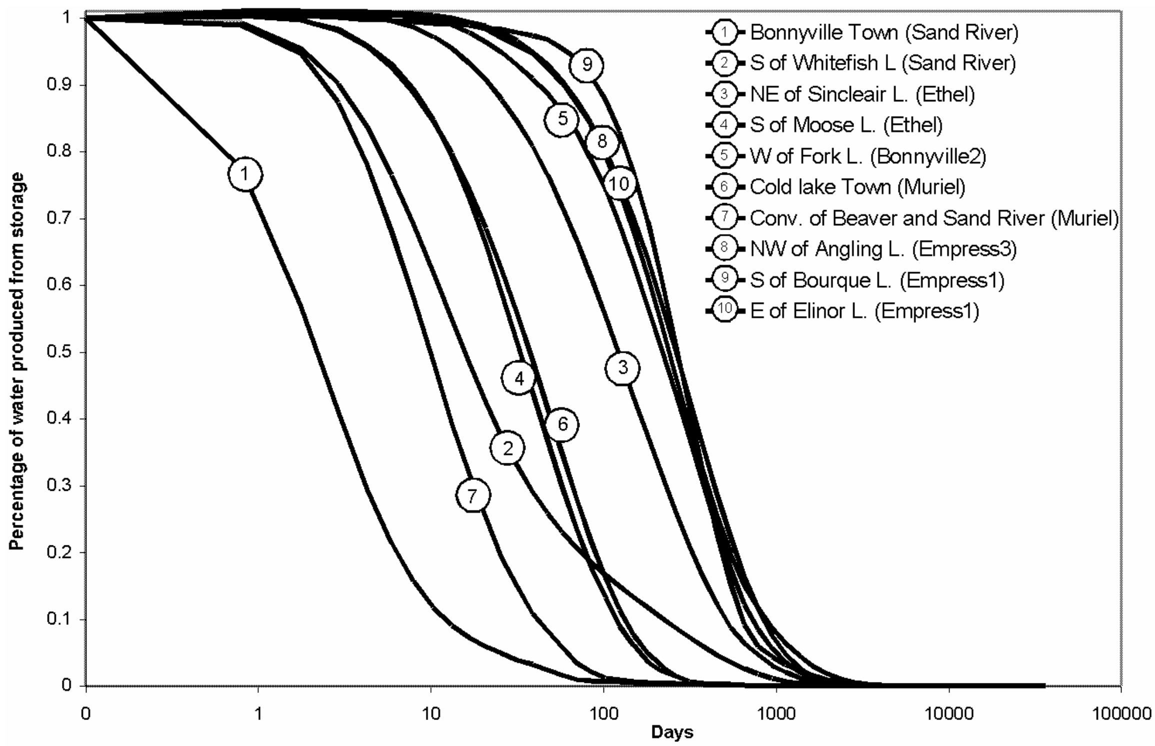

Figure 3. Transition curves for various pumping scenarios from different aquifers (names in brackets) at selected locations.

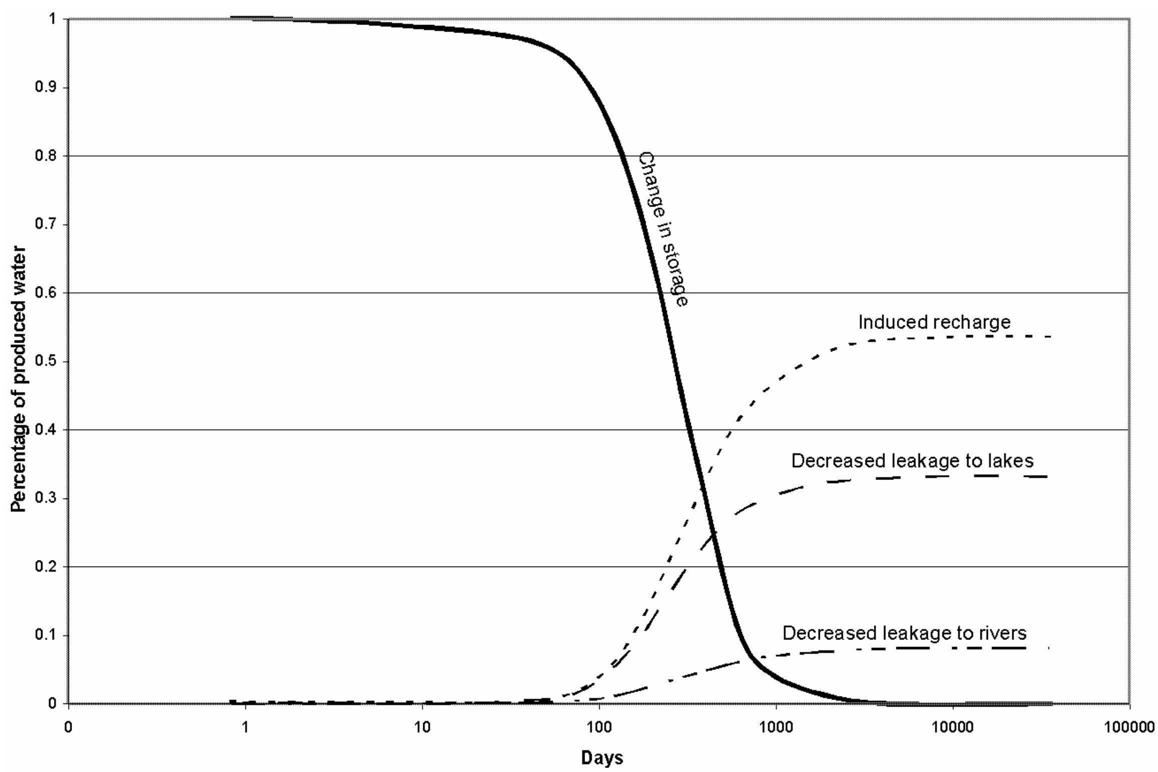

Figure 4. Graph showing an example of the transition from produced water derived from storage to induced leakage from/to surface water bodies.

Towards Seamless Interactions Between Geologic Models and Hydrogeologic Applications

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Introduction. Integration of stratigraphic reconstructions and hydrogeologic applications represents a significant challenge. In recent years, different geomodeling tools (e.g., gOcad, EarthVision) and approaches have been developed to provide solutions to this particular problem. One of those solutions is to build computer-based three-dimensional (3-D) geologic framework models (GFM) made of interlocked surfaces (Ross et al. 2002). Not only can these models be viewed as "repositories" of the stratigraphic knowledge (Mallet 2003), they can also be used as the backbone for further discretization, whose type and resolution are adapted to fit the specific needs of any particular application that requires properties to be integrated and analyzed. Therefore, once it is available in a study area, such a model provides a common framework for all project team members, as opposed to a more traditional practice in which geologic information is stored in different media and dispersed through a series of independent end-products. Apart from the geometrical and topological advantages, an obvious benefit of using an integrated 3-D modeling approach is that it reduces redundancy and risks of inconsistencies and helps to streamline updating procedures. Another advantage is that it does away with the necessity of redoing much of the interpretation and stratigraphic modeling to meet the specific requirements of various applications; in the end, time savings can be huge.

3-D geologic models and hydrogeologic applications. An increasing number of applications require that all the available hydrogeological information be incorporated into a full three-dimensional conceptual model (e.g., Frind et al. 2002). Therefore, hydrogeologic numerical models are definitely among the most important "client" applications for 3-D geologic models. However, computational grids for numerical modeling must be optimized to produce accurate and stable numerical solutions such that some geometric generalizations may be done in practice (Anderson and Woessner 1992). As a result, multi-layered hydrostratigraphic models are often initially designed to fit the specific requirements of both the numerical modeling strategy and a particular software package (e.g., MODFLOW, FEFLOW, FRAC3DVS, etc.). The main advantage is that the hydrostratigraphic model is readily available for numerical modeling. However, this approach has a number of disadvantages. The model may not contain sufficient stratigraphic details to meet the requirements of a subsequent numerical modeling phase, or for another application within the same project; considerable effort may then be required to add the right degree of complexity to the stratigraphic reconstruction. For example, simplified stratigraphic grids may be appropriate to model groundwater flow at a regional scale, but more detailed grids are required to model contaminant transport or to delineate well capture zones three-dimensionally (e.g., Frind et al. 2002). Furthermore, even in regional groundwater flow modeling, detailed knowledge of the stratigraphic architecture is needed to consistently map the estimated or probable range of values for some key parameters (e.g., recharge rates, hydraulic conductivities) (Figure 1). The resulting maps can then be used in the calibration process. Therefore, a detailed 3-D geologic model is very helpful even though the complex geometry of the units may not be represented as true layers in the numerical model. The detailed 3-D model can also provide the continuous and/or simplified layers for the numerical model (Figure 2). In fact, the needed simplifications/approximations are even more likely to be consistent if they are carried out after such a 3-D geomodeling effort is achieved. Therefore, a more integrated approach would be to design a stratigraphic model based on the level of stratigraphic detail required by the most demanding application of a project from which more simple models are created to fit the specific geometric requirements of other less demanding applications.

Another interesting application is to use 3-D geologic models to evaluate aquifer vulnerability to contamination, particularly in cases where an aquifer is overlain by several discontinuous units. Since these models provide consistent data for unit distribution and thickness, and can integrate soil properties and hydrogeologic parameters, they can contribute significantly to determine the different parameters required by many currently used vulnerability methods. The GFM can also be used to readily estimate physical parameters such as groundwater downward time-of-travel (TOT). The notion of downward TOT is implicitly used in many vulnerability assessment methods and it is sometimes used as the main indicator of vulnerability to contaminant transport by natural groundwater recharge (GSW 1991) or by large accidental liquid spills (Maxe and Johansson, 1998). A method called Vulnerability-Time-Of-Travel (VTOT) was developed recently (Ross et al. 2003) to assess the vulnerability of aquifers to downward transport of conservative dissolved contaminants at a regional scale using a GFM. The vulnerability of an aquifer to contamination is assessed from the estimated downward TOT from the surface through the different units overlying the aquifer. To achieve this, hydrogeologic parameters such as mean infiltration rates and volumetric water contents or effective porosities estimated for the different units are added to a stratigraphic grid created from a GFM (e.g., Figure 1). Calculations are applied to the grid to approximate the one-dimensional advective, nonreactive, solute time-of-travel through the layered system. Results are then grouped into downward TOT classes which provide a relative vulnerability index based on a parameter having a real physical meaning.

Conclusion. The purpose of constructing a 3-D geologic model is to obtain a consistent representation of the stratigraphic architecture, as it is understood from the available data, and to use it for qualitative and quantitative geologic/hydrogeologic analyses. It is our view that a three-dimensional modeling approach is the most adequate way to capture the subsurface complexity of most geologic settings which can lead, in the context of an integrated approach, to improved hydrogeologic appraisals. With increasing availability/accessibility to technology, 3-D geomodeling is expected to become a standard in the near future. This will improve interactions among the different specialists and end-users and will eventually lead to a better integration of geological information in the management of groundwater resources and associated decision-making processes.

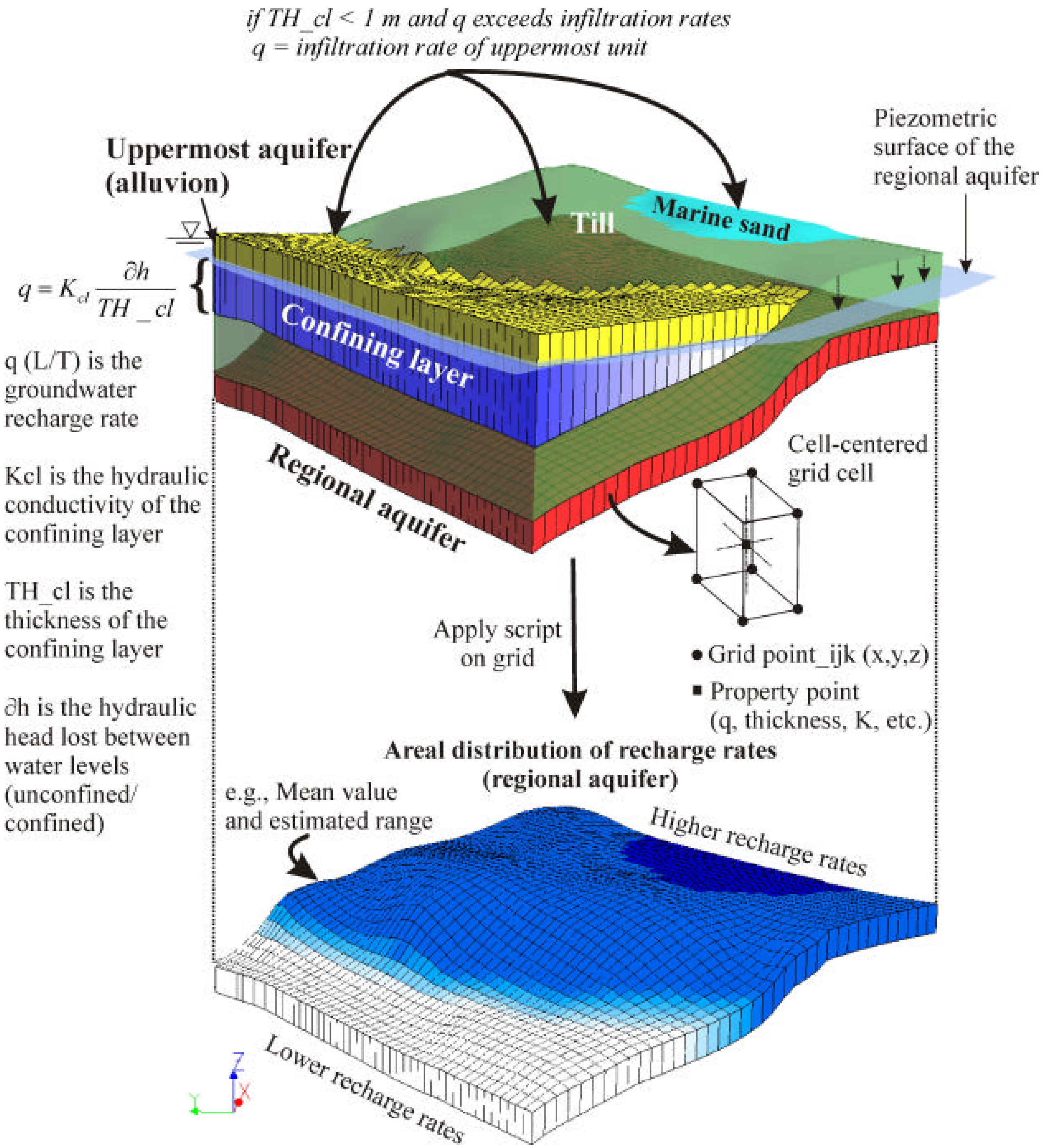

Figure 1. A curvilinear 3-D stratigraphic grid built from a geologic framework model (GFM) made of interlocked surfaces can be used for parameter estimation. Different grids can be built from the same GFM to fit the specific requirements of an application. In this schematic example, such a grid is used to map the areal distribution of recharge to the regional aquifer which may in turn be useful to provide a proper zonation of this key parameter for a hydrogeologic numerical model which contains less geometrical information. A 3-D geologic model is the most adequate tool to provide information such as the subsurface distribution and thickness of low permeability layers and can be used to estimate recharge rates and to properly map the estimated range of these values.

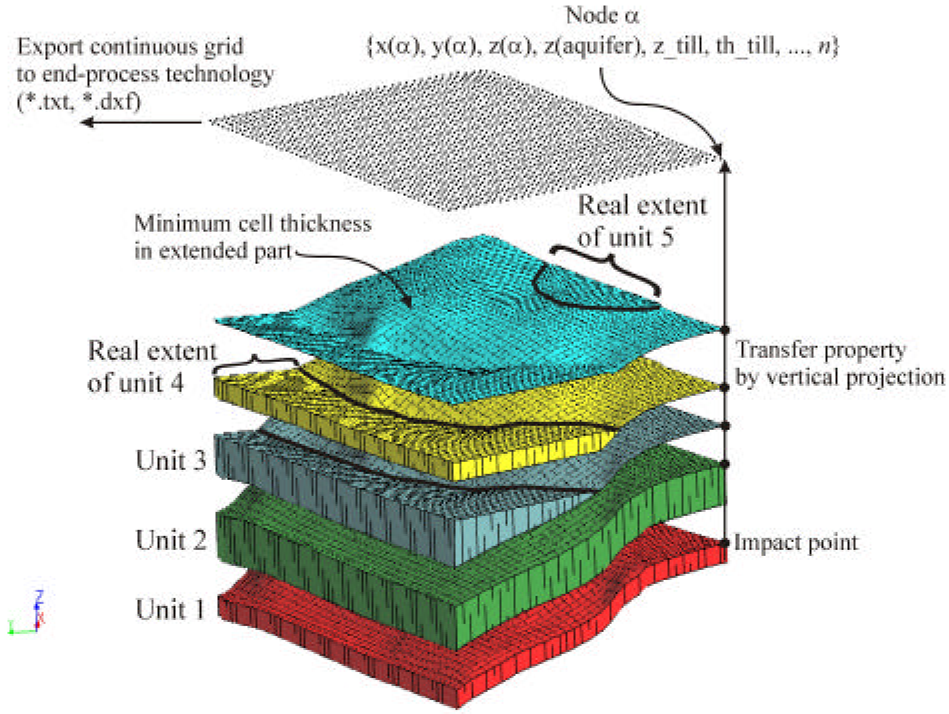

Figure 2. Continuously meshed layers can be generated from a geologic framework model made of discontinuous interlocked surfaces. The coordinates and the properties (e.g., thickness) of each layer are then transferred to a unique and continuous grid which, at the end of the process, contains all the needed stratigraphic information. This grid is then exported to the end-process technology using a standard file format. This procedure is particularly useful when continuous units are required and when the 3-D grid generation tools of the geomodeling system are not compatible with the code used to model the flow.

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Buried-valley Aquifers: Delineation and Characterization from Reflection Seismic and Core Data at Caledon East, Ontario

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Buried valley aquifers are an important source of water supply in Ontario. They are significant to water resource managers as interest grows in source water protection, security of supply, and in constraining estimates of watershed-scale water balances. Prospecting methods for this aquifer type have seldom used modern exploration techniques to discover, target, and assess reservoir potential and flow-system properties. The town of Caledon East, located on the southern flank of the Oak Ridges Moraine, east of the Niagara Escarpment (Figure 1) is facing a water supply problem. Buried-valley aquifers are one possible source of additional water, but are currently poorly understood in the area. This abstract provides a preliminary analysis of recent geophysical and sedimentological data collected in the area and places it in a regional stratigraphic context.

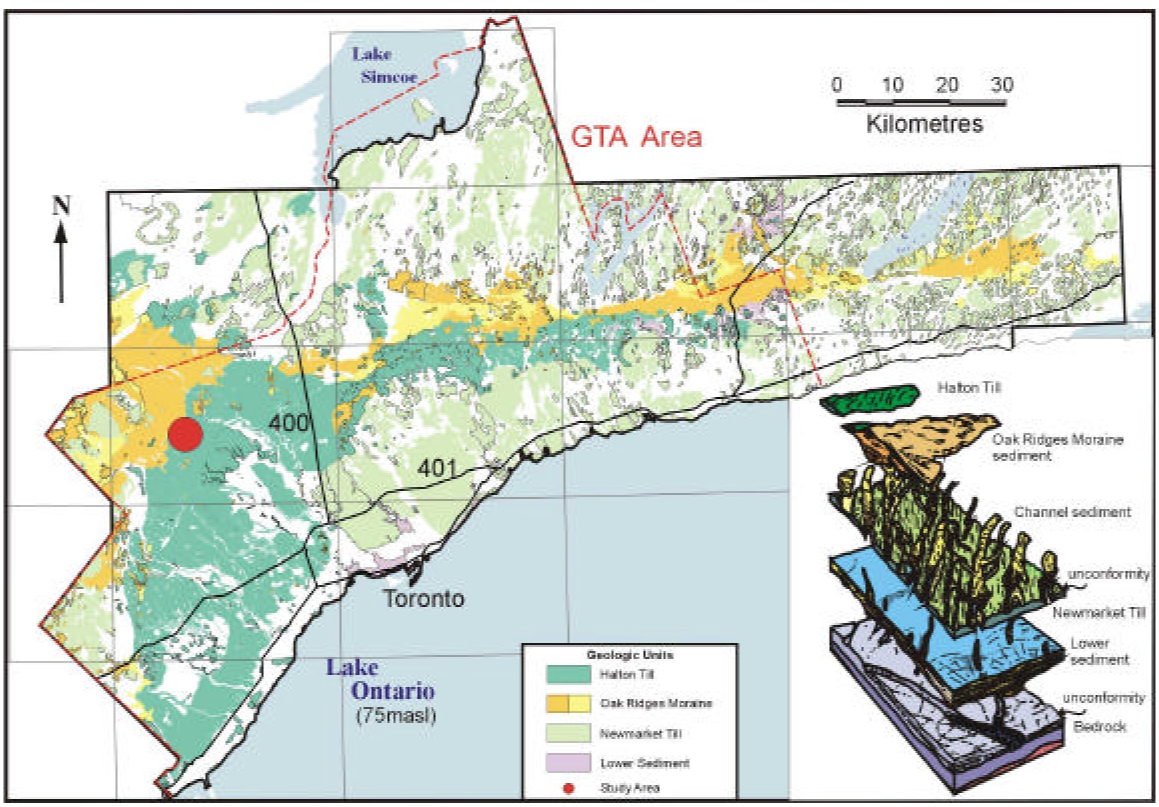


Figure 1. a) Location and generalized geology map of the Greater Toronto Area. b) Conceptual rendition of the stratigraphic architecture and the principal stratigraphic units of the GTA (see Sharpe et al., 1996).

Sparse archival borehole data outline an ~E-W trending bedrock valley, that appears to connect eastward with the larger Laurentian valley (Figure 2). To investigate the extent, depth, and architecture of

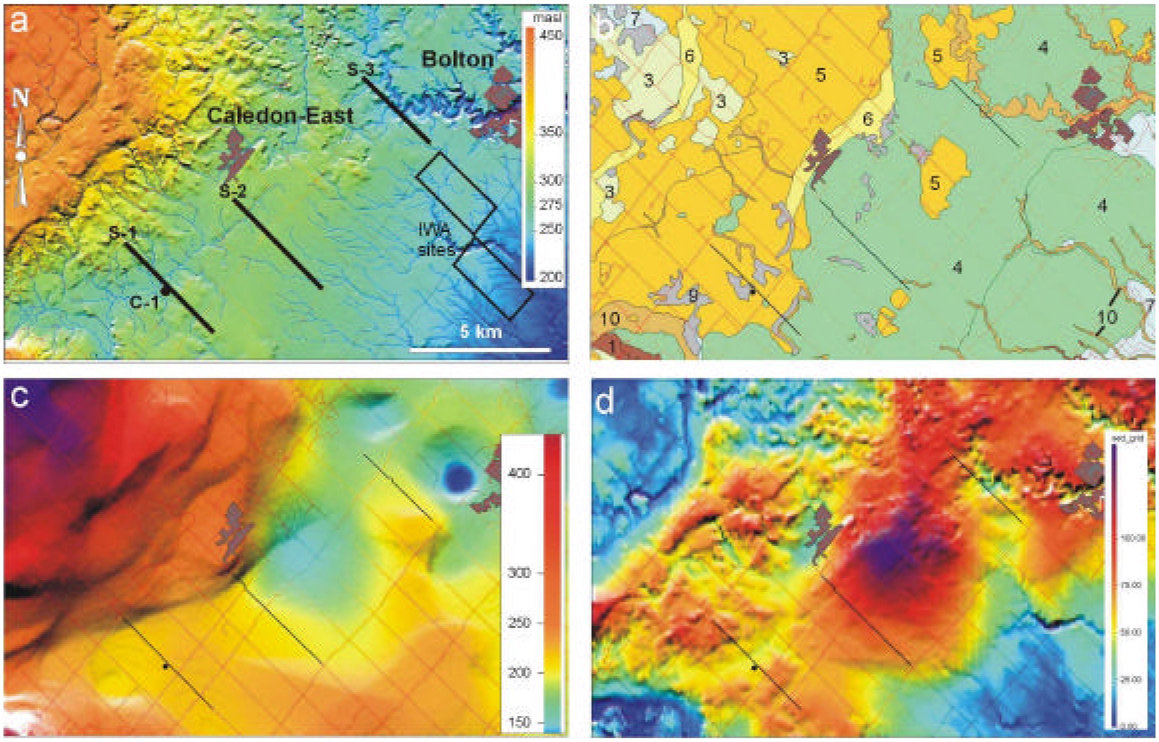
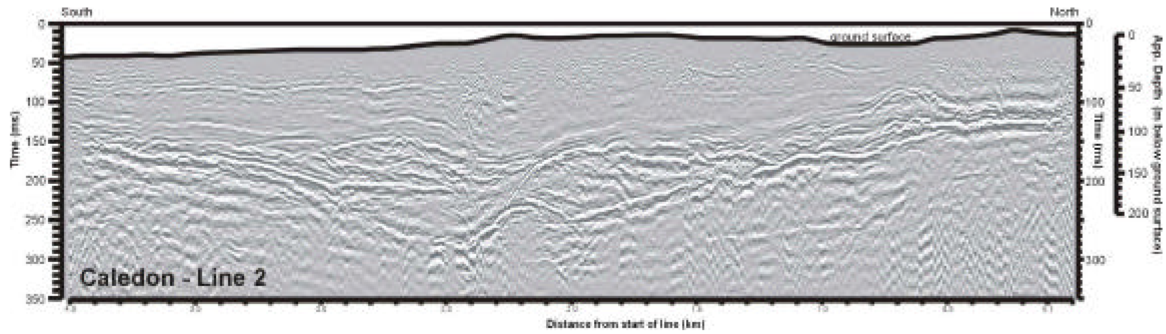


Figure 2. Geological context of study site. a) Digital elevation model (DEM) of the area with seismic sections (e.g. S-1) and borehole sites (C-1, IWA sites) indicated. b) Surficial geology map. Numbers refer to geological units: 1 - bedrock, 3 - sandy till, 4 - silty Halton Till, 5 – Oak Ridges Moraine sand, 6 – glacifluvial sand, 7 – glacilacustrine silt, 9 – organic, 10 – alluvium. c) Bedrock surface DEM modified from Russell and Stacey (2001). Scale is in metres above sea level. Borehole C-1 revealed bedrock 100 m deeper than indicated by the bedrock DEM. d) Sediment thickness map. Note thick region of sediment between seismic lines S-1 and S-2 coincides with a region of outcropping ORM sediment over a bedrock low. Scale is in metres.

the suspected bedrock valley, and its sedimentary fill, high-resolution geophysical and geological data were collected. This work included ~10 line kms of reflection seismic data, along 3 profiles spaced at intervals of 4-6 km, downhole geophysics, and detailed sediment logging data from an ~ 180m-deep, continuously cored borehole (Figure 2a). Several cored boreholes from a nearby landfill investigation of the Interim Waste Authority (IWA sites, Figure 2a) provide additional detailed geological context.

Results confirm the presence of and delineate the suspected bedrock valley that is ~100 m deep, ~2-4 km wide that appears to trend and widen to the northeast (Figure 2c). Seismic reflector patterns tied to borehole data show 4 main elements (Figures 3 and 4).

1. A basal, semi-continuous, high-amplitude reflector seismic facies that is interpreted as shale and limey bedrock of the Georgian Bay Formation.
2. Overlying bedrock is a continuous, relatively coherent high-amplitude facies ~10 m thick that is interpreted to be diamicton.
3. A <100 m thick seismic facies of high-amplitude, less continuous, truncated and inclined reflectors that is interpreted to be stacked sand and gravel sets with cut-and-fill and cross-bedding structures. This seismic facies is inferred to represent high-energy deposition from a subglacial fluvial system.
4. An 80-100 m thick, low-amplitude, weakly planar seismic facies that is interpreted to be sand and silt. Borehole data indicate increasing mud content upward in this seismic facies (Figure 4).



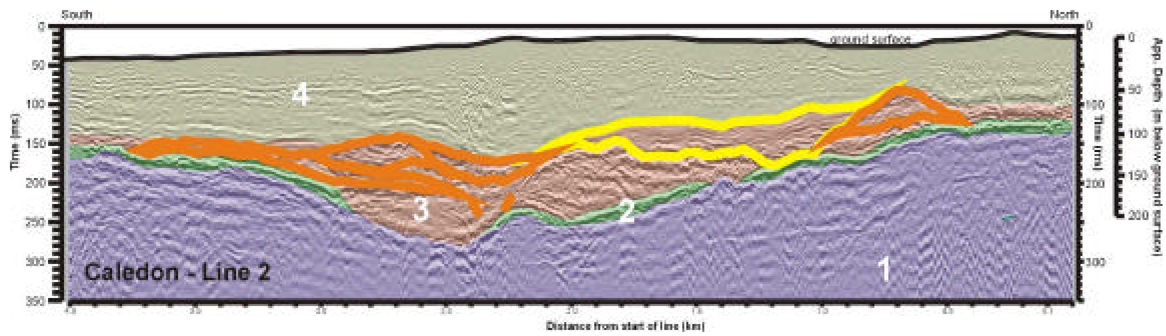


Figure 3. Reflection seismic profile presented as an amplitude plot (a) an interpreted line drawing (b). Number in b are; 1 – bedrock, 2 – diamicton or coarse gravel on bedrock, 3- gravel, 4 – fining upward unit of sand and silt.

The succession is interpreted to correlate with the regional Oak Ridges Moraine and Halton Till stratigraphic units (Barnett et al. 1998). Similar structures and coarse sediment have been interpreted from seismic facies and confirmed with continuous core in the region (Pugin et al. 1999; Russell et al. 2003; Sharpe et al. 2003). Coarse sediment of unit 3 provides up to ~100 m thick and ~ 2 km-wide target for hydraulic testing. This buried gravel deposit, located along the axis of the valley, is a potentially new and previously unrecognized aquifer.

Acknowledgements. Drilling and core collection was supervised by Steve Davies. The reflection seismic data was collected by Dave Schieck, GAPS. Core logging was completed by George Gorrell. The Ontario Geological Survey provided funding to the Conservation Authorities Moraine Coalition for data collection.

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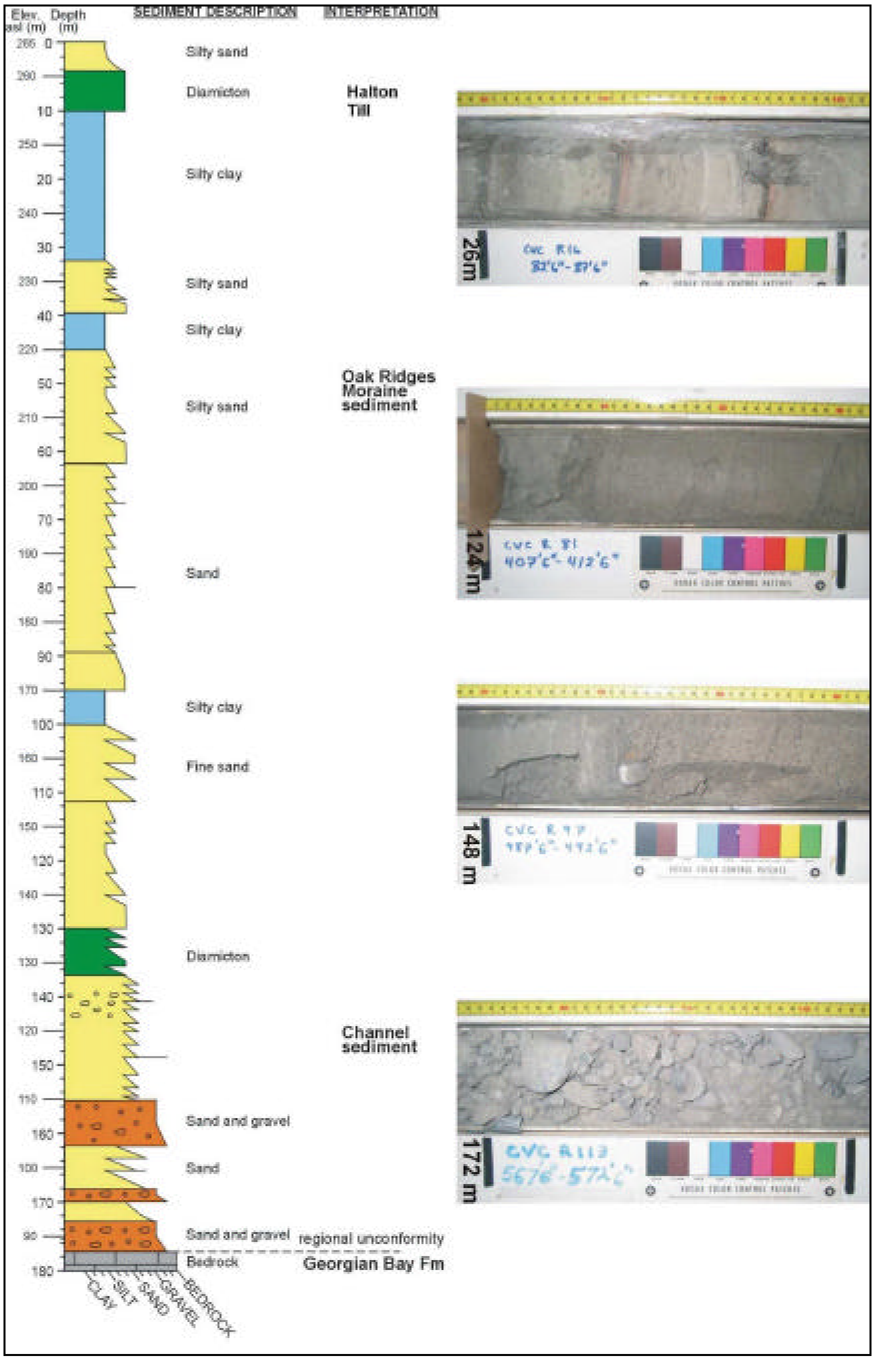

Figure 4. General log of borehole C-1 sediment core and selected photos of sediment facies. Note coarse sediment of the channel fill overlain by a succession of fining upward sand and silt cycles.

Updating of the Three-dimensional Hydrogeological Model of the Virttaankangas Area, Southwestern Finland

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Introduction. The Virttaankangas glaciofluvial/glaciolacustrine complex has been studied intensively for more than 40 years in order to supply the 285,000 inhabitants of the Turku area with adequate amounts of good quality potable water. The results of the earlier studies were summed up in the first three-dimensional (3-D) model of the Virttaankangas area by Artimo et al. (2003 a, b).

Starting point of the study. By contemplating the results of the first 3-D-modeling, it became apparent that further studies were needed in certain areas to ensure the dimensions and the architecture of the hydrogeological units. Some of the further work had already been suggested by Artimo et al. (2003 a), though some of the major improvements to the model had become possible due an increased amount of field data. Also the new increased size of the model enabled us to depict the continuity of hydrogeological units with a higher degree of precision.

There was no need to alter the division of the six hydrogeological units of the Virttaankangas model; the units were applied just as they were in the earlier 3-D model. To depict the northern and eastern outskirts of the silty–clay overlying the glaciolacustrine fine sand – silt sediments and the resulting confined aquifer, the modeled area was extended from the earlier 54 km^2 to 80 km^2 (10 x 8 km) (Figure 1).

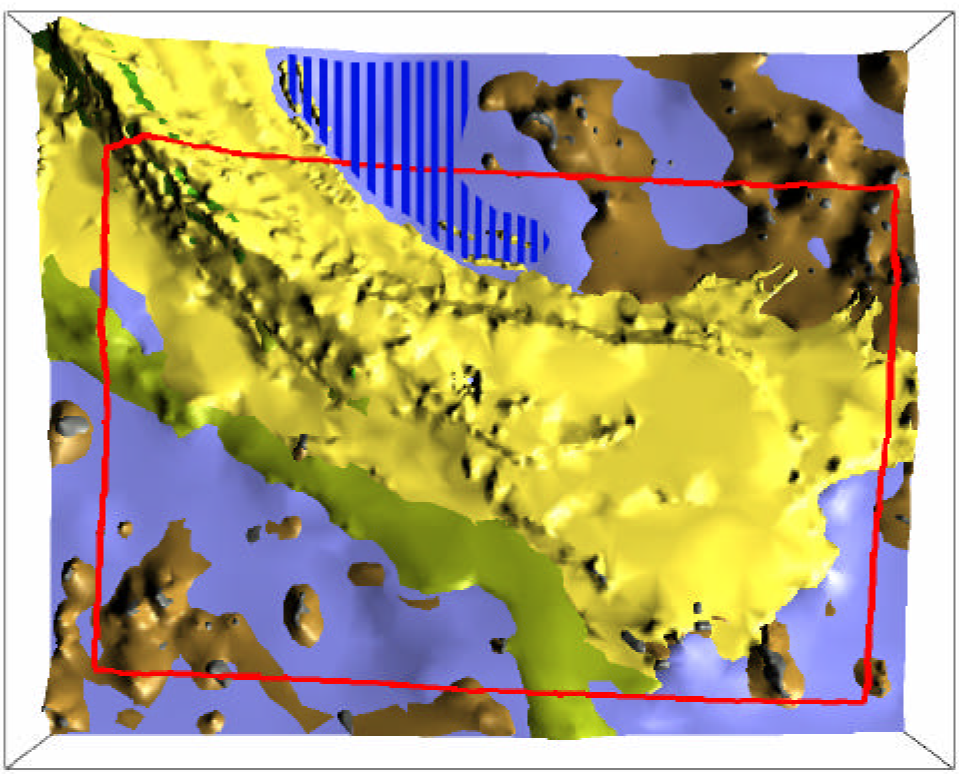

Figure 1. Updated Virttaankangas 3-D model (10 x 8 km = 6.2 x 5.0 miles). The red box shows the limits of the older Virttaankangas 3-D model. The area of artesian ground water occurrence is rasterized.

Field work. After the completion of the first 3-D model, many additional studies have been done in the study area. The results of the first 3-D modeling were partly used to plan the further studies. These studies included:

- Nearly 50 borings into bedrock and 15 borings to the uppermost surface of the silt-clay unit, which supports the perched groundwater table.
- Several kilometers of ground penetrating radar (GPR) sounding lines, which gave a high resolution picture of the topmost 10 to 15 meters of the sediments coarser than fine sand.
- 23.7 kilometers of gravimetric measurement lines made by Geological Survey of Finland in the area of the confined aquifer.
- Re-interpreting older aeromagnetic studies (Mattson et al 1991) (possible since new drilling data was in use), which lead to better understanding of the shape, depth, and continuity of bedrock depressional valleys.
- Refining the picture of the bedrock topography made possible the confirmation of certain sedimentological features, like the directions of paleoflows which deposited the coarsest unit.
- Locating and mapping 22 of the artesian wells on the northern edge of Virttaankangas model area by interviewing local artesian well owners. They were asked about information on their wells' depth and other observations concerning the installation of the well. This information was analyzed together with spatial well data and discharge data.
- Pumping and infiltration tests in the different locations of the esker system. These made it possible to gain information on the hydraulic conductivities of different areas.
- Performing geochemical investigations including groundwater isotope studies, pH measurements, and tracer tests. All the data obtained from these studies were added into the 3-D -model's primary data.

Methods. All the primary data were digitized and uniformed to the same coordinate system (Finnish Coordinate System, Projection Gauss-Krüger, YKJ) and the same elevation system (N60), meters above mean sea level. Digitizing was made mainly by using Surfer 8® by Golden Software Inc. All the data were interpolated using a standard kriging interpolation method (50 x 50 meters grid size, resulting grid size 200 x 160 cells). The grid size was chosen such that it would adequately represent the data without getting too heavy to calculate. No statistical analysis of the data to support kriging was done, since the geological interpretation of the units' shape and dimensions gave considerably better results. However, the gridding was supported by adding dummy observations where needed to coincide with the geologic interpretation.

Some additional work was needed to better define some surface matrices. Especially, the surface of the bedrock did not coincide with the input data in a satisfactory manner. That was the case in places where the surface inclination trends were abrupt, particularly in the area of the deepest depression. To fix the problem, the residual data points (e.g. difference between the original data values and the gridded surface) were also interpolated, and the resulting two grids were added together. By doing so, the shape of the bedrock surface fits better with the data and geologic interpretation.

Surfer grids, one for each top surface unit, were imported to EarthVision 7™ –program, where the actual 3-D model was calculated. All of the grid surfaces were treated as depositional units, i.e. the space between two surfaces is filled with the material defined by the upper grid and the rest of the unit is cut away.

Results. The updated Virttaankangas hydrogeological model consists of six units: bedrock, till, glaciofluvial coarse, glaciofluvial /-lacustrine fine, silt-clay, and littoral sand (Figure 2). The division of the units is based on the assumption that the variation of hydraulic conductivity within the defined unit is smaller than the variation between two different units.

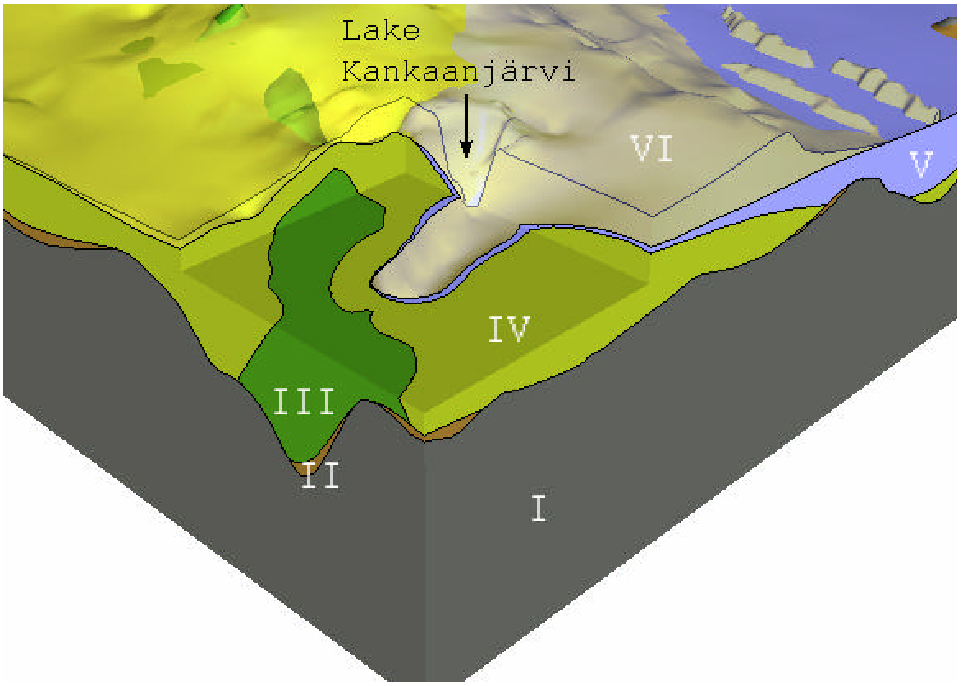

Figure 2. The hydrogeological units of the 3-D model. I Bedrock, II Till, III Coarse glaciofluvial sand and gravel. IV Fine glaciofluvial / -lacustrine sand to silt. V Silt-clay. VI Littoral sand.

The shape of the lowest unit, bedrock, has become more detailed, and the important features such as the depth and the shape of the depressions and rises are more accurate. The existence of the till unit in the modeled area is controlled by field observations and drilling data. The coarse unit has undergone only minor changes. The glaciofluvial /-lacustrine sand unit has changed considerably, since the new interpretation shows that the unit continues three kilometers further away (north) from the feeding esker causing the confined aquifer and artesian groundwater occurrence. The silt-clay unit has become more detailed in the vicinity of key areas of the planned groundwater infiltration. Also the shapes and the boundaries of the perched aquifers have become more accurately defined due to the enhanced picture of the silt-clay unit. Finally, the features of the littoral sand unit are more detailed than before; the new model shows the locations of beach ridges and some of the morphologically undetectable kettle holes, (MUKH –structures, proposed by Mäkinen 2003).

Conclusions and future work. The updating of the Virttaankangas 3-D model has resulted in a larger and more detailed model of the area. The most important results of this work are:

1) The new model shows the interconnection of the main esker system and the confined aquifer areas and their relation to the shape of the hydrogeological units, especially the bedrock, glaciofluvial / -lacustrine fine and the silt-clay units (Figure 3).
2) The complex architecture of the area around Lake Kankaanjärvi has been depicted in detail (Figure 2). These improvements together with the more detailed overall 3-D picture of the Virttaankangas area have made it possible to use the structural data from the 3-D model to compile the multi-layered ground water flow model, which will be developed in the near future. The depiction of the deeper groundwater layer and the perched groundwater layers will be combined with the 3-D model after the groundwater flow modeling is finished.

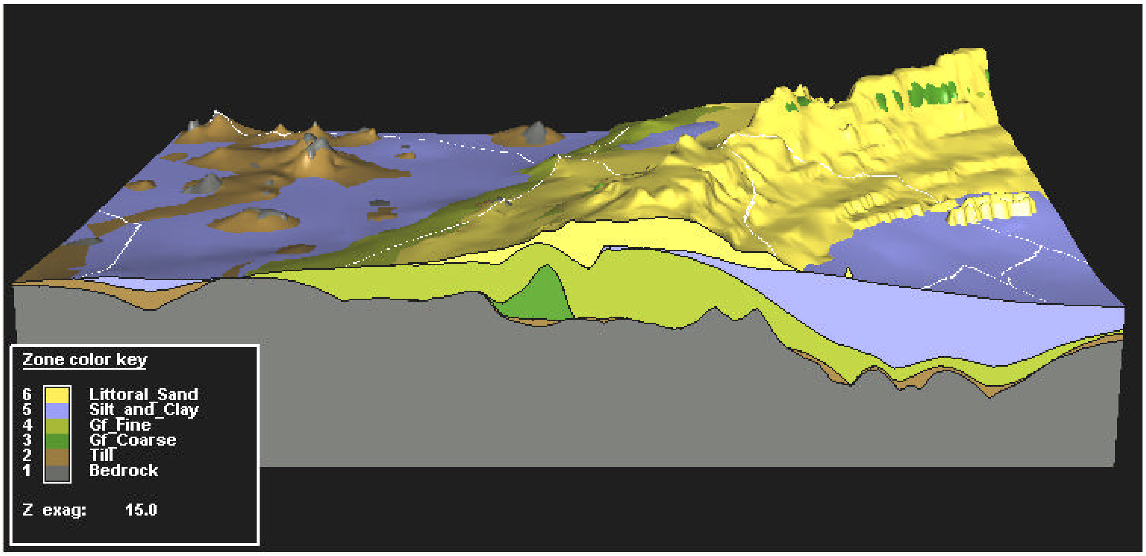

Figure 3. Cross-section of the model. Note the continuous silt-clay unit under the littoral sand. Z exaggeration is 15 x, vertical dimension of the model is 160 meters (175 yards).

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Basin Analysis Applied to Modelling Buried Valleys in the Great Lakes Basin

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Basin analysis and regional hydrogeology. Basin analysis involves the examination of geological attributes throughout a basin that then permits interpretations of the architecture, fill, formation, and evolution of a sedimentary basin. Understanding the geological history of a basin improves where data collection, synthesis and analysis occurs at local and regional scales. Basin analysis thus provides a foundation to develop an accurate basin model. The model can be used to improve the extrapolation of knowledge from data-rich to data-poor areas in order to predict the nature of the basin fill. The value of this approach has been thoroughly demonstrated in the exploration for and the assessment of energy and mineral resources. Broader application of basin analysis to problems of aquifer delineation and characterization could likely improve the ability to understand groundwater systems.

One element of the basin model, the stratigraphic framework, may be expressed, for example, in terms of rock type (lithostratigraphy), rock architecture (event-sequence stratigraphy), age (chronostratigraphy), or rock properties such as seismic velocity (seismic stratigraphy). This information may then be expressed in map form, an example of which is the traditional geological map. Depending on the goals of the study, a basin model may also be expressed in terms of fluid properties such as hydrochemistry and hydraulic fluxes.

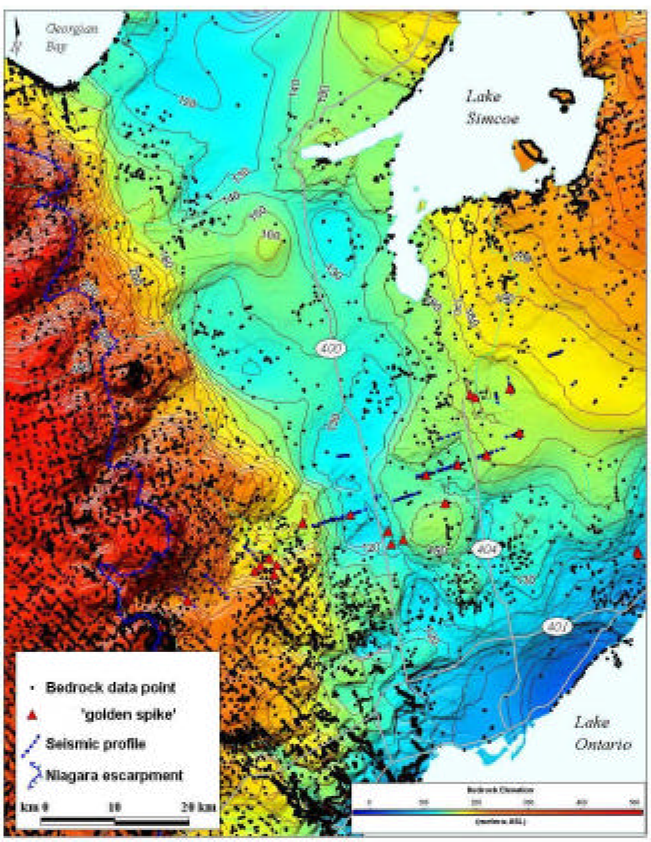

Figure 2. Topographic interpretation of the Laurentian valley based on available outcrop, borehole and reflection seismic data (modified from Logan et al., 2004). Note sparse data support in main valley trends. Surface interpolated using Inverse Distance Weighting (IDW).

Applying basin analysis to regional hydrogeology studies enhances the understanding of flow systems at local, regional, and basin scales. In larger basins, such as the Great Lakes basin, data support may be insufficient to adequately render a 3-D stratigraphic model of the basin or key elements of the basin architecture (buried valleys, Figure 1). One way to offset poor data suppport is to improve our knowledge and use of conceptual models, particularly process models that guide understanding of the geological history of a basin. For example, the rendering of both bedrock and sediment hosted buried valleys for regional groundwater modelling has demonstrated the benefit of integrating conceptual information. Integration of synthetic input may be used to define a more plausible valley architecture that then permits improved continuity of hydraulic fluxes in the flow system (e.g. Kassenaar this vol.). In this paper, we focus on a concepual framework for buried valleys in southern Ontario and the role of basin analysis in data collection, model development, and improving assessment of the regional hydrogeological significance.

Buried valley conceptual models. More than a 100 years after Spencer (~1890) inferred that a Tertiary Laurentian river network played a key formative role in shaping the Great Lakes basin, no clear idea of the geometry, extent, and the sedimentary fill in any buried valley in southern Ontario has been established. For example the Laurentian bedrock valley (Figure 1), connecting Georgian Bay to Lake Ontario, continues to be characterized from water well records with little new data contributing to systematic studies of its origin and architecture. The Laurentian valley is more than 25 km wide and 80 km long, >100 m deep, and covers an area of > 3500 km^2. A conservative estimate of the sediment fill volume is ~350 km^3. It is likely to play a key hydrogeological role in both regional and watershed-scale flow systems.

A variety of mechanisms and hypotheses for the formation and fill of bedrock valleys are suggested by recent studies in southern Ontario (e.g., Scheidegger, 1980). Erosional mechanisms likely acted in combination and were influenced by structural, lithologic, and topographic controls. Crustal geophysical data and lineament analysis suggest a relationship may occur between structural elements

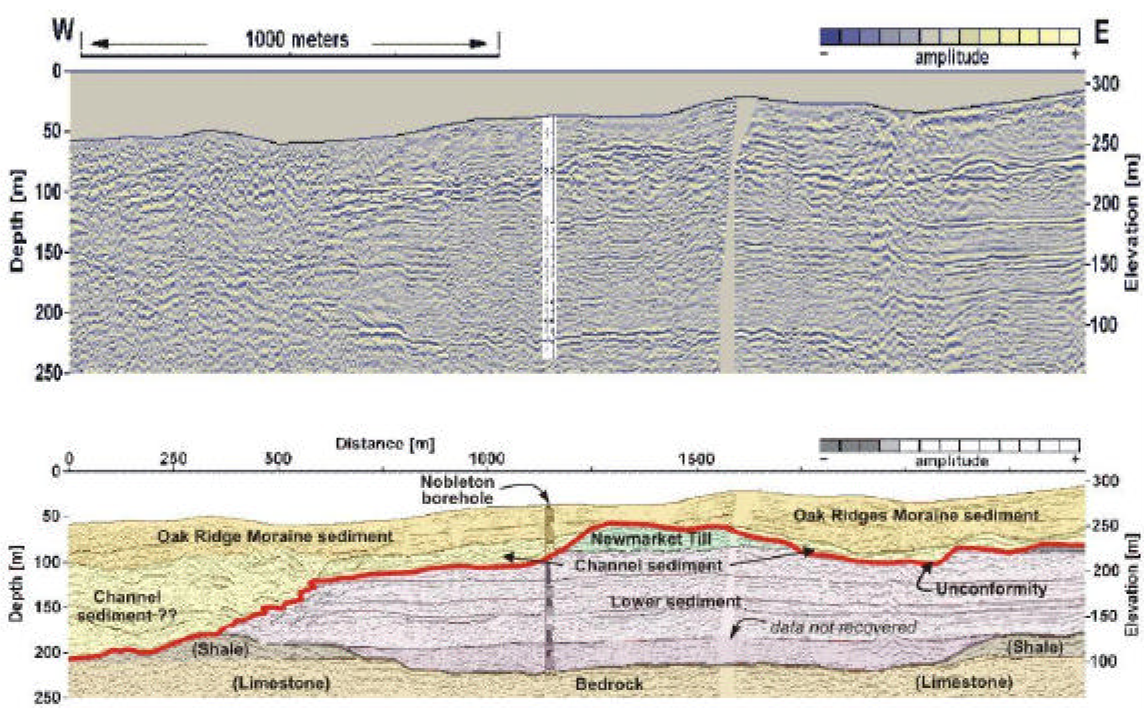

Figure 2. Seismic profile (A) and interpretation (B) in the Nobelton area of the buried Laurentian valley, indicating a bedrock-sediment unconformity where the bedrock valley cuts through shale to limestone bedrock (modified from Pugin et al., 1999). Unconsolidated sediment hosts a series of nested valley scales that locally truncate the horizontal seismic reflectors and erodes to bedrock. Note position of the seismic velocity profile (A) and sediment log (B; Figure 3).

(e.g., fractures) and the location of buried valleys (e.g., Eyles and Scheideger, 1995). Lithology and topography may also have affected the erosional action of pre-glacial, sub-aerial fluvial (e.g. Spencer, 1890), glacial (e.g,. Straw, 1968), or subglacial fluvial systems (e.g., Kor and Cowell, 1998) with each process producing different valley morphologies and erosional forms (e.g., Gilbert and Shaw, 1994). Subsequent fill of eroded valleys may have occurred during multiple cycles of sedimentation, erosion, and re-sedimentation. Nested, sediment-hosted tunnel valleys of the current Laurentian valley document (Figure 2) this process of cyclic erosion and fill (Pugin et al., 1999).

It is apparent that valley origin, orientation, geometry, and fill characteristics have developed in response to a complex set of processes that require an integrated basin approach to advance understanding of their geological origin. Furthermore, improved conceptual models of buried valleys help guide enhanced strategies for the exploration, delineation, and characterization of buried-valley aquifers. However, the processes that formed such valleys and deposited their thick sedimentary fills are poorly known and few critical data have been gathered to test basin models with respect to the valley origin as an ancestral drainage system or other origins.

High-resolution reflection seismic, borehole, and core-logging data are necessary to develop conceptual models and analysis of the buried Laurentian valley (Figures 2 and 3). These data provide the first architectural information on portions of the Laurentian valley system, as well as insights into the complex history of the thick overlying sediment infill of the valley. For instance, depositional and erosional episodes have produced a complex sediment facies arrangement in nested bedrock and ediment-hosted valleys.

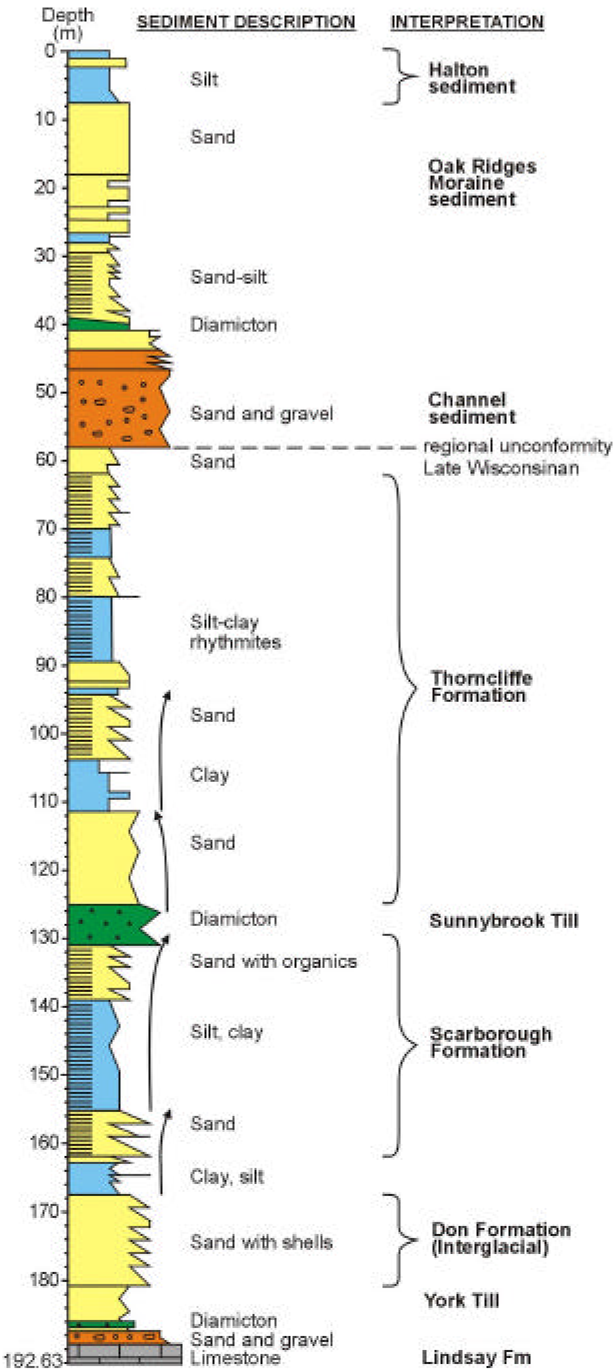

Figure 3. Continuously-cored ~192 m borehole along the Nobleton seismic line (Figure 2). The borehole shows ~70% of sediment fill in the buried Laurentian valley is interglacial (Don Fm) to middle Wisconsinan (Thorncliffe Fm) age (58-190 m depth). These units correspond to the horizontal seismic reflectors in Figure 2. This succession is truncated by a Late Wisconsinan unconformity that is overlain by a fining upward succession of gravel and sand that is interpreted to be subglacial flood deposits. Note that 1 km to the west (Figure 2), the Late Wisconsinan unconformity is incised to bedrock and the Laurentian valley fill is predominantly massive sand deposited by rapid sedimentation.

The nested stratigraphic architecture of buried valleys may significantly affect both horizontal and vertical aquifer connectivity and continuity. Furthermore, the complexities of compound valley fills (Figures 2 and 3) illustrate the need for integrated geological and hydrogeological studies that foster the collection and analysis of data to develop evolving conceptual models. These improved conceptual models should allow hydrogeologist to more confidently link model areas with sound control data to those that are poorly-constrained. Ideally, such realizations can quantitatively describe this extrapolation using the support of spatial geostatistics derived from sedimentological data and knowledge of the basin.

Acknowledgments. The authors appreciate the contribution of Jim Hunter, Sue Pullan, and Andre Pugin in providing high-quality reflection seismic data, processing, and interpretation. Charles Logan prepared Figure 1. Reviews of this paper by C. Logan and R. Knight helped to clarify the paper.

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Facilitating 3-D Analysis with Standardization Information – The Role of the National Geologic Map Database

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The U.S. Geological Survey (USGS) and the Association of American State Geologists (AASG) are mandated by Congress to provide a National Geologic Map Database (NGMDB) of standardized geoscience information that can be used to address societal issues and improve our base of scientific knowledge. This partnership serves to advance both the goal of building the NGMDB and the need for each geological survey to improve their ability to deliver map information to their users. This collaborative activity also involves the Geological Survey of Canada, universities, and the private sector.

We are addressing the mandate in three phases: 1) we are building various Web-accessible databases (e.g., a Geoscience Map Catalog of bibliographic information about maps and related information, a geologic names lexicon, and a Geologic Map Image Library); 2) we are engaged in a comprehensive standards-development effort (including the design and testing of the requisite conceptual and physical data model, and development of a standard science language for describing geologic features) in collaboration with the North American Data Model Steering Committee and international groups; and 3) we are designing a Web-accessible, distributed database of geologic map information created and served by the numerous project partners.

This paper emphasizes the NGMDB effort to promote wider use of geologic maps by coordinating development of a common, standardized framework for describing earth materials and for managing (in a standard data model) the information in map databases. The NGMDB standards-development effort is described at http://ncgmp.usgs.gov/ngmdbproject/ (see especially the NGMDB progress reports in the Digital Mapping Techniques Proceedings).

Why should we try to standardize the content and format of geologic maps? So that our maps can be better understood and more widely used by the public. Geologic maps tend to be somewhat unique products that differ, in their focus and characteristics, from earlier geologic maps of the same area and even contemporary maps of adjacent areas. This occurs because: 1) geologic concepts and mapping techniques evolve over time; 2) a project's budget and scope dictate the mapping scale and time allotted for field work; and 3) geologic mapping, especially in three dimensions, is a complex process that is undertaken for reasons as varied as the search for mineral deposits or the characterization, management, and protection of groundwater resources. However, to promote the wider use of geologic maps, especially by non-geologists, some degree of standardization of the map product is desirable. Otherwise the concepts, descriptive terminology, and even the layout and organization must be, to some degree, learned anew for each map and database.

The NGMDB's most significant standards-development challenge has been to define science terminology that is broadly accepted by the geoscience community, and therefore broadly used by geologists as they create map databases. A standard terminology also is critical to acceptance and use of geologic information by non-geologists, and so the terminology must include clear, concise names and definitions of various characteristics of earth materials that are most relevant to societal issues (e.g., textural, engineering characteristics, and groundwater flow properties of unconsolidated materials at land surface and at shallow depth). The NGMDB project invites interested geologists, hydrologists, and others to participate in defining this terminology.

Regarding the format of geologic maps and the data model within which this information is managed in a database, geologic maps most commonly are created and published in vector format, and the data model under development by the NGMDB and others was designed to support that format. Typically, geologic maps show the geology at land surface or at a specified depth or geologic horizon, and are two-dimensional in nature. Figure 1 shows the general data model design being implemented by the NGMDB, simplified to four locations (or "bins") where information can be stored, with each bin containing many database tables and fields. [For further information, see http://ncgmp.usgs.gov and Soller and Berg (in press).]

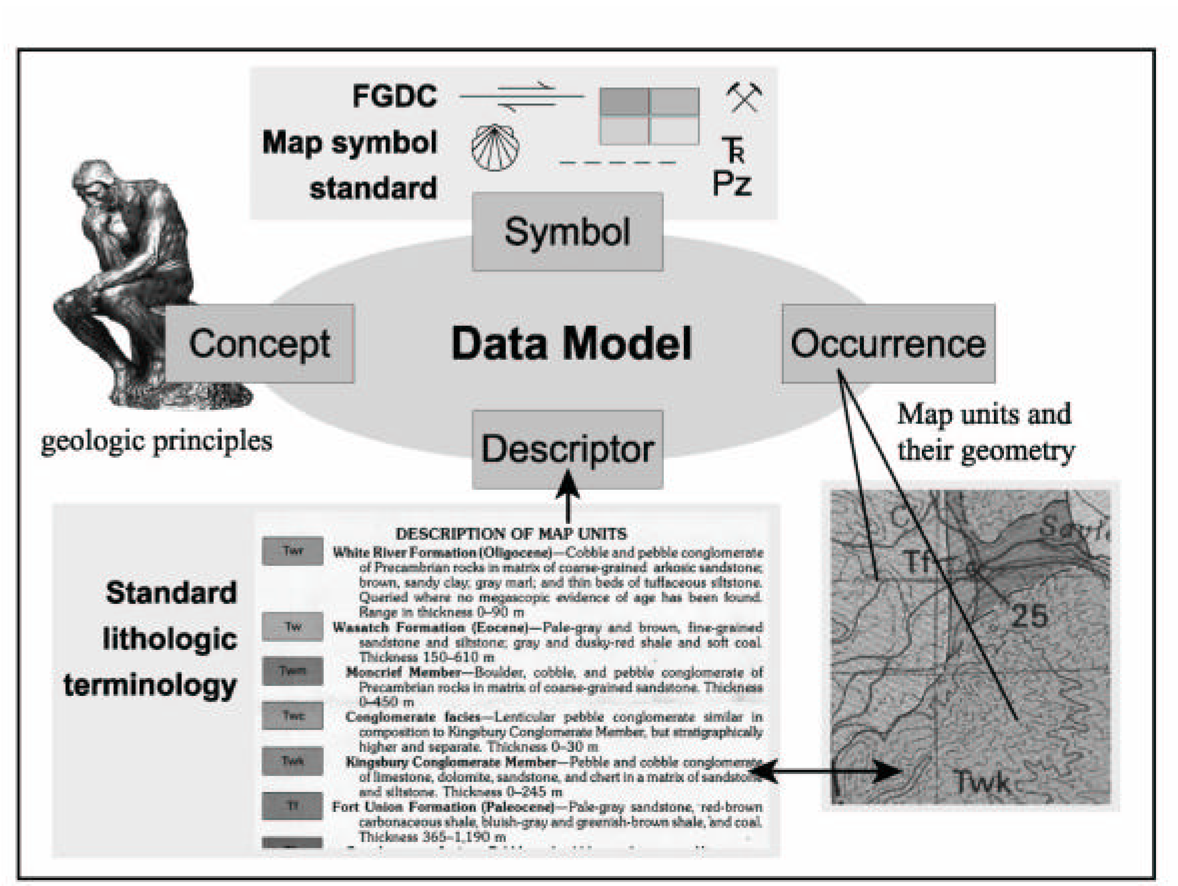

Figure 1. Simplified representation of the data model and its application to a typical, 2-D geologic map. The presence of a geologic unit on the map, referred to in the data model as an "occurrence" of that map unit, is described by: 1) its bounding contacts and faults, whose coordinates are stored as the unit's "geometry", and 2) its physical properties, which are stored as the unit's "descriptors." A more detailed description of the data model is found in Soller and Berg (in press).

Three-dimensional representations of geology can be achieved by various means including the stack-unit map, a set of stacked surfaces (in vector or raster format), or by a true, voxel-based grid. The most traditional 3-D approach is vector-based stack-unit mapping, where a vertical stack of surface and subsurface geologic units are combined into a 2-D map unit. The stack-unit characterizes the vertical variations of physical properties in each 3-D map unit. Can the data model under development by the NGMDB and others support this data type? As noted in the 3-D symposium in 2002, the data model can do so (see Figure 2a), although it has not yet been applied in this fashion.

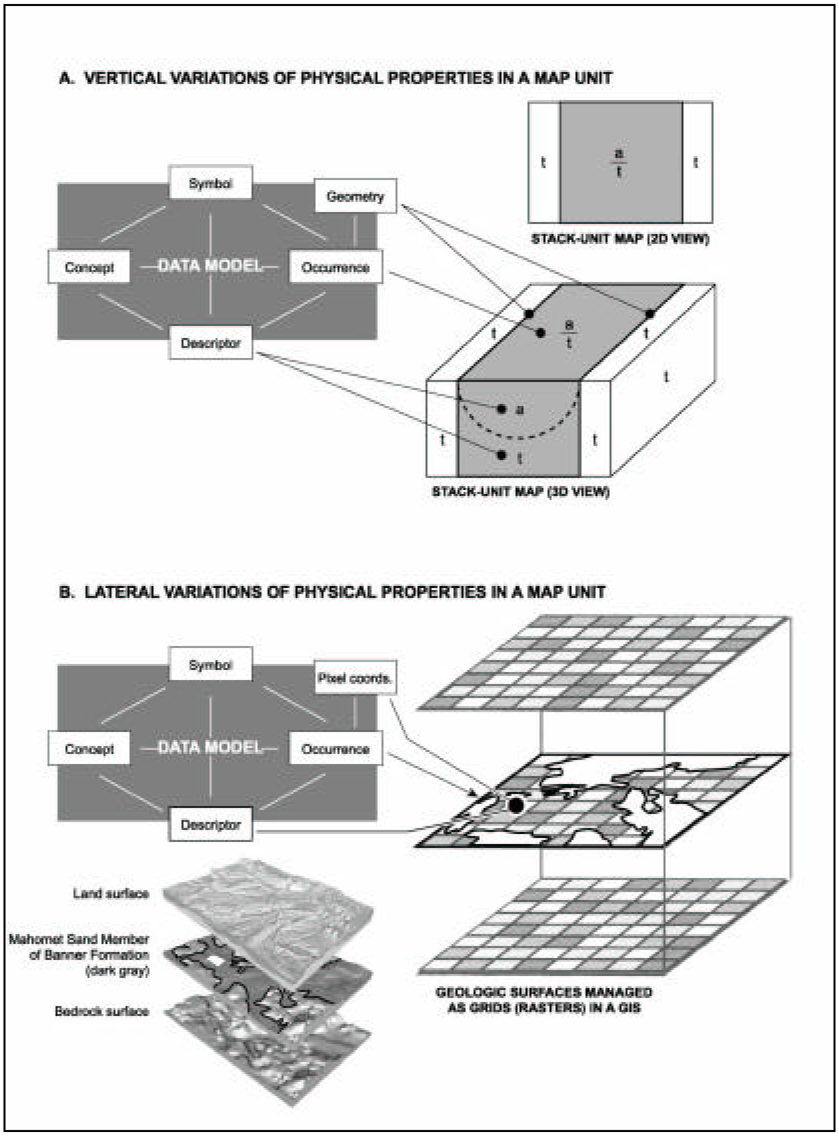

Figure 2. Approaches for representing 3-D map information and managing it in the data model. (A) Vector-based stack-unit maps depict the vertical succession of geologic units to a specified depth (base of the block diagram). Mapping approach characterizes vertical variations of physical properties in each 3-D map unit. An alluvial deposit (unit "a") overlies glacial till (unit "t"), and the stack-unit labeled "a/t" indicates that relation; unit "t" indicates that glacial till extends to the specified depth. The stack-unit's occurrence (the map unit's outcrop), geometry (the map unit's boundaries), and descriptors (physical properties of the stacked geologic units) are managed as they are for a typical 2-D geologic map. (B) Raster-based stacked surfaces depict buried geologic units and can include data on lateral variations of physical properties. In (B) from Soller et al (1999), the upper surface of each buried geologic unit was represented in raster format as an ArcInfo Grid file. The middle grid is the upper surface of a large aquifer, the Mahomet Sand, which fills a pre-glacial bedrock valley in central Illinois. Each geologic unit in raster format can be managed in the data model similarly to that for the stack-unit map. The Mahomet Sand is continuous in this area, and represents one occurrence of this unit in the data model. Each raster, or pixel, on the Mahomet Sand surface has a set of map coordinates that are recorded in a GIS (i.e., the data model bin that is labeled "Pixel coordinates", which is the raster corollary of the "Geometry" bin for vector map data). Each pixel can have a unique set of descriptive information, such as surface elevation, unit thickness, lithology, transmissivity, etc.).

Map unit descriptions, whether on traditional (2-D) geologic maps or vector-based stack-unit maps, apply to the entire unit. As a consequence, if a map unit's texture is described as "generally sandy, although fining to the east," the unit cannot be readily subdivided into areas that are sandy and those that are finer. This can be a limitation to users, especially when using the map for detailed studies. In contrast to vector-based stack-unit maps, voxel maps show every part of a geologic unit as a unique point known as a volume-pixel or voxel. Each voxel can have a unique set of attributes, therefore lateral and vertical variations in texture within the geologic unit can be described in detail. Such information is difficult to collect at depth, and so in studies where this type of representation is needed, voxel attributes tend to be computed from a few point measurements within the geologic unit.

Another approach, raster-based stacked surfaces, offers a useful compromise between vector-based stack-unit and voxel-based mapping. In this approach, a set of 2-D elevation maps show, in raster format, the surface of each buried geologic unit. These surfaces are in many cases rasterized from conventional, vector-based maps. Unlike the vector-based stack-unit map, they provide the opportunity to model the surface elevation and thickness of each unit, and to assign unique physical properties to each location on the unit's surface. Although not as detailed as a voxel representation, this approach requires less information and fewer assumptions about the 3-D variation of properties within the unit, and can be created using conventional GIS software (e.g., ArcGIS). Lateral variations in a physical property such as texture can be recorded; this is informative for units such as alluvium, which may have distinct subenvironments with different characteristics (e.g., coarser material in the main channel, and finer material in overbank areas and tributaries).

Raster-based stacked surfaces (and probably, by extension, voxel-based maps) can be represented in the data model, as shown in Figure 2b. This raster-specific information can significantly improve the value of geologic data when applied to, for example, groundwater modeling. The 3-D geometry of the glacial aquifer shown in Figure 2b was provided to a private groundwater consortium in order to develop a regional groundwater flow model. The aquifer is composed of coarse sand and gravel in the main channel but is finer-grained in the tributaries because sediment dammed the margins of the main channel, causing lakes to form in tributaries. When the 3-D information was provided to the consortium, the authors did not have sufficient data to assign to the units any lateral variations in texture. As a result, the groundwater modelers had to assume a homogenous aquifer. Raster surfaces that showed lateral variations in sediment texture would have enabled the modelers to consider the heterogeneity that was known to exist within that aquifer.

The NGMDB project is working with other U.S. and Canadian agencies and the U.S. Federal Geographic Data Committee to develop these standards. We invite geologists and other scientists to work with us to build standards that will be long-lived and useful to geologists in the field collecting and interpreting new information, and to non-geologists who may choose to consider using geologic information to address complex societal issues.

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Integrating 3-D Facies Analysis of Glacial Aquifer Systems with Ground-water Flow Models: Examples from New England and the Great Lakes Region, USA

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Modern ground-water flow models, geotechnical studies, and science-based land-use planning require knowledge of the distribution of surficial earth materials from land surface to the top of bedrock (e.g., Masterson and others, 1997a,). To be useful, modern geologic maps must portray such information three dimensionally in a way that is consistent with the regional stratigraphic framework, geotechnical classifications, and the most recent understanding of geologic depositional processes (Masterson and others, 1997b, Central Great Lakes Geologic Mapping Coalition, 1999). The evolution of 3-D geologic maps of glacial meltwater deposits demonstrates new 3-D mapping and analytic techniques now available for these studies in the desktop computer environment.

The highly productive glacial aquifers in the valleys and lowlands of the northern U.S. are composed of ice-channel, glaciofluvial, glaciolacustrine, and glaciomarine deposits, which traditionally have been differentiated as lithostratigraphic formations (e.g., Willman and Frye, 1970; Lineback and others, 1983; Stone and others, 2002). Within these formation-rank units, informal allostratigraphic units comprising numerous glacial lakes and outwash systems can be distinguished (Stone and others, 2002; U.S. Geological Survey, 2001; Stone and others, in press). These individual lake and stream deposits are further related to ice-margin retreat positions in the relative stratigraphy of ice-sheet recession in various depositional basins. Detailed geologic maps (1:24,000 scale) permit precise mapping of meltwater sedimentary units within each glacial lake or valley outwash system (Jahns, 1941 and 1953; Koteff, 1966). These units, known as *morphosequences* (Koteff and Pessl, 1981), are the smallest mappable stratigraphic units on detailed geologic maps.

Morphosequences are bodies of stratified meltwater sediments that are contained in a continuum of landforms, grading from ice-contact forms (eskers, kames) to non-ice-contact forms (flat valley terrace, delta plains), that were deposited simultaneously at and beyond the margin of a glacier, and graded to a specific base level. Morphosequences each consist of a proximal part (head) deposited within or near the ice margin, and a distal part deposited farther away from the ice margin. Both grain size and ice-melt collapse deformation of beds decreases from the proximal to the distal part of each morphosequence. The head of each morphosequence is either ice marginal (ice contact) or near ice marginal. Ice-marginal morphosequences were deposited in contact with the ice margin. The heads of many ice-marginal morphosequences extended well up into the ice margin in channels and tunnels; melting of adjacent and subjacent ice caused the collapse of these headward sediments to lower positions where they commonly were buried by later sediments. Near-ice-marginal morphosequences were deposited short distances in front of the ice margin, separated from it by valley segments too steep for deposition. The surface altitude of fluvial sediments in each morphosequence was controlled by a specific base level, either a glacial-lake water plane or a valley knickpoint. Few morphosequences extend distally more than 10 km, and most are less than 2 km in length. In any one basin, individual morphosequences were deposited sequentially as the ice margin retreated systematically northward. Consequently, in many places the distal, finer grained facies of a younger morphosequence stratigraphically overlies the proximal, coarse-grained facies of a preceding morphosequence.

Six original types of morphosequences diagrammed by Koteff and Pessl (1981) are recognized across the northern U.S. Lacustrine-fan and marine-fan types are known from the northeastern U.S. (Stone and others, in press). Examples of three new types of morphosequences, deposited within holes and channels in glacial ice, are now known. Figure 1 presents these ten types of morphosequences relative to proximal-to-distal and fluvial-to-lake/marine depositional environments of the original classification. The names of these deposits have been modified (Stone and Stone, in press) from the

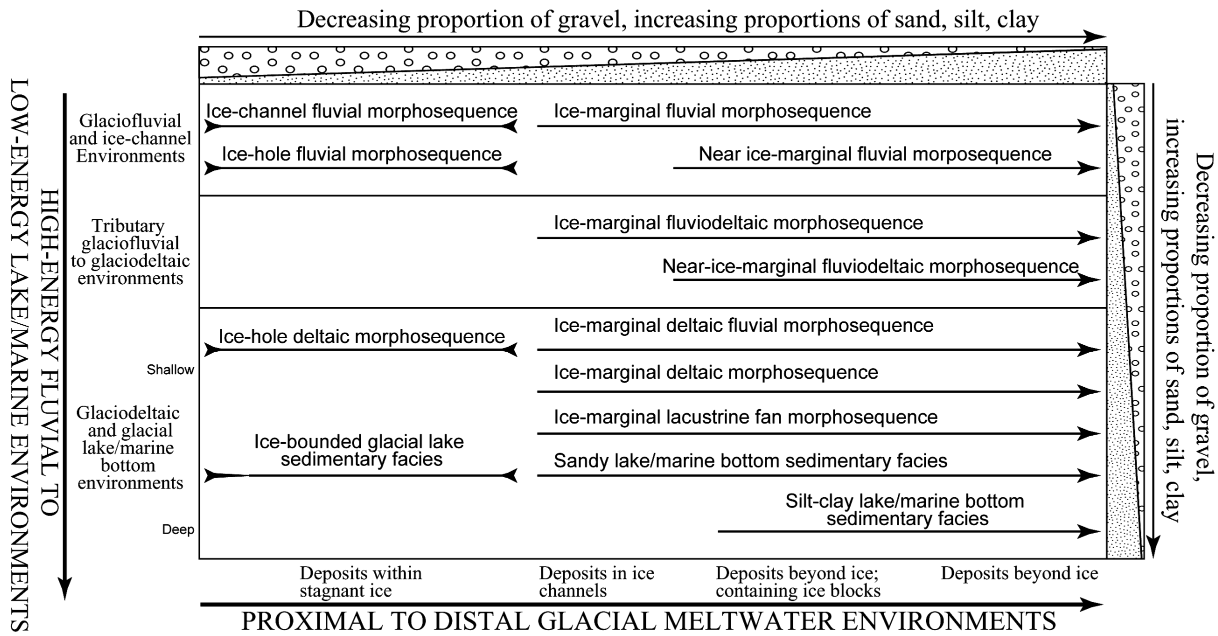


Figure 1. Relationships of ten types of meltwater morphosequences to proximal-to-distal glacial meltwater environments, and high-energy fluvial to low-energy glacial lake/marine environments. Trends in the varying proportion of gravel, sand, silt, and clay in these deposits are shown schematically.

original terminology of Koteff and Pessl (1981) to emphasize the descriptive features and the depositional environment of each morphosequence type.

Within the continuum of landforms, each morphosequence contains an assemblage of coarse- to fine grained *sedimentary facies* that were deposited contemporaneously. A meltwater *sedimentary facies* is a body of sediment that contains strata of similar texture and structure, and which is differentiable from other bodies of sediment possessing different lithic characteristics. Glacial meltwater sedimentary facies are combined either in facies assemblages within morphosequences, or are present as single mappable bodies of sediment in the distal parts of basins (Figure 2). Morphosequences typically consist of combinations of downstream-fining glaciofluvial and glaciodeltaic facies, which are related to specific environments of deposition along the path of meltwater flow from ice-proximal to distal environments (Figure 1). Through comparative studies of modern active environments (e.g., Boothroyd and Ashley, 1975; Gustafson and Boothroyd, 1987), these descriptive facies may be related to depositional facies within the stratigraphic framework of Pleistocene deposits (Stone and Force, 1982; Stone and others, 2002; Stone and others, in press). Recent mapping studies demonstrate how deep exposures, boreholes, geophysical surveys, and water-well records are used to subdivide morphosequences into a series of related sedimentary facies (U.S. Geological Survey, 2001).

The following section on *Sedimentary Facies in Glacial Meltwater Deposits* explains and illustrates (with diagrams) the 11 sedimentary facies (shown on Figure 2) that are recognized within the meltwater deposits of the region (modified from Stone and others, in press). Facies characteristics are distinct enough that these material units may be used as hydrostratigraphic facies in regional and local groundwater flow models (e.g., Anderson, 1989). Representative hydraulic conductivities, based on pump tests, infiltration tests, and contaminant plume flow velocities from locales with well documented 3-D stratigraphic control, are presented and highlighted (italicized) in this section.

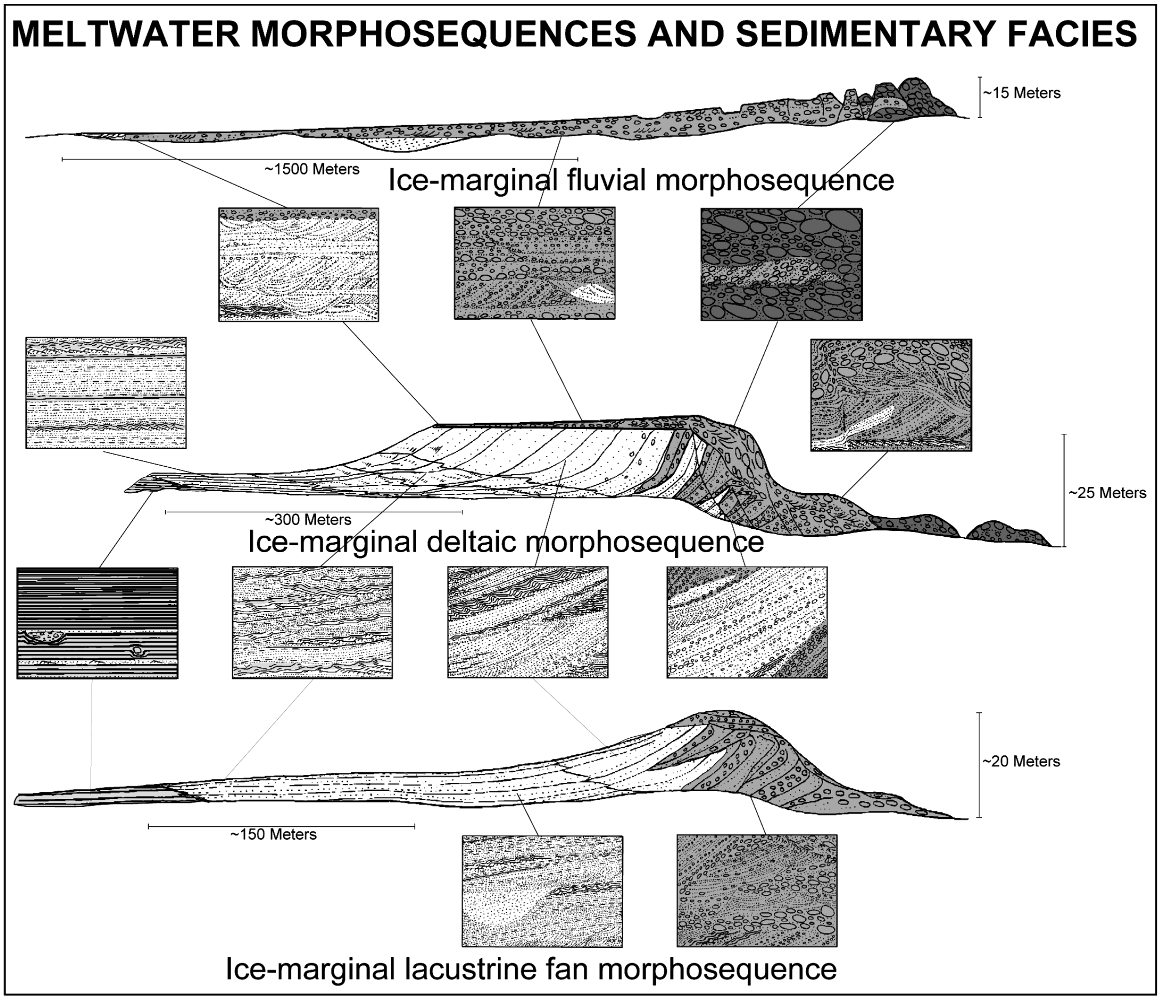
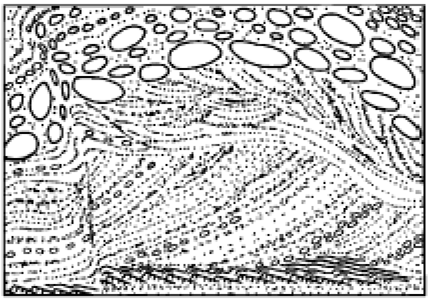


Figure 2. Assemblages of meltwater sedimentary facies within selected types of morphosequences (modified from Stone and others, in press). See section below on *Sedimentary Facies in Glacial Meltwater Deposits* for a detailed description of the 11 sedimentary facies.

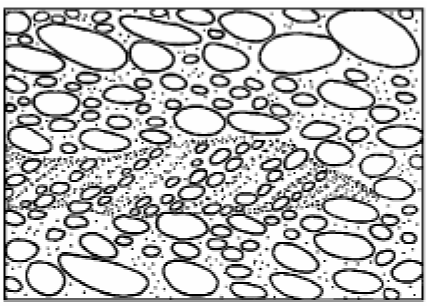
SEDIMENTARY FACIES IN GLACIAL MELTWATER DEPOSITS

GLACIOFLUVIAL SEDIMENTARY FACIES



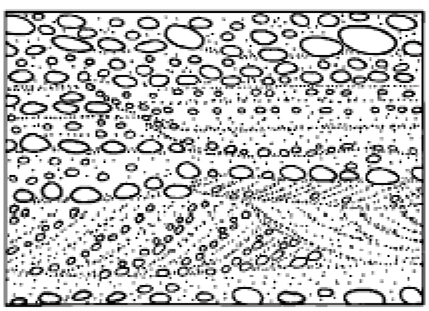
Sand and Gravel Ice-Channel Glaciofluvial Facies

Pebble-cobble gravel beds, massive planar bedded, planar-tabular crossbedded
Interbedded medium-coarse sand, planar bedded, planar-tabular and trough crossbedded, ripple laminated
Minor sets of silt and clay laminae
Three to 30 m total thickness
Horizontal hydraulic conductivity 88 m/day,
Ratio of horizontal to vertical conductivity 3:1
In ice-contact esker and ice-channel deposits



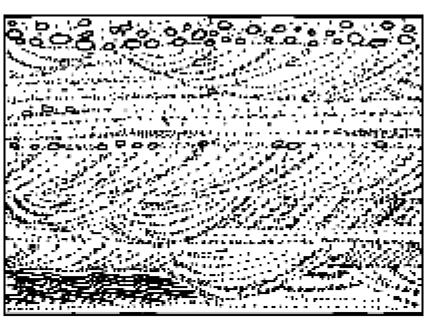
Coarse Gravel Glaciofluvial Facies

Cobble-boulder gravel beds, coarse sand matrix, massive planar bedded, planar-tabular crossbedded
Minor interbedded medium-coarse sand beds, planar-tabular and trough crossbedded, ripple laminated
No silt or clay beds
Two to 15 m total thickness
Horizontal hydraulic conductivity 106 m/day,
Ratio of horizontal to vertical conductivity 3:1
At ice-marginal head of morphosequences



Sand and Gravel Glaciofluvial Facies

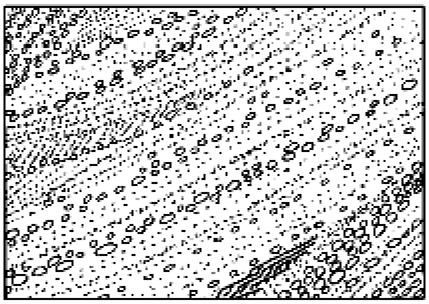
Pebble-cobble gravel beds, massive planar bedded, planar-tabular and trough crossbedded
Interbedded medium-coarse sand beds, planar-tabular and trough crossbedded, ripple laminated
Minor sets of silt laminae, minor clay
One to 15 m total thickness
Horizontal hydraulic conductivity 88 m/day,
Ratio of horizontal to vertical conductivity 3:1
In outwash deposits and as delta topset beds



Coarse Pebbly Sand Glaciofluvial Facies

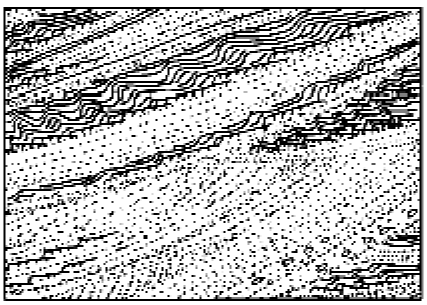
Coarse pebbly sand beds, massive planar bedded, planar-tabular and trough crossbedded
Interbedded pebble gravel beds, and medium-coarse sand beds, planar bedded and ripple laminated
Minor sets of silt laminae, minor clay
One-half to 8 m total thickness
Horizontal hydraulic conductivity 73 m/day,
Ratio of horizontal to vertical conductivity 3:1
In distal outwash or delta topset deposits

\GLACIODELTAIC SEDIMENTARY FACIES



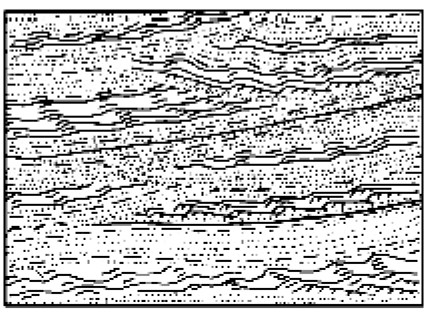
Sand and Gravel Glaciodeltaic Foreset Facies

Pebble-cobble gravel in planar-tabular and trough foreset beds, parallel bedded, minor openwork gravel
Interbedded fine-coarse sand in trough foreset beds, parallel bedded, planar-tabular crossbedded, and ripple laminated
Some sets of silt laminae, minor clay, minor flowtills
Two to 30 m total thickness
Horizontal hydraulic conductivity 85 m/day,
Ratio of horizontal to vertical conductivity 3:1
In proximal parts of deltaic deposits



Sandy Glaciodeltaic Foreset Facies

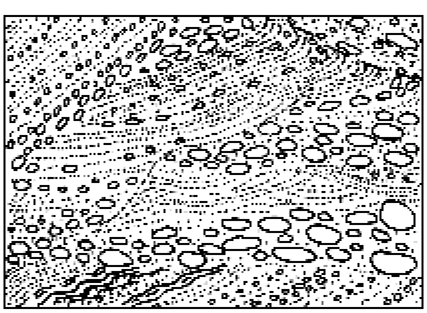
Fine-coarse sand in planar-tabular and trough foreset beds, parallel bedded, ripple laminated
Interbedded fine pebble gravel in planar-tabular foreset beds, parallel bedded
Interbedded sets of draped silt and minor clay laminae
Two to 30 m total thickness
Horizontal hydraulic conductivity 61-45 m/day,
Ratio of horizontal to vertical conductivity 5-10:1
In central and distal parts of deltaic deposits



Fine Sand Glaciodeltaic Bottomset Facies

Fine-medium sand in planar and trough bottomset beds, parallel bedded, ripple laminated
Interbedded sets of draped silt and minor clay laminae
Two to 10 m total thickness
Horizontal hydraulic conductivity 45-21 m/day,
Ratio of horizontal to vertical conductivity 10-30:1
In distal parts of deltaic deposits

GLACIAL LAKE/MARINE-BOTTOM SEDIMENTARY FACIES

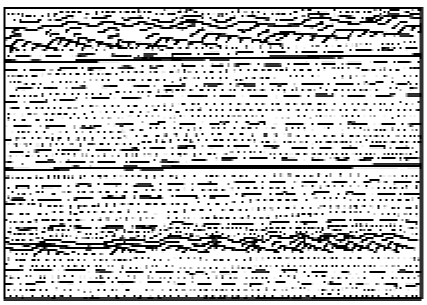


Sand and Gravel Glaciolacustrine Fan Facies

Pebble-cobble gravel, coarse sand, and minor flowtill in planar-tabular and trough foreset beds, parallel bedded, planar-tabular crossbedded
Local compact till at top of section
Minor interbedded fine-medium sand, parallel bedded, ripple laminated
Minor interbedded sets of draped silt and minor clay laminae
Two to 20 m total thickness
Horizontal hydraulic conductivity 85 m/day,
Ratio of horizontal to vertical conductivity 3:1
In proximal parts of lacustrine/marine fan deposits

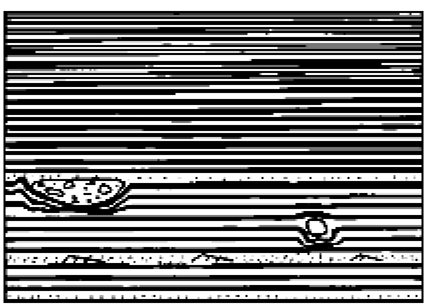
Sand-Silt Glaciolacustrine Fan Facies

Fine-medium sand in planar and trough bottomset
beds, parallel bedded, ripple laminated
Interbedded sets of draped silt and minor clay laminae
Two to 20 m total thickness
Horizontal hydraulic conductivity 45 m/day,
Ratio of horizontal to vertical conductivity 10:1
In distal parts of lacustrine/marine fan deposits



Sandy Glacial Lake or Marine Bottom Facies

Fine sand-silt, irregularly spaced parallel laminae,
ripple laminated
Interbedded sets of silt and clay laminae
Marine facies contains massive silt-clay
10 to 60 m total thickness
Horizontal hydraulic conductivity 9 m/day,
Ratio of horizontal to vertical conductivity 100:1
In lake-bottom deposits proximal to deltaic deposits



Silt-Clay Glacial Lake-Bottom Facies

Silt-fine sand and clay in irregularly spaced parallel
laminae or regularly spaced varve couplets, minor
ripple laminated
Minor interbedded fine sand, parallel laminated,
ripple laminated
2 to 60 m total thickness
Horizontal hydraulic conductivity 3 m/day,
Ratio of horizontal to vertical conductivity 100:1
In distal lake-bottom deposits

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Visualizing the Stratigraphic History of Buried Depositional Units in the Amargosa Basin, SW Nevada and in Berrien County, SW Michigan

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The Amargosa Basin in southwestern Nevada and Berrien County in southwestern Michigan are two very different geologic environments that have been studied in an attempt to visualize and understand the depositional history of the subsurface geologic units. These studies are funded by the U.S. Geological Survey to not only understand and characterize the subsurface geology in the study areas, but to apply this understanding to water issues relating to quality, quantity, and contamination of the ground-water system. In both study areas, stratigraphically complex shallow aquifers have been studied using borehole data and three-dimensional (3-D) modeling of lithologic data, combined with surface geologic mapping and knowledge of the basin's depositional history.

The Amargosa Basin is a semiarid desert environment in southwestern Nevada. The study area is approximately 75 by 25 km or 1875 sq km (47 by 16 miles or 752 sq miles). The depositional history is characterized primarily by alluvial infilling of a tectonically formed basin that is intermittently internally drained, and infrequently the location of regional ground water discharge. Much of the deep basin fill is Miocene coarse-grained sedimentary rocks and tuff on Paleozoic limestone. Overlying Pliocene and younger rocks are of greater interest as aquifers because of the shallow water table in the basin. Drillholes in the northern part of the Amargosa Basin have intersected the modern water table at approximately 90 m. However ground water does intersect the surface today in the southern part of the basin. Where ground water intersects the ground surface in this arid environment, unique fine-grained deposits are formed as the vegetation at the wet soggy marsh-like environment traps eolian fines and preserve a unit of palustrine deposits characterized by the presence of freshwater limestone, fine silts and sands, and infrequent organic vegetative mats. Quaternary and Cenozoic volcanic basalts, ashes, and tuffs are also interbedded within the alluvial and palustrine units. The presence of two major intermittent drainages, the Amargosa River that enters the basin from the northwest, and Fortymile Wash that enters the basin from the northeast convolute the Amargosa Basin history. The convergence of the drainages, and the eventual exit of the Amargosa River from the basin, is tectonically controlled by buried and exposed faults expressed in geophysical interpretations as well as regional tectonism in the Death Valley area where the Amargosa River ends in a closed depression. This regional tectonic control has also caused the river to migrate from north to south across the northwest trending basin. The resulting basin fill in the Amargosa is an extremely complex interfingering of coarse- to fine-grained alluvium derived from the regional volcanic and limestone mountain ranges, fine grained playa and palustrine deposits, eolian sands, and finally, numerous interbedded volcanic units.

Berrien County in southwestern Michigan is approximately 54 by 25 km or 1350 sq km (34 by 16 miles or 544 sq miles). A variety of surficial deposits that comprise the principal aquifers in the county are the result of regional advances and retreats of the latest Pleistocene continental glaciers. The modern water table is between <1 m and 290 m below the surface, however the average depth for water is between 9 and 17 m. Glaciofluvial deposits range in thickness from 20 to 150 m above Paleozoic bedrock. The late Wisconsin glacial meltwater deposits leave a history of till sequences, coarse to fine grained fluvial sands and gravels, and ice marginal deltaic sequences including lake sediments. Two major drainages, the Paw Paw River from the northeast and the St. Joseph River from the southeast merge in the center of the county and flow west into Lake Michigan. Alluvial terraces are preserved adjacent to the drainages, and these deposits as well as the glaciofluvial deposits are capped by fine-grained eolian fine sand. Sand dunes are found adjacent to Lake Michigan, and infrequently preserved inland. Deep oil and gas exploration drillholes completed throughout the county intersect early Mississippian to late Devonian sandstone, shale and limestone below the glacial deposits. The bedrock is nearest the surface in the southern part of the county, where it is less that 20 m below the surface. There is less than 100 m of surface elevation variability (177-271 m) over the entire county today; however, the paleosurface, expressed by the top surface of the buried Paleozoic bedrock, has a surface variability of between 125 and 145 m.

Drillhole data were compiled for both areas from a number of sources, including state records for water wells, private industry, local engineering companies, USGS and state exploratory boreholes. Mining records were available from the Nevada study area. Considerable effort was made to cull descriptions from boreholes that were poorly located or lacked detail. An attempt was made to sample sites over as broad an area as possible. In the Amargosa basin, records from 505 boreholes were used; in Berrien County records from 5919 water well holes were initially compiled. The first step in the data analyses was to simplify the driller's descriptions to an internally consistent set of lithologic descriptors that could be used as stepping-stones to geologic interpretations. These initial sedimentary lithologic descriptors, sixteen in the Amargosa Basin and thirteen in Berrien County, are defined by the characteristics of the driller's nomenclature, for example gravel, sand and gravel, clay, and sand. These lithology units were used in Rockworks 2002 to generate cross sections and 3-D lithology models. These initial lithology units were converted into stratigraphic units that have genetic facies meaning. In the Amargosa Basin for example, gravel, sand and gravel, and sand, clay and gravel were grouped to from an alluvial unit, and clay and sand into a playa unit. In Berrien County, sand and a trace gravel, and sand and clay, were grouped into a lacustrine unit, and clay and a trace gravel, into a till unit. In both study areas, subsurface stratigraphic units form a complexly interfingering sequence with poor age constraints. Because of these geologic complexities, no attempt was made to define a stacked sequence of units. Instead, the interpreted stratigraphic units were treated as interval data and using the application in Rockworks designed to visualize geochemical or interval data, 3-D images were produced to visualize the predicted distribution of these stratigraphic units. Geologic facies models and geophysical data are used to constrain the size and shape of the resulting volumes representing the stratigraphic units. This same technique has been used on the volcanic-rock units in the Amargosa Basin. Use of this technique does not result in a predictable stacked stratigraphic sequence throughout the basin, nor does it explicitly account for dipping beds. However, this technique is useful in mapping stratigraphically complex sequences where specific facies environments may be related to aquifer quality.

Depth to Bedrock: Three-dimensional Bedrock and Overburden Thickness Methodology for Mineral Aggregates and Groundwater Geology Mapping in Ontario

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The Ontario Geological Survey (OGS) has developed a methodology for determining an area's bedrock elevation and overburden thickness, that provides a valuable tool for carrying out groundwater geology mapping projects. OGS is also responsible for producing Aggregate Resources Inventory Papers (ARIPs), which are used in municipal planning to help assure future supplies of crushed stone, sand and gravel. A key component of each ARIP is a bedrock resource map that shows the distribution of suitable bedrock and thin-drift areas (generally < 8m overburden). Starting in 2004, the 3-dimensional bedrock and overburden thickness methodology will be used in creating the ARIP bedrock resource maps.

Data used in determining the bedrock surface and overburden thickness include: a provincially standard digital elevation model (DEM), provincial water well records, geotechnical boreholes, and surficial and bedrock geology maps. Supplementary data include: topographic maps, aerial photographs, and Landsat imagery. Data sets are assessed and appropriately filtered. For example, boreholes with reported surface elevations differing by more than 10 m. from the DEM are excluded from interpolations, because their locations may be inaccurate.

Borehole layer information is translated to "bedrock" or "overburden" using an OGS translation table and database query. The depth to bedrock for each borehole is calculated. Borehole bedrock elevations are calculated as DEM elevation minus depth to bedrock. Outcrops are assigned DEM elevation as bedrock elevation, and vertices of thin-drift areas are assigned DEM elevation minus 1 m.

Kriging is used to interpolate an initial bedrock elevation surface from all the bedrock elevation points. Wells not reaching bedrock (overburden wells), but going deeper than the initial kriged surface, are assigned a bedrock elevation of DEM elevation minus well depth. These elevations are added to the interpolation set, which is kriged again to honour the deep overburden wells. This bedrock surface is carefully inspected in plan and perspective views for evidence of problems in the dataset. Once the data problems are resolved, the bedrock elevation surface may be kriged again. Figure 1 illustrates the bedrock elevation computations.

An overburden thickness surface is calculated as DEM minus bedrock elevation surface. The mineral aggregates geologist uses the overburden thickness information, bedrock geology, and land use information to draw preliminary bedrock aggregate potential areas, which are checked during fieldwork. New information from fieldwork is used to finalise the Selected Bedrock Areas for ARIP mapping. Figures 2 and 3 illustrate the overburden thickness and aggregate potential derivations.

This approach is also used by OGS in 3-dimensional groundwater mapping projects and Groundwater Resource Information Papers (GRIPs). This methodology enables the production of bedrock topography maps, overburden thickness maps and 3-dimensional models of fundamental stratigraphic units. Stratigraphic "picks" are used to refine the continuity of key units.

The following software is used by OGS in this work:

- Microsoft ® Access ® database software.
- ESRI ® ArcGIS ® and Spatial Analyst ® geographic information system software.

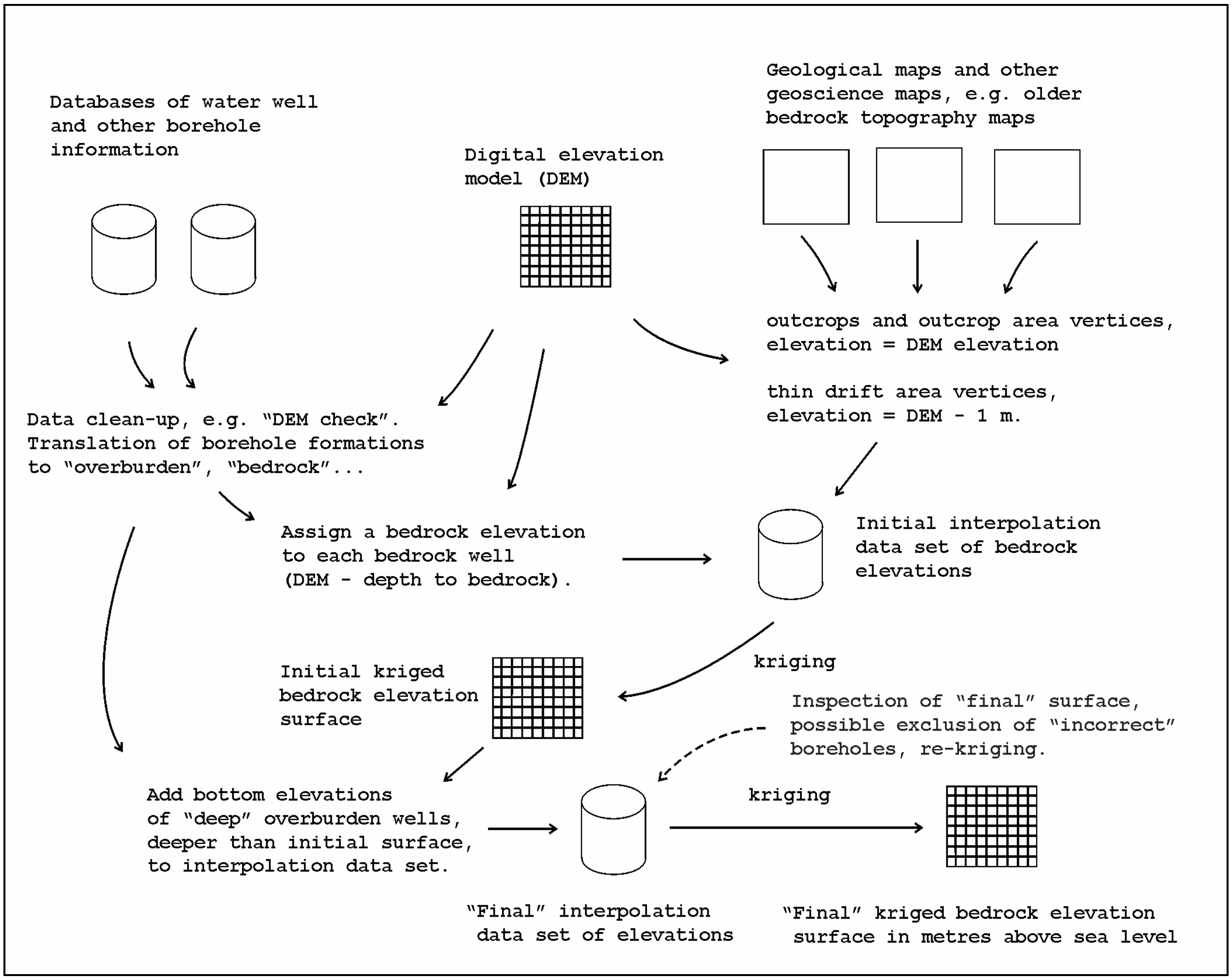

Figure 1. Computing the bedrock elevation surface.

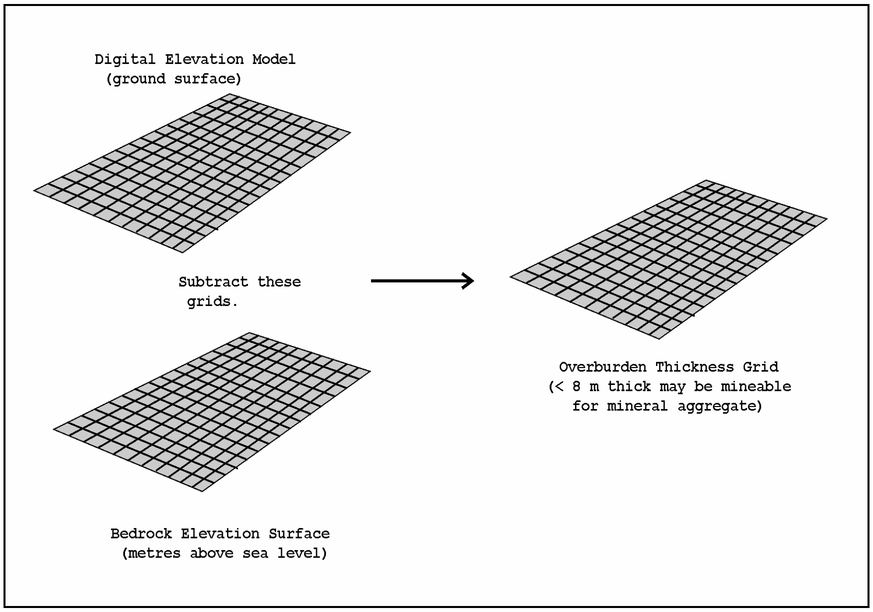

Figure 2. Calculating the overburden thickness.

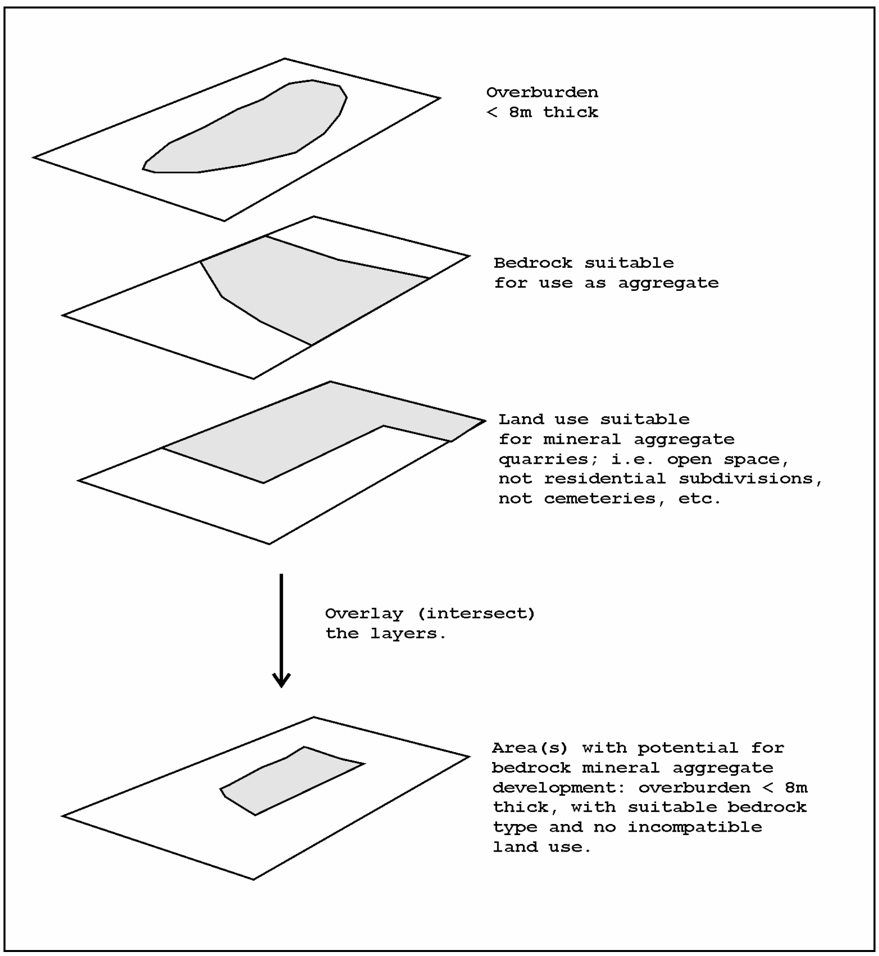

Figure 3. Determining bedrock mineral aggregate potential.