Geological Survey of Canada Open File 1449

Three-Dimensional Geological Mapping for Groundwater Applications

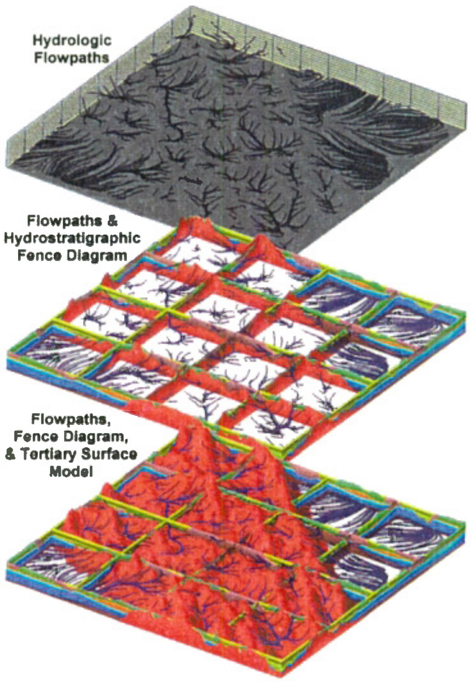
Workshop Extended Abstracts

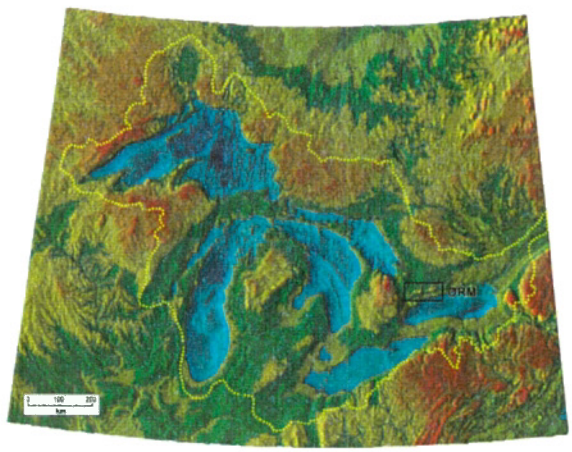
Denver, Colorado - October 26, 2002

Convenors:

L. Harvey Thorleifson, *Geological Survey of Canada*

Richard C. Berg, *Illinois State Geological Survey*





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sponsored by

Geological Survey of Canada
601 Booth Street
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and

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Available from
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

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Thorleifson, L.H., Berg, R.C.
2002: Three-Dimensional Geological Mapping for Groundwater Applications; Geological Survey of Canada, Open File 1449, 87 p.

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Introduction - The Need for High-Quality Three-Dimensional Geologic Information for Groundwater and Other Environmental Applications

Thorleifson, L.H.[1] and Berg, R.C.[2]
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The pressing need for high quality 3-D geological information on shallow deposits has become apparent since the 1960s as growing attention has been paid to environmental and land-use issues, particularly in urban and suburban areas (e.g., Larson and Hackett, 1965). After much emphasis since the 1970s on contaminated sites, attention is now shifting to regional groundwater systems, to ensure their long-term sustainable development (Sun and Johnson, 1994; Bradbury et al., 2000; Rivera et al., 2002). Geological reports and maps therefore are increasingly required by decision makers to provide a more rational basis to balance demands of sustainable groundwater use, mineral resource development, and safe burial of wastes.

Geological mapping has been a cornerstone of the methods used by geologists to understand earth history. Based on the challenge of incomplete geological information from commonly sparse data, geologists have evolved methods for acquisition, selection, classification, and management of information to permit the best possible interpretations. Importantly, geologists have developed process-based models as a means of predicting what likely occurs between and beyond the observations (e.g. Walker and James, 1992; Miall, 1999).

With accelerating technological capabilities, however, a new era in geological mapping is rapidly unfolding as new tools are developed. There now are new drilling and geophysical techniques to acquire data, increasingly powerful computer hardware and software to manage large databases as well as to analyze and portray models of complex geology. Computing and data-handling capabilities equal to or greater than the mainframes once accessible only to petroleum geologists at the largest exploration companies now reside on almost any desktop, and even in portable computers.

Geologists have been quick to seize these new data acquisition and analysis opportunities, but have also found that with these new capabilities come daunting challenges. Whether individual geologists resist or pursue these new technologies, the geological mapping community will benefit from a lively exchange of ideas on how best to use this new generation of tools. More importantly, the users of geological information will benefit from this exchange as well, as applications are enhanced.

The best new technology provides little help to a geologist confronted with sparse data. In contrast to the mapping methods many of us first learned to use in mountainous areas with abundant exposures, 3-D mapping of near-surface geology, especially in areas of low relief, has to rely on data from drilling and geophysical investigations that only reveal glimpses of the lateral and vertical extent of the strata in the subsurface (USGS, 1999). Where data are available, the majority typically comes from water well drillers' descriptions of the near-surface materials. The interpretation of this low quality data is heavily reliant on the few sites that have been adequately logged and interpreted. The success of many 3-D mapping projects therefore depends on a few carefully selected stratigraphic reference sites, and interpolations of the intervening geology are best guided by a firm comprehension of the geologic processes responsible for the deposits (e.g. Miall, 2000; Sharpe et al., 2002; Anderson, 1989; Fraser and Davis, 1998).

Pressing demands for information in relation to critical water resource and environmental questions are becoming more compelling at the same time that technological capability is accelerating. But there is a continuing lack of high quality data, even in the densely populated and industrialized parts of the U.S., Canada, and Europe that are covered by thick glacial deposits, where the ongoing challenge of complex geology produces a sustained and urgent need for developing optimal mapping and modeling methods. We therefore must ensure good communication among mappers who are experimenting with new ways to deal with large datasets, developing ways of integrating data of variable quality with high quality test holes and geophysics, and developing methods to construct 3-D geological models of appropriate detail that can be used for land and water applications such as hydrogeologic modeling.

The October 26, 2002 workshop in Denver on "Three-Dimensional Geological Mapping for Groundwater Applications" is a response to this need. The meeting is a follow-up to a similar workshop held at the 2001 North-Central GSA meeting in Bloomington, Illinois (Berg and Thorleifson, 2001). The Illinois State Geological Survey and the Geological Survey of Canada have chaired both events.

The workshops have been offered to provide opportunities for geologists to share information on methods for construction of 3-D geological maps intended for groundwater and other applications. The abstracts for workshop presentations that are included in this Open File Report address (1) strategically acquiring new data and managing large legacy databases, (2) methods for model construction and validation, and (3) facilitating appropriate interaction between geological mappers and other users such as hydrogeologists. The emphasis is on shallow deposits that host potable groundwater and that are the context of most waste-disposal and other environmental and hazard issues.

It has become apparent to the workshop conveners that methods for dealing with large data sets and making 3-D geologic and groundwater models vary widely. Therefore, a forum for discussions among active 3-D mappers who have dealt with similar challenges, have new ideas and findings, and have been involved with user groups that rely on geologic information for their decision making is needed. By having these discussions, we will all be better able to design best practices, and recognize the need for different approaches in different settings.

The workshop presentations address the importance of geological mapping, the digital infrastructure that now is required to handle maps, and key methods required to build the models. In addition, case studies from across the U. S., Canada, and Europe address the use of, and the need for, 3-D geological information, specifically targeting requirements for 3-D geological information for groundwater applications. The emphasis of the presentations is not so much to discuss the intricacies of the geology, but rather the processes of data acquisition, model construction, and model application.

The organizers of the workshop have benefited from interacting with the presenters and participants, and hope that those involved with the meeting have gained equally from having participated. The challenge is to ensure that the workshop is a step toward improving our response to the needs of our clients.

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Hydrogeologic mapping and aquifer vulnerability modeling in Florida: 2D and 3D data analysis and visualization

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Data analysis and modeling within the infrastructure of geographic information systems (GIS) applications are invaluable assets with respect to groundwater resource management and protection. In Florida, ground water comprises more than 90% of potable water resources, which are used by a population of more than 16 million. With an increase of more than 7000 residents per week, demands on Florida's ground-water resources continue to intensify in highly populated areas, especially in the midst of a five-year drought. Hydrogeologic research framed around application of 2D and 3D software tools allows simple and clear visual representation of natural systems and processes that need to be understood by environmental managers and elected officials.

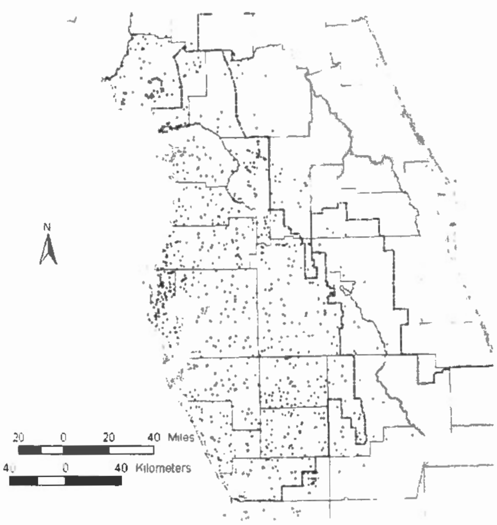

Figure 1. SW Florida Subsurface Mapping Project study area and well locations.

Two hydrogeology projects utilizing such tools are underway at the Florida Geological Survey (FGS). The first of these projects, the Southwest Florida Subsurface Mapping Project, is developing structure contour and isopach maps for seven lithostratigraphic units and four hydrostratigraphic units over a 14,500 mi.^{2} (37,500 km^2) region based on geologic data from more than 1,050 wells (Figure 1). The study area includes a 10-mile wide buffer zone to help address edge control issues. Lithologic samples from most of these wells have been inspected for lithostratigraphic and hydrogeologic characteristics via binocular microscope. Hydrologic and geophysical data have also been interpreted to yield point elevations. The goal of this mapping effort is to deliver a highly resolved geologic framework of southwest Florida for use in water resource protection efforts. This hydrogeologic framework will be delivered as map sheets, an ArcView 3.2a (AV) project and an interactive ArcIMS Internet application. The second project discussed herein is the Florida Aquifer Vulnerability Assessment (FAVA) project. FAVA is a developing methodology using GIS as a tool for predicting the relative contamination potential of Florida's ground-water resources. Current plans for delivery of this product include map sheets and an ArcView 3.2a project with a user interface to allow adjustment of parameters. We envision this vulnerability modeling effort to be contaminant-specific and scalable.

Southwest Florida Subsurface Mapping Project. Data available for use within this subsurface mapping effort (described above) are of widely varying spatial accuracy. For example, a worst-case scenario includes a set of borehole cuttings (with abundant "cavings") collected at 10-foot intervals, with the best available location identifying only the section number of the Public Land Survey coordinate system. As such, not only is there a ± 10-foot uncertainty in depth, but the elevation range within that section (one square mile) adds to the vertical uncertainty. Lateral uncertainty (latitude/longitude) also exists. A "control point" best-case scenario includes a continuous wireline core (including sharp stratigraphic contacts and definitive hydrologic data) with a surveyed elevation and a surveyed or post-processed GPS latitude/longitude coordinate. Databases in this project are designed to capture these aspects of X-Y-Z accuracy for subsequent analysis. "FGS_Wells" is a database utilizing Microsoft (MS) Access to store borehole location data, sample type (cores, cuttings, and sample intervals), available data types (e.g., lithologic, stratigraphic, geophysical logs), construction data (casing depth and diameter, etc.). The second database, "FGS_Picks," stored in an MS Excel spreadsheet, contains litho- and hydrostratigraphic intervals (including liberal and conservative elevation ranges) and calculated thicknesses.

Once the databases are populated, they are saved as .dbf (dBASE 4) files. These files are then added to an AV project as tables. The "FGS_picks" table is then joined to the "FGS_Wells" table using the well number fields as the join field. Using a custom script, this joined table is simultaneously converted to an AV point shapefile and re-projected to the Florida Department of Environmental Protection (FDEP) standard projection (Albers). Raster grids and contours are then calculated for each surface and thickness using Spatial Analyst (ver. 2.0a).

Quality assurance of the unit surface elevations and thicknesses is assessed through an iterative process. For each layer, settings are used to yield irregular, non-smoothed surfaces during grid generation using the spline – regularized interpolator, with a grid-cell size of 1.5 mi^2 (4 km^2). By performing this step, anomalous elevations and thickness are readily identified once the interpolated surface is contoured. The anomalous data are then assessed for spatial accuracy (X-Y-Z), including data-entry and spreadsheet-calculation errors. Lithologic descriptions are reviewed as needed to identify anomalies related to carbonate dissolution or to refine unit boundaries based on improved understanding of the local stratigraphy. Control points (unit elevations) representing perturbations due to karst processes are excluded from the database unless they represent depressions on the order of more than two square miles.

The 3D Analyst (ver. 1.0) extension of AV is also helpful in identifying control points of poor quality and inaccuracy between actual elevations and interpolated surfaces. Wells plotted within 3D scenes (Figure 2) can be represented by color-coded poles extruded across the grid surfaces. Although the same method can be accomplished by grid calculations, the visual representation of elevation uncertainty for each control point has value as a quality assurance tool.

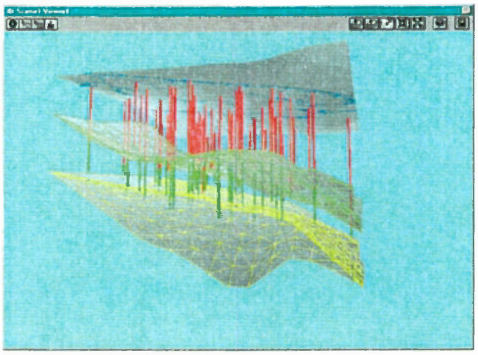

Figure 2. Wells projected from land surface through aquifer

Once anomalous control points have been addressed, spline settings are optimized to yield a more representative geologic surface while minimizing false surface characteristics such as closed contours (up warping and down warping) in areas where no control data exists. Arthur and others (1998) and Abert and others (2000) note the value of automated surface interpolation, which is especially desirable when iterative processes as described above are needed or when interim map products need to be generated.

Another application of 3D Analyst involves comparison of grids to identify erroneous intersects, such as subsurface units arching above (breaching) land surface. Moreover, 3D visualization of the final maps are useful for reasons described above with respect to delivery of hydrogeologic knowledge to stakeholders.

Florida Aquifer Vulnerability Assessment Project.

The FAVA project, which is still under development, involves generation of a GIS-based model designed to allow prediction of the contamination potential of Florida's ground water. Baker and others (2002) provide details on the status of this project, which includes exploring geostatistical methods on which the model will be based (e.g., weights of evidence, fuzzy logic) or a numerical model involving estimation of travel time of a conservative contaminant from land surface to "top of ground water" within a confined or unconfined aquifer system. Considered a refinement of the DRASTIC (Aller and others, 1987) model, FAVA is more robust and accounts for Florida's karstic terrain. Key spatial layers of the FAVA conceptual model (Figure 3) include: land surface, soil permeability, thicknesses of confining units, depth to water, and the percentage of an area covered by karst features. The latter two GIS coverages are significant with respect to the focus of this paper.

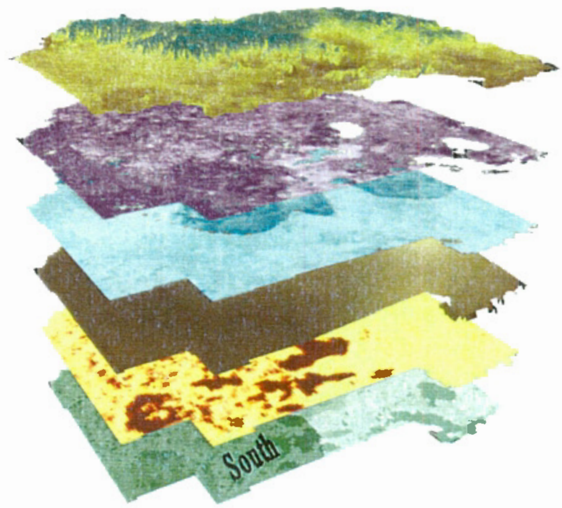

Figure 3. FAVA conceptual model (see text). Vertical exaggeration of topography (top layer) is 20x. The bottom layer reflects a FAVA output.

Accuracy of these two coverages ("percent karst depression" and "depth to water") relies heavily on the accuracy of the digital elevation model (DEM) on which they are based. The U.S. Geological Survey (USGS) Spatial Data Transfer Standard 7.5-minute DEM (30 m resolution) was initially considered for use in the FAVA project. USGS Fact Sheet 040-00 reports that the 30m DEM being considered generally has a vertical accuracy of 23 feet (7 m), with approximately 10 percent of the grid values having a vertical accuracy of 26 - 49 feet (8-15 m). For the FAVA project, a more accurate DEM is required. As such, the FDEP, with assistance from the FGS, is constructing a new statewide DEM by using ArcScan to vectorize contours from USGS 1:24,000 topographic maps. Once issues regarding these vectors are addressed (e.g., edge-matching misaligned and misattributed vectors, fixing incomplete or cut depressions, etc.), and quality assurance measures are followed, the new DEM yields a vertical resolution equal to the contour interval. As a quality assurance tool, 3D projections (using 3D Analyst or ArcScene 8.1) are useful for identifying problem areas with respect to accuracy of the grid surface. For example, the FDEP grid can be visually compared with the USGS DEM to note discrepancies that warrant further review.

A similar application can be applied for quality assurance of the "depth-to-water" coverage. For the FAVA project, "depth-to-water" is calculated using the method described in Sepulveda (2002). Rather than modeling this surface over the entire state, however, physiographic provinces are used as tiles. In Florida, many of these provinces reflect differing hydrogeologic settings, thus lending support to the concept of water table modeling on a provincial basis. In addition to grid and table calculations as tools to assess accuracy of the model, 3D visualization provides a "first pass" evaluation of accuracy. For example, problem areas exist where the depth-to-water coverage exceeds land-surface elevation, yet no surface-water bodies exist (Figure 4).

With a highly resolved and accurate land surface DEM, many options exist for generation of a grid coverage that characterizes karst-feature distribution for use within the FAVA model. Because the FDEP/FGS DEM includes attributed depressions as points and as closed polygons, the topographic-depression coverage can be calculated as: 1) polygons (arcs), 2) percent depression per unit area, 3) a point (or polygon) density grid using a specified search radius, and 4) a point (or polygon) density grid applying a "distance to" buffer. These methods are currently being evaluated by FAVA project staff and members of the technical advisory committee. Further, use of the Z-factor in the attribute table makes possible the calculation of intersects with the base of the confining layer. As such a "penetrating karst feature density" grid can be calculated and visualized with 3D software.

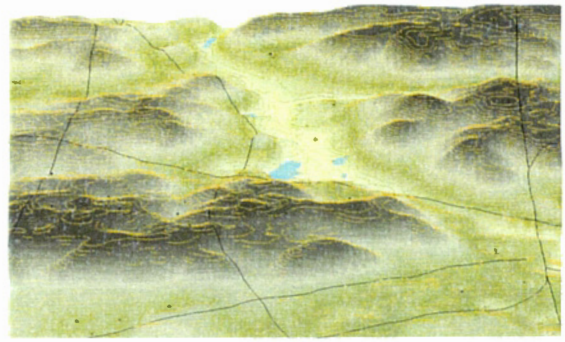

Figure 4. Intersect between "depth to water" grid (blue) and FGS/FDEP DEM.

Conclusions. Three-dimensional characterization of data provides professionals in engineering, geoscience, and resource regulation/management with the opportunity to better visualize topography and hydrogeologic systems, and therefore gain a more comprehensive understanding of our ground-water resources. Indeed, expectation of 3D techniques is becoming more commonplace. Toward this end, many are taking advantage of 3D animation functionality (e.g., "fly throughs") to illustrate concepts pertaining to time and space. Moreover, 3D visualization provides a tool for quality assurance of data in 3D space.

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Three-dimensional geologic modeling of the Virttaankangas aquifer, southwestern Finland

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Introduction. The Virttaankangas glaciofluvial/glaciolacustrine complex is part of the largest esker system in southwestern Finland (Fig. 1). A plan has been prepared for the area that will involve the production of an artificial groundwater reserve from infiltrated river water for the use by the city of Turku and its surrounding area. The amount of river water infiltrated into the esker aquifer will be about 1.3 $m^3 s^{-1}$. This is about 0.5 % of the mean flow of the River Kokemäenjoki, which will be the initial source of the water (Jaakko Pöyry Infra 2001). The artificially infiltrated groundwater will be supplied to 285,000 inhabitants of the Turku area in the beginning of the year 2007.

The complex structures within the unconsolidated Quaternary deposits hosting the groundwater reserve needed to be mapped in detail. Therefore, a three-dimensional (3-D) hydrogeological conceptual model of the Virttaankangas area that identified and characterized the main hydrogeological units of the aquifer, was constructed. This model, along with subsequent groundwater flow models, will be the keys in planning and guiding both the infiltration of the river water into the aquifer and pumping of the resulting groundwater from the aquifer to the Turku area.

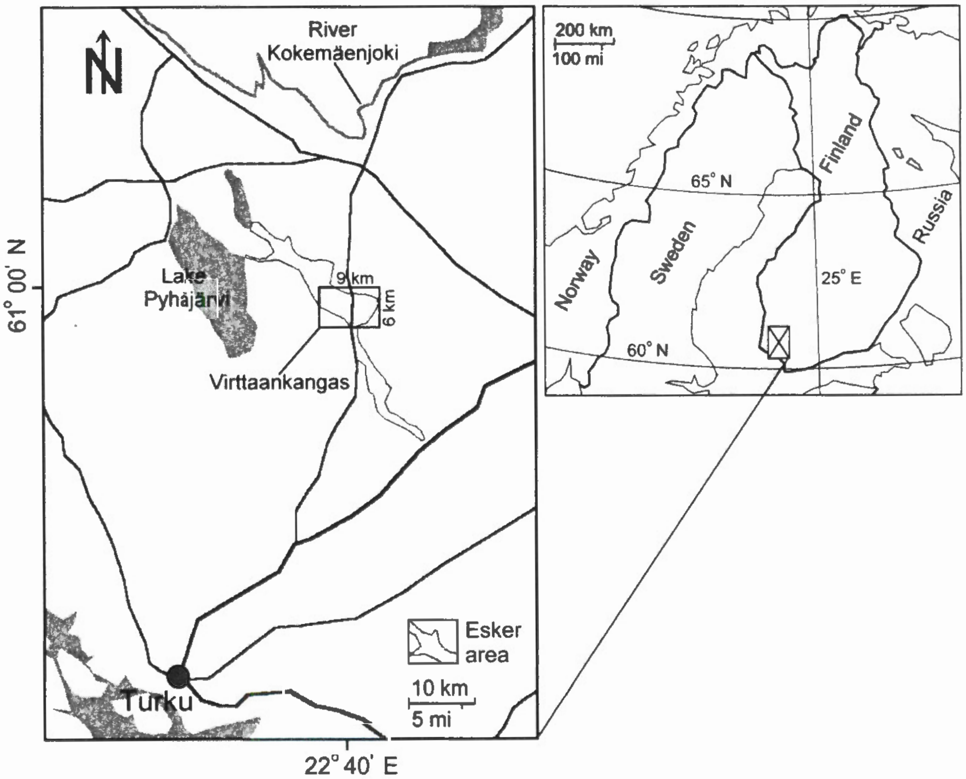

Figure 1. The location of the study area.

Research material. The Virttaankangas area has been the object of numerous geological investigations since the 1960's. The research data obtained from the previous studies includes 131 drilling logs, ground penetrating radar soundings, seismic soundings, gravimetric measurements, permeability tests, and pumping tests. Recent sedimentological interpretations of the area (Mäkinen 2001) have provided a new framework to combine all the research data into a 3-D hydrogeological model of the Virttaankangas aquifer.

Methods. The major hydrogeological units of the aquifer identified based on the available data include the relatively impermeable bedrock, one till unit, a coarse grained glaciofluvial unit, a glaciofluvial/glaciolacustrine unit, a glaciolacustrine clay and silt unit, and a littoral sand unit (Fig. 2). The architecture, as well as preliminary interpretations of the hydraulic properties of the units, were defined.

The 3-D mapping project was done in cooperation with the University of Turku and the Illinois State Geological Survey. Data were prepared with Surfer® software and the final 3-D modeling was done with EarthVision© geologic modeling software. The Virttaankangas 3-D model was also introduced to the EarthVision Viewer© program, which offers flexible and versatile functions to view the extent and structures of the hydrogeological units of the model.

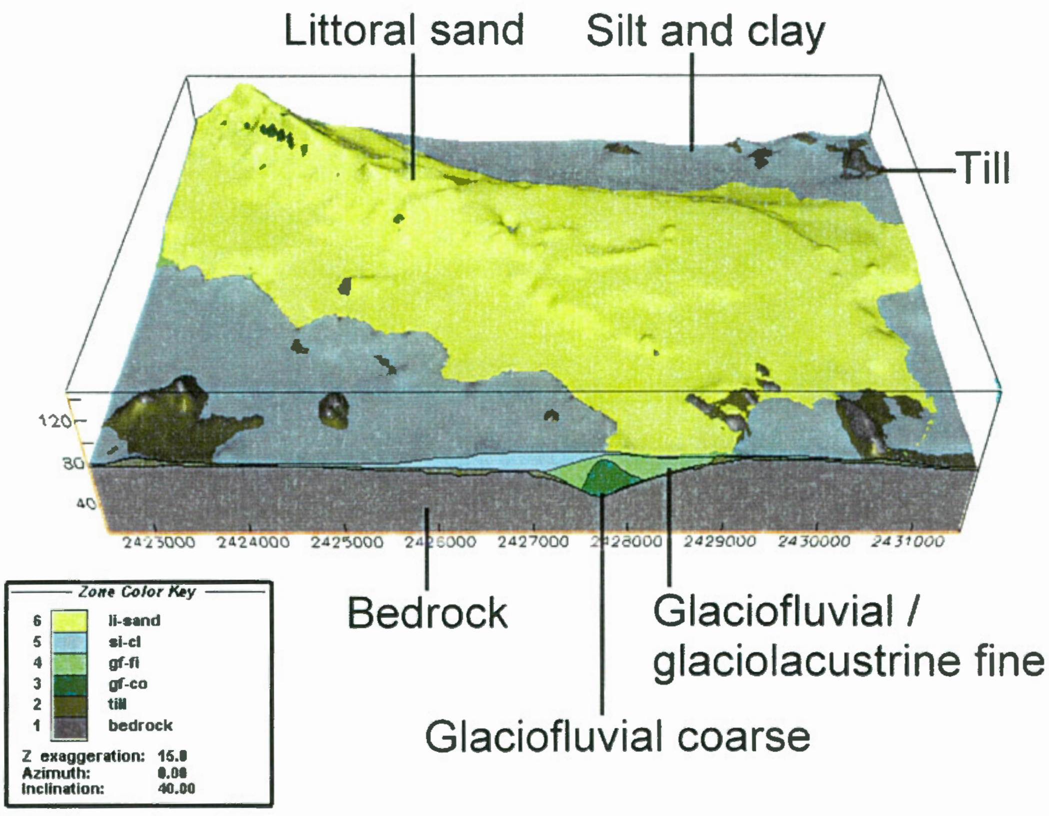

Figure 2. The hydrogeological units of the 3-D model.

Conclusions. The 3-D hydrogeological model provides a tool to visualize the aquifer, to locate suitable infiltration areas, and to protect the aquifer from possible contamination. Furthermore, the 3-D geological model can be used in groundwater flow modeling to provide a geologically consistent conceptual model of the study area. This also includes the interpretation of the vertical and areal distribution of hydraulic properties within the modeled units. The experiences obtained from this study can be further applied to other glaciated regions in Europe and North America.

Additional material about the Virttaankangas 3-D model can be found from the following Internet address: http://users.utu.fi/a/akartimo/3dmodel/english/

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Mapping the Subsurface of Waterloo Region, Southwestern Ontario, Canada

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Background. Pressures directed at protecting and preserving the quality and sustainability of groundwater resources within the province of Ontario have greatly increased over the past decade. The impacts of rapid urban expansion from metropolitan centres and nutrient management practices in rural areas must now be considered when assessing the long-term preservation of groundwater. Wise land-use planning is essential, especially within recharge areas where aquifers are replenished and are most susceptible to contamination. A detailed understanding of the properties and 3-dimensional architecture of Quaternary deposits is critical if well informed decisions regarding land use are made.

As a significant start to this process, the federal and provincial geological surveys have cooperatively undertaken an extensive program of Quaternary geology, hydrogeology and database management within the Oak Ridges Moraine of south-central Ontario (Sharpe et al. 2002). The Oak Ridges Moraine is a provincially significant geological feature extending for well over 100 kms north of Lake Ontario. Sensitivities over land use are paramount within this area. Details of this multidisciplinary geoscience program can be found at http://sts.gsc.nrcan.gc.ca/orm/index.asp. Future studies within other areas of the province should attempt to follow a similar approach.

The Sedimentary Geoscience Section of the Ontario Geological Survey (OGS) is embarking on a new program as part of a provincially-mandated directive referred to as "Operation Clean Water". Several projects are being undertaken as part of this program. These include: 1) the generation of a seamless, 1:50 000 scale, attributed Quaternary geology map of southern Ontario (Bajc et al.2001); 2) the development of data model standards for 3-dimensional mapping and hydrogeological studies (van Haaften 2002); 3) the assemblage and filtering of subsurface information (mainly MOEE water well data) by selected Conservation Areas in southern Ontario following the methods employed by the Grand River Conservation area in their 3-dimensional studies (Holysh et al, 2000); and 4) the generation of a 3-dimensional model of Quaternary geology within the Regional Municipality of Waterloo. This article summarizes the current status of 3-dimensional studies within the Regional Municipality of Waterloo (RMOW). The project is being undertaken cooperatively with the RMOW and the Grand River Conservation Authority (GRCA).

The RMOW is the largest municipal user of groundwater in Canada. Its average daily production exceeds 160,000 cubic metres supplying water to about 395 000 residents (1999 Biannual Groundwater Monitoring Report, RMOW). The region is centrally located in the interlake area of southwestern Ontario and occupies an area of approximately 1400 sq. km. Lying within the region is the Waterloo Moraine, an interlobate feature composed of interbedded sand and gravel. Deposits of the Waterloo Moraine contain a significant proportion of the water extracted for municipal use within the region.

The RMOW is one of the most advanced municipal governments in Ontario in terms of its hydrogeological monitoring programs. It utilizes more than 130 dedicated observation wells to record water levels, monitor water quality and measure aquifer pressures on a regular basis (1999 Biannual Groundwater Monitoring Report, RMOW). The RMOW is also fortunate in that both the University of Waterloo Ground Water Research Institute, a world class hydrogeology department and the Quaternary Sciences Institute, are situated within the region. The GRCA is also very active in both surface and subsurface water monitoring programs. Numerous studies, dealing with Quaternary stratigraphy, sedimentology and groundwater modelling have been undertaken within the RMOW. Most of these have been undertaken by the staff and students of the University of Waterloo or consultants that obtained their training at the university. The GRCA has also produced a comprehensive technical report on the regional ground water conditions within the Grand River watershed.

Objectives and Work Plan. The main objective of this project is to generate a 3-dimensional geologic model of the Quaternary geology of the RMOW to assist with hydrogeologic modelling. Quaternary studies over the last 4 decades have already resulted in a fairly good understanding of the Late Wisconsinan stratigraphic record of the region. Most studies, however, focussed on till stratigraphy with little detail directed to the intertill stratified drift. Facies modelling of these deposits will be undertaken to bolster the geological model already in place. The record of pre-Late Wisconsinan deposits is fragmentary and requires further study as well.

The development of a 3-dimensional geologic model requires that a strong understanding of the Quaternary geology exist by the geology team. To this end, the author spent 8 weeks in the field during the summer of 2002 observing landscapes, classifying terrain, examining existing natural and man-made exposures and undertaking detailed sedimentological studies of stratified deposits exposed mainly in licensed sand and gravel pits. Several cores recently drilled for the RMOW were also logged in detail to become familiar with the deposits of the Waterloo Moraine and some of the older stratigraphic units.

The second phase of this project will involve the compilation and examination of as many datasets as possible that record subsurface geology within the region. The highest quality datasets reside at the RMOW and the University of Waterloo Earth Sciences Department. Numerous studies that required continuous coring of the overburden have been undertaken by both the region and the university. These records will be studied in detail and will form the basis of the derived 3-dimensional geological model. Abundant subsurface information is also stored within a geotechnical database created by the Geological Survey of Canada (GSC) during the early 1970's as part of its UGAIS program. This database is somewhat dated and requires updating. Geotechnical records are likely contained within the files of the region's engineering department as well as with private consulting firms. Additional information is also contained within field notes of Dr.P.F. Karrow who mapped the Quaternary geology of the Stratford-Conestogo areas for the GSC and the Cambridge and Guelph areas for the OGS. Most of this information will however, address the near-surface stratigraphy of the region. The MOEE water well database will also be used to produce derived bedrock topography and drift thickness maps.

All of these datasets will be stored within a database with a structure following that proposed by the OGS as part of its data modelling exercise (van Haaften 2002). Preliminary interpretations of these data will be undertaken using 3-dimensional viewing software such as ViewLog, Rockworks, Gocad and Surfer. Following this initial interpretation, additional geological information will be obtained to address gaps in the datasets as well as to assist with the geological modelling exercise. Geophysical surveys, including ground penetrating radar and shallow reflection seismics will be undertaken in areas of poor exposure and areas where suspected buried bedrock valleys occur. Additional continuous coring of the overburden to bedrock will be undertaken to fill-in gaps, address geological problems and target potential older records in buried bedrock valleys.

The final phase of the geological modelling exercise will involve the analysis of the existing water well database to determine whether it can be trained to yield useful information on the subsurface stratigraphy of the region. A similar exercise was undertaken by the GSC in the Oak Ridges Moraine dataset with mixed results (Russell et al. 1998). Most problems arise from the over-representation of clay in the stratigraphic sequence and the inability to distinguish between sand and gravel and coarse grained till.

Regional Geologic Setting. Bedrock outcrops are uncommon within the RMOW. The position of formational contacts is inferred from irregularly spaced boreholes that penetrate the bedrock surface. The region is underlain by southwesterly-dipping dolostones of the Guelph Formation and interbedded green to grey shales and dolostones of the Salina Formation. The approximate contact between the 2 formations passes under the cities of Kitchener-Waterloo just west of the Grand River. Thin to medium-bedded dolostones of the Bass Island Formation subcrop in the extreme northwestern corner of the region in Wellesley Township.

Drift thickness within the RMOW is highly variable. Depths frequently exceed 30 m and occasionally surpass 100 m, especially within the Waterloo Moraine. The bedrock surface slopes gently from an elevation of approximately 350 m asl in the northwest to 225 m asl in the southeast. The extension of the Dundas buried valley and its tributaries into the region likely accounts for added bedrock relief.

Although the record of Late Wisconsinan glaciation within the RMOW is relatively well understood, the record of older glacial and non-glacial events is fragmentary. Many publications summarizing the current status of knowledge of the Quaternary stratigraphy have been published over the past 4 decades. Most references pertinent to this study can be found in the citations following a paper by White and Karrow (1999) on the urban and engineering geology of the Kitchener-Waterloo area as well as within a recent paper on the origin of the Waterloo kame moraine (Karrow and Paloschi 1996).

The Quaternary record preserved within the RMOW is characterized by repeated glacial advances of ice lobes originating from the Lakes Huron-Georgian Bay and the Erie-Ontario basins. Indicator lithologies assist with determining provenance. For example, till originating from the Huron-Georgian Bay lobe often contain clasts of Proterozoic-aged metasedimentary rocks, including jasper conglomerate, Gowganda Formation tillite and quartzites. Erie-Ontario lobe tills often contain mottled red and green Queenston Formation shales and red to white sandstones and siltstones. Grenville marble is occasionally encountered as well.

Pre-Late Wisconsinan drift has been encountered at numerous locations within the RMOW. It consists of a complex sequence of older, fine- and coarse-textured tills and stratified deposits. The Canning Till, a fine-textured till displaying a reddish colour is the only formally named pre-Late Wisconsinan till unit recognized within the RMOW. The reddish colour of this till is likely derived from Queenston Formation red shales that outcrop below the Niagara Escarpment to the east. An Erie-Ontario source lobe is suggested (White and Karrow 1996). Alluvial channel-fill deposits containing organic remains have been encountered at a few sites. The Waterloo interstadial site has been dated at 40 ka BP and represents the deposits of a Middle Wisconsinan non-glacial episode (Karrow and Warner 1984).

The main Late Wisconsinan glaciation is represented by the Catfish Creek Till. This silty to sandy till of northern provenance is often overconsolidated and forms an important marker horizon within the region (Karrow 1988). It occurs frequently in borings, roadcuts and sand and gravel pit and river bank exposures. Following a significant retreat of ice from southwestern Ontario (Erie Interstade), competing lobes of Huron-Georgian Bay and Erie-Ontario ice advanced into the region. Significant moraines are associated with some of the till sheets. For example, the Macton Moraine represents the outer limit of the Mornington Till and the Paris Moraine represent the outer limit of the Wentworth Till. The Waterloo Moraine was constructed during the ice advance that deposited the Maryhill Till.

The Waterloo Moraine. The Waterloo Moraine is defined as an irregular tract of gently rolling to hummocky terrain occupying an area of approximately 500 sq. km. It lies west of the Grand River from Hawkesville in the north to New Dundee in the south and extends westward to Phillipsburg. Distinct spurs of sand and gravel extend outward from the moraine to the north, west and south. The relationship of these spurs to the Waterloo Moraine is under investigation. The vast accumulations of sand and gravel comprising the Waterloo Moraine are sometimes blanketed by clayey Maryhill Till or sandy Port Stanley Till. The moraine is believed to be the product of the ice advance that deposited the Maryhill Till (Karrow and Paloschi 1996). This clay-rich till, which is often interbedded with glaciolacustrine deposits, occurs as layers at the base, within and above the morainic deposits. The layers are discontinuous in all 3 environments.

All of the sand and gravel deposits comprising the moraine are mapped as ice-contact stratified drift. This classification is likely based solely on geomorphology since there are very few exposures within the moraine proper. The stratified deposits comprising the Waterloo Moraine are an important aquifer for the RMOW. A better understanding of the depositional environments into which these sands and gravels were deposited is essential to better predict where the greatest potential for additional groundwater reserves exist.

New Findings. Several new observations were recorded as part of the field work that will assist with the development of the geological model. The Waterloo Moraine has been described as a hummocky to rolling tract of land. Some of the hummocky terrain is in fact interpreted as erosional or dissected in origin. Dissection likely occurred during and shortly following retreat of the Erie-Ontario lobe from the region and drainage as glacial lakes drained and base level fell. Surface morphology throughout the region should be classified to assist with the determination of facies models. Few exposures within the moraine actually display ice-contact features such as faults and chaotic bedding as shown on published maps. The moraine appears to be composed of a complex network of subaquatic fan, deltaic, braided stream, subglacial conduit and kame/kettle depositional environments. The youngest morainic sediments were likely deposited within a transitional basinal to shallow lacustrine environment. In fact, the glaciolacustrine environment appears to dominate most of the deposits observed in sand and gravel pit exposures. Coarsening upward sequences indicate basin filling or shallowing processes late in the development of the moraine. Most paleocurrents obtained from planar cross-beds, trough cross-beds and steeply-dipping foreset beds within the moraine indicate paleoflow towards the west to northwest. This is consistent with an Erie-Ontario source lobe for the moraine.

Aside from general statements describing coarsening upward sequences, few descriptions are available on the nature of the morainic deposits at depth. Exisitng borehole logs should be studied to determine the nature of the lower morainic deposits. Future searches for substantial groundwater resources within the morainic deposits should be focussed on depressions in the upper surface of the Catfish Creek Till where subglacial meltwaters associated with the advancing Maryhill ice would be directed. One might expect linear bodies of coarse-grained sediment with high permeability and hydraulic conductivity within these depressions.

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Three-dimensional Geologic Mapping for Transportation Planning in Central-northern Illinois: Data Selection, Map Construction, and Model Development

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Introduction. To prepare for a highway improvement project, the Illinois Department of Transportation (IDOT) contracted with the Illinois State Geological Survey (ISGS) to conduct a 15-month, three-dimensional (3-D) geological mapping program along a 24-mile (39 km) segment of Illinois Route 29 in central-northern Illinois from just north of Chillicothe (Peoria County) northward into southern Bureau County (Figure 1). Route 29 is located on the west side of the Illinois River, mostly at the base of a steep and highly dissected bluff (~200 ft (61m) high) composed of Pennsylvanian bedrock (mainly shale, limestone, and coal) overlain by thin (mostly <50ft/15m) glacial deposits along the southern 8.6 miles (13.8 km) of the high-way, and thick (>200 ft/60m) glacial deposits along the northern 5.0 miles (8.1 km) of the highway. The middle and extreme southern portions of the highway traverse Illinois River floodplain and Wisconsin Episode outwash terrace deposits for 10.4 miles (16.7 km).

Figure 1. Location Map.

The mapping has supported the development of derivative map products specifically tailored to address various construction conditions, predict areas of possible geologic hazards (e.g., landslides and mine subsidence), and locate groundwater supplies for rest areas and other development that may follow highway construction. The mapping also supports the preparation of IDOT's Environmental Impact Statement for the construction project by characterizing hydrological conditions, slope stability, erosion and sedimentation, and showing how geology potentially impacts ecological systems.

The succession of Quaternary deposits in the area reflects the interaction of multiple glacial advances with a major river system, the Mississippi, that has drained much of the upper Midwest United States. Glaciers from the Lake Michigan Lobe have advanced westward across the study area numerous (at least four) times during the Quaternary. The course of the southward-flowing present-day Illinois River in the study area overlies and generally parallels the bedrock valley that last carried the ancestral Mississippi River about 20,500 years ago, when the maximum glacial advance of the Wisconsin Episode diverted the ancestral Mississippi River westward into its present course. In the study area, where these multiple glacial events impinged on a major river in an area of significant bedrock relief, the result was a succession of glacial, fluvial, eolian, and alluvial, deposits and interglacial paleosols, reflecting numerous complexly superimposed episodes of erosion, deposition, and stability.

Because of the geological complexities that were encountered, it was necessary to develop two 3-D geological models. (1) A regional 3-D model, which covers about a 200 mi^2 (518 km^2) area centering on the highway, delineates unlithified materials from land surface to the bedrock surface. Regional mapping and modeling were necessary to better understand the geology and increase our ability to predict the lithostratigraphic units near IL29. (2) A more detailed model, covering the area extending about 200 feet (61m) on either side of the highway centerline, also was compiled to differentiate lithologic units to a depth of about 50 feet (15m) and provide highway engineers with needed site-specific information.

Data Compilation and Evaluation. For the mapping program, the ISGS compiled and evaluated all existing borehole data on file at the ISGS and IDOT, selected the "best" available data for inclusion in the 3-D mapping, and conducted field investigations to verify existing information and fill in data gaps. The database used to compile the maps and models consisted of descriptive logs of 354 water wells, 339 highway engineering test borings (123 of which were <10 feet deep), 40 shallow hand-auger borings, and 17 test borings for coal, for construction of an oil pipeline, and other engineering work. It also included descriptions and samples from 251 field exposures, continuous cores and geophysical logs from seven ISGS boreholes, and about 9 line-miles of seismic reflection profiles to help define the depth to the bedrock surface along the southern portion of the highway.

Verifying the locations of water wells and evaluating the accuracy of their accompanying logs required considerable time. Locations were verified by (1) comparing the owner of record listed on the permit with plat books (and in some cases orthophotos), (2) telephoning well owners and drillers to ask them where wells were drilled, (3) finding addresses in computer white- and yellow-pages directories, and (4) field checking. The accuracy of well logs was evaluated by comparing their content with information of known accuracy from nearby test borings and/or described and sampled outcrops. Records with over generalized logs, or logs obviously inconsistent with the known geology were labeled as suspect.

Development of a conceptual regional geologic framework began at the outset of the project with an evaluation of published and unpublished work (including ISGS field notes, theses, ISGS reports, maps, aquifer studies, and regional geologic studies), continued during the interpretation of existing and newly collected data, and continues to this day as new information is gathered. Our initial stratigraphic model included eleven lithostratigraphic units, the present model includes 26 units.

The winter field season in Illinois was the best time to explore for and study natural exposures in the valleys of the many short but fairly steep tributaries that drain the uplands west of the Illinois River. Fortunately, some large, well-exposed, and relatively complete outcrop sections were discovered early in the season. Description, measurement, and sampling of these sections confirmed aspects of the conceptual model and provided a good hands-on feel for what appeared to be the major till and glacial-fluvial units of the upland area. The results of this field experience became the basis for assigning the various materials described in water wells and highway borings to units in the lithostratigraphic model.

While field work proceeded, database specialists extracted location data and descriptive logs for water wells and other borings from the ISGS well data archive (an Oracle database) and reformatted them for import into our analysis software (RockWorks99 and ArcView 3.2). A series of Arc shapefiles of well locations, and base maps compiled from DRGs and digital orthophotos of the study area, were assembled into an ArcView project file. The drillers' descriptive logs were imported into RockWorks by translating the inconsistent, informal, slangy descriptions typically used by water well drillers, and even the so-called "standard" descriptive approaches used by soils engineers and geologists, to a standard set of lithologies. While not truly "standard," this "consistent" terminology allowed for the conversion of thousands of unique descriptive terms to a limited vocabulary of about 40 lithologic keywords in RockWorks parlance. Keyword interpretations were assigned to descriptions ranging from rigorous geologic language to obscure drillers' words (e.g., "muscatine", which refers to clean gravel, such as used in a water well's gravel pack.

Lithostratigraphic Interpretation. RockWorks was used to create a lithologic strip log for each of the hundreds of boreholes and exposures, which were then compared to each other and to nearby high-accuracy records from described outcrops and key boreholes. Lithostratigraphic assignments for the various materials in the strip logs were recorded in the RockWorks spreadsheet. Logs in which red or gray till units, paleosols, loesses, and peat beds were apparent provided some initial confidence that such "marker beds" seemed to correlate over certain segments of the study area. However, as often happens, it was discovered that not only were there multiple red and gray till units, but also that lithologies and mineralogies of these units were similar, and that paleosols, loesses, and peats were missing in many places, or that several peat beds occurred in the succession. A further complication was that the ancestral Mississippi River had occupied the valley several times and younger sand and gravel units filling the lower part of the bedrock valley were inset into earlier gravels with little or no lithologic difference distinguishable from a driller's record.

Cross-Section and Map Construction. As groups of logs were interpreted and lithologic and lithostratigraphic striplogs were created, the cross section function of RockWorks was used to produce well-to-well cross sections (Figure 2). These were key to adjusting stratigraphic picks, refining correlations, and improving the understanding of not only the succession of units, but also areal variations in their thickness and elevation. With cross sections created along dozens of N-S, E-W, and diagonal lines, it soon became clear that the sand and gravel units of the lower part of the valley interfingered with multiple till units and that some of the earlier complexity was resolvable.

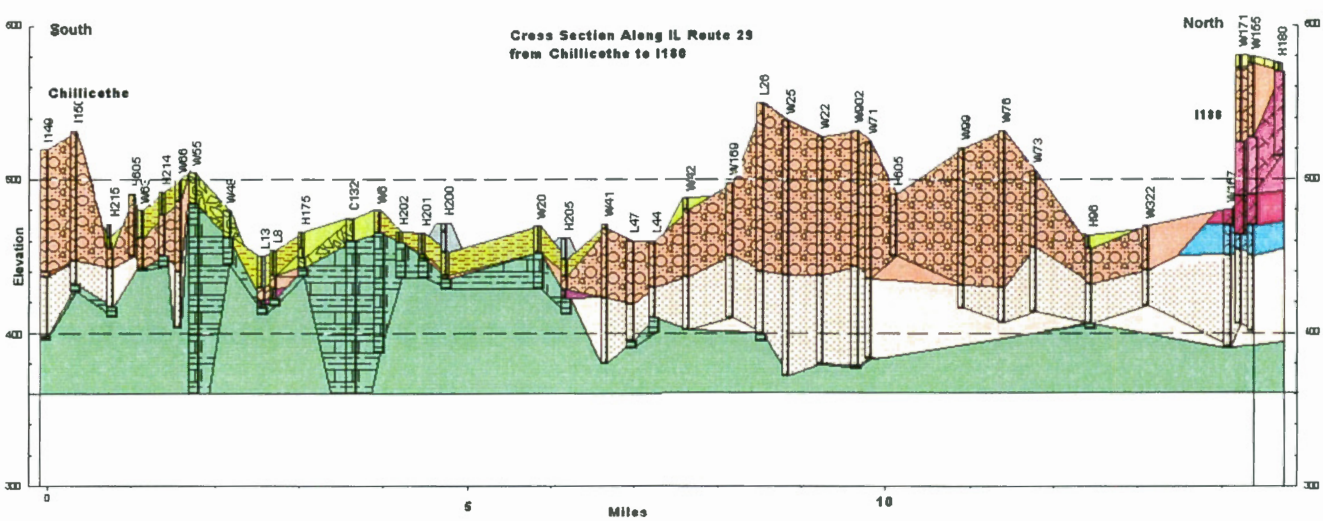

Figure 2. Well-to-well cross section on the east side of the Illinois River along the course of Illinois Route 29 (medium gray = bedrock; dots, circles, and light gray = sand and gravel; dark gray [north] = diamicton).

In combination with the cross sections, 2-D surface models of the tops of major stratigraphic units were created to evaluate trends and further check the tentative correlations. For example, Figure 3 shows a 2-D model of the top of the Sankoty Sand created with RockWorks. The darker gray tones in the middle of the figure show that the elevation of the top of the Sankoty is low in the Illinois River valley, where it was scoured by meltwater torrents during the Wisconsin Episode. Locations of boreholes and outcrops are shown on the map. The pits and peaks on such surfaces and the relationships revealed in cross sections were used to repeatedly refine correlations. By mid-April, 2002, a preliminary set of lithostratigraphic picks had been worked out for nearly 700 boreholes and outcrops.

A radiocarbon date for a key unit received in late April, forced a flurry of reinterpretations that altered the stratigraphic picks in parts of 35 or 40 boreholes in an important part of the study area. A second round of test drilling to check geophysical findings for a follow-on effort continued in late summer as the contract was extended, but time for reinterpretation had run out and changes to the database had to pause while contract deliverables were created. At this time (early May, 2002), a finalized RockWorks database, a spreadsheet of lith-ostratigraphic tops and associated lithologic files, was turned over to staff-members responsible for more refined modeling and visualization.

3-D Model Development. The final step was development of the 3-D geological models. Rather than using a software package to create a 3D stratigraphic model directly from borehole data, individual surfaces were modeled and then put into a single 3-D model. The regional geologic model was developed from the Rock-Works database using a suite of software applications. Rock-Works 2002 and Excel were used for data management, ArcInfo and Surfer were used for modeling and visualizing individual surfaces and isopachous maps, and Rockworks2002 was used for grid manipulations (e.g., additions, subtractions), translating grids between various software formats, and final 3-D model construction and visualization.

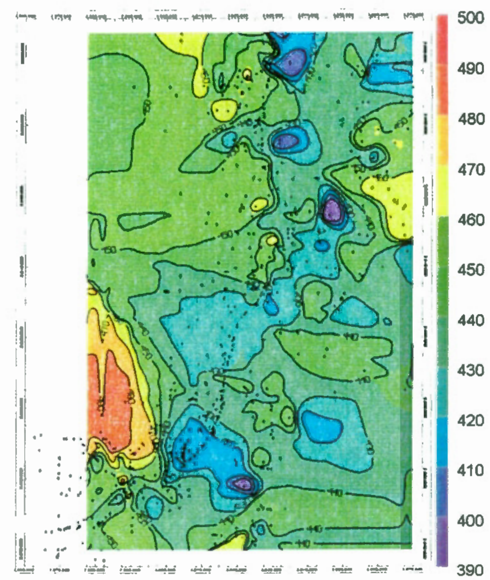

Figure 3. Exploratory 2-D model of the top of the Sankoty Sand.

Although 26 different stratigraphic units were defined in the early stages of the project, several of those units were found to have limited extent or to be very difficult to distinguish from an over-lying or underlying deposit, and so were combined with other units. The final stratigraphic framework used for the regional 3-D modeling included 13 units, which were themselves single units or combinations of several lithostratigraphic units. The first surfaces modeled were the land surface and bedrock surface. Surfaces of model stratigraphic units were created beginning at the base of the succession and proceeding upward to land surface. Most of the surfaces modeled were the bottoms of stratigraphic units. After initially creating each surface model, residuals were calculated and checked against the borehole picks. To make sure surface models did not intersect incorrectly, residuals were also calculated between each surface and the overlying and underlying surface picks from the borehole data.

The land surface model was constructed using elevation data from digital line graph (DLG) files for the topographic quadrangles in the mapping area. Elevation data were interpolated using ArcInfo and checked against the topographic quadrangle maps. The resulting grid was imported to Surfer and generalized to coincide with the dimensions of the regional model.

The bedrock surface elevation model (Figure 4) was generated using information from the boreholes in the RockWorks database, bedrock picks from wells near, but outside of the mapping area, and borehole data that were collected by IDOT during installation of French drains adjacent to the highway. Also used were historic maps of outcrop occurrences together with field observations of outcrop areas from this project. In these areas, elevations from the land surface model were used as supplemental data points for construction of the bedrock surface topography model. This ensured that bedrock outcrops were modeled as coincident with the land surface.

The Sankoty Sand Member of the Banner Formation (a thick, regionally extensive pre-Illinois episode sand and gravel unit) is a widespread aquifer in the study area. For this reason, delineation of its top surface was a priority during stratigraphic interpretation and, therefore, its top was modeled (Figure 5) rather than its bottom. This priority during stratigraphic interpretation made it much easier to construct a "well-behaved" regional surface model, particularly since several other less-continuous units directly overlie this surface.

The first three surface models above the top of the Sankoty Sand include the bottoms of 2 sand units (both are tongues of the Pearl formation) and a diamicton (Hulick Member). Because the sand units were all described similarly in well logs and the diamicton was discontinuous, they were very difficult to model independently. However, the conformable relationships between the Sankoty top and the bottom of these units allowed the model to use the top of the Sankoty to control the bottom surfaces of the units.

Most of the remaining bottom-surface models (Illinois and Wisconsin episode diamictons, a sand/silt/sand sequence, and a surficial outwash sand and gravel) were created directly using picks from the boreholes. This was possible because these units are widespread and lithologically distinct from overlying and underlying units. All of these surfaces were treated as truncating surfaces within the model.

Other surfaces near the top of the stratigraphic succession were handled differently. Between two Wisconsin Episode diamictons (Tiskilwa Formation and Batestown Member) is a discontinuous sand and gravel whose bottom surface was modeled by creating an isopach from the borehole thickness data and subtracting this isopach from the bottom surface of the uppermost diamicton (mainly Batestown).

Finally, the bottom surface models of units at land surface (alluvium, colluvium, and loess) were created by first modeling their thicknesses and then subtracting the individual models from the land surface model. These surfaces were treated as truncating models, allowing them to downcut any underlying surface model they intersected. Even though loess was deposited conformably on the paleo land surface, sparse data points and errors in the data and in the land surface model made it impractical to model it as conformable to the underlying unit.

When all of these surfaces were completed, RockWorks2002 was used to build them into a single volume model. First, a blank volume model of the desired dimensions was created. The lowest surface model (bedrock surface) was then introduced and all node values below this surface were re-coded to equal the bedrock stratigraphic code. Successive surfaces up the stratigraphic column were incrementally added until the land surface model was reached. In each case, the corresponding stratigraphic code was used to re-code blank cells located under the new surface model.

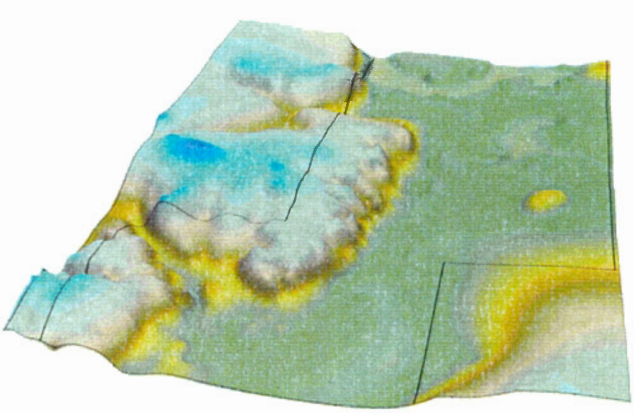

Figure 4. Modeled bedrock topography.

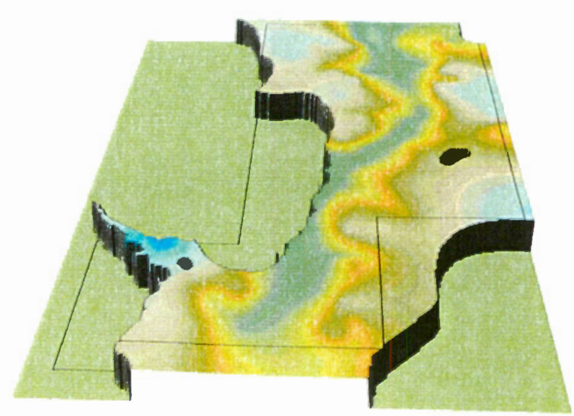

Figure 5. Modeled Sankoty Sand surface.

Representing bedrock subcrop hydrostratigraphy in a multi-layer MODFLOW grid

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With the growing power of desktop computers and recognition of the sensitivity of groundwater flow to geologic heterogeneity, better representations of the subsurface environment are now possible and desirable in flow models. Decisions whether or not to represent any given heterogeneity, such as stratigraphic pinchouts, depend on the scale of the problem and the goals of numerical simulation. However, at any scale, discontinuous hydrostratigraphic units conflict with the numerical requirement of continuous MODFLOW grid layers. We present a method to simulate stratigraphic pinchouts at bedrock subcrops using MODFLOW layers that are reduced to a minimum thickness, with fictitious parameters where the hydrostratigraphic unit is not present. To our knowledge, details of such a method have not previously been discussed. Yager (1997) briefly described a similar method of accounting for layers that pinch out beneath weathered bedrock.

In southeastern Wisconsin, erosion at the bedrock surface over geologic time has truncated the Paleozoic strata (Figure 1a) that dip gently eastward toward the Michigan basin. Surficial unlithified sediments were deposited during Pleistocene glaciations. Progressively younger bedrock units, including an aquitard and various aquifers, are exposed from west to east in contact with the overlying glacial material. In parts of southeastern Wisconsin, this subcrop geometry provides avenues of flow between shallow and deep groundwater systems. In such bedrock settings, accurate simulation of flow requires a realistic representation of such linkages. We applied our technique in the construction of a large flow model of southeastern Wisconsin for regional groundwater management and planning (Bradbury et al., in preparation).

Large datasets, containing well log locations and elevation of formation tops and bottoms in each well, are often used to build regional flow models. Surfaces that enclose hydrostratigraphic units can be created in the form of contour maps or triangulated irregular networks (TINs) based on these data (Jones et al., 2002). Beyond where hydrostratigraphic units are truncated, these surfaces are undefined because required elevation data do not appear in well logs (Figure 1a). Conventional flow modeling practice accommodates such pinchouts by representing different hydrostratigraphic units within individual model layers, or by varying leakance in aquitards for quasi three-dimensional models (Anderson and Woessner, 1992). Alternatively, dipping hydrostratigraphic units can be represented by hydrogeologic property zones that cross-cut horizontal model layers. Compared to our method, these approaches are more difficult to implement with large datasets based on well logs.

For our regional groundwater flow model for southeastern Wisconsin (Bradbury et al., in preparation), we mapped the top elevation surface of each hydrostratigraphic unit as a TIN and constructed a MODFLOW grid structure with the same number of layers as hydrostratigraphic units. Initial MODFLOW grid layer elevations were uniform and assigned default values (eastern end of Figure 1b) above the elevation of land surface. Beginning with the bottom hydrostratigraphic unit and model layer, we interpolated each of the TIN elevation datasets to the appropriate MODFLOW layer bottom and top arrays using an inverse-distance weighted algorithm (Figure 1b). The interpolated tops of model layers 1 and 2 now represent the land surface and bedrock surface, respectively; therefore both surfaces intersect the default tops of stratigraphically lower layers at locations where the underlying hydrostratigraphic units pinch out (western end of Figure 1b). Common pre- and post-processing software available for MODFLOW (Groundwater Modeling System [GMS], and Groundwater Vistas) allows correction of such inconsistent layer elevations by requiring a minimum layer thickness, for example 1 ft, from the top of the model grid downward. The resulting MODFLOW layer structure is shown in Figure 1c.

Such a MODFLOW layer structure is vertically distorted, with layer thicknesses that have considerable variation to conform to the hydrostratigraphic units. Although this distortion introduces some error into the finite-difference approximation, the error is considered to be small (Anderson and Woessner, 1992; McDonald and Harbaugh, 1988). Although numerical errors can also occur due to irregular grid spacing, we used identical column and row dimensions in the area of interest of our model. A more serious error due to grid distortion can occur with particle tracking used in solute transport (Zheng, 1994), however the hydraulic conductivity zonation we use minimizes this possibility. Because layers of minimal thickness (i.e., 1 ft) are used to represent areas where hydrostratigraphic units are in fact absent, we assigned fictitious parameters consisting of high vertical hydraulic conductivity and low horizontal hydraulic conductivity to the relevant layers in these areas. In this way, vertical flow is not impeded and no significant horizontal flow can occur. The effect of this MODFLOW layer configuration is that, in the vicinity of the hydrostratigraphic unit subcrop, flowpaths easily traverse these "dummy" layers between shallower and deeper layers (Figure 2), yet the calculation of hydraulic head in the model is not affected.

Representing bedrock subcrop hydrostratigraphy using thin layers with fictitious parameters allows a hydrogeologically accurate representation of flow that is convenient to use with large datasets of well logs containing hydrostratigraphic unit top and bottom elevations. With minor modifications, it can also be used in other situations, such as where discontinuous hydrostratigraphic units onlap onto assumed impermeable crystalline basement, or where several model layers are used to represent significant thickening of a hydrostratigraphic unit (Figure 2b). We employed our technique in all these situations in the regional flow model for southeastern Wisconsin (Bradbury et al., in preparation) and found that no significant numerical difficulties occurred with MODFLOW operation and model calibration.

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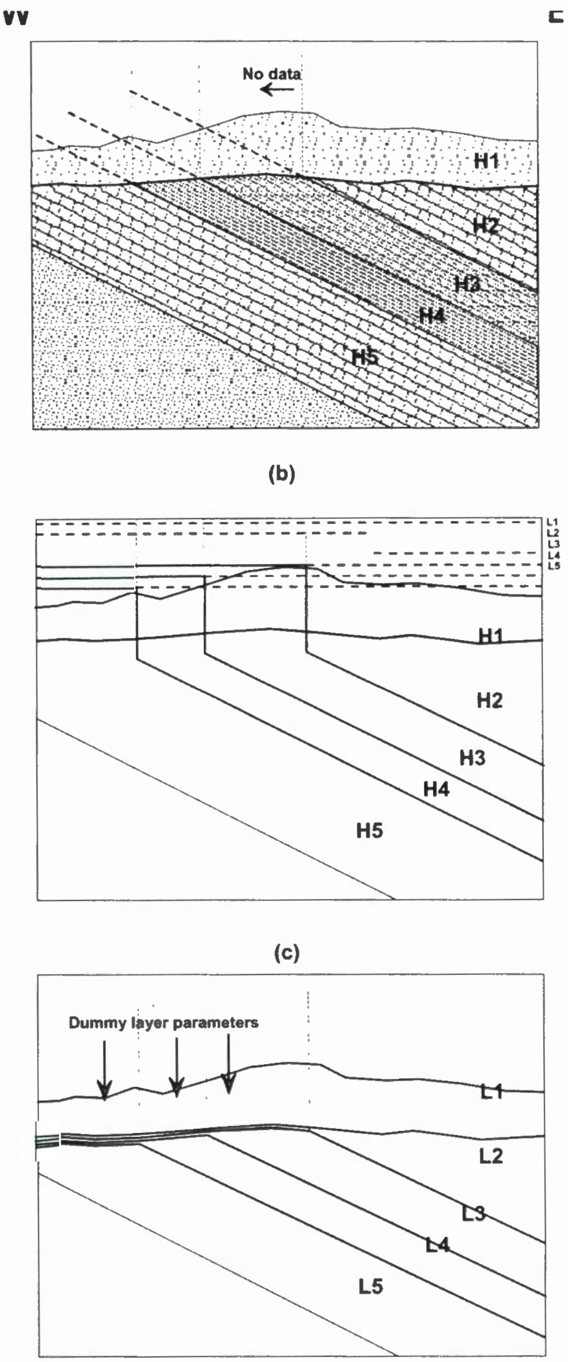

Figure 1. **Simplified schematic diagram (with significant vertical exaggeration) of hydrostratigraphic unit representation in MODFLOW grid. (a) Bedrock subcrop hydrostratigraphy with units designated H1-H5, (b) Interpolation of unit top elevations to default MODFLOW layer arrays L1-5, (c) Thin areas of layers L2-4 assigned fictitious parameters.**

(a)

(b)

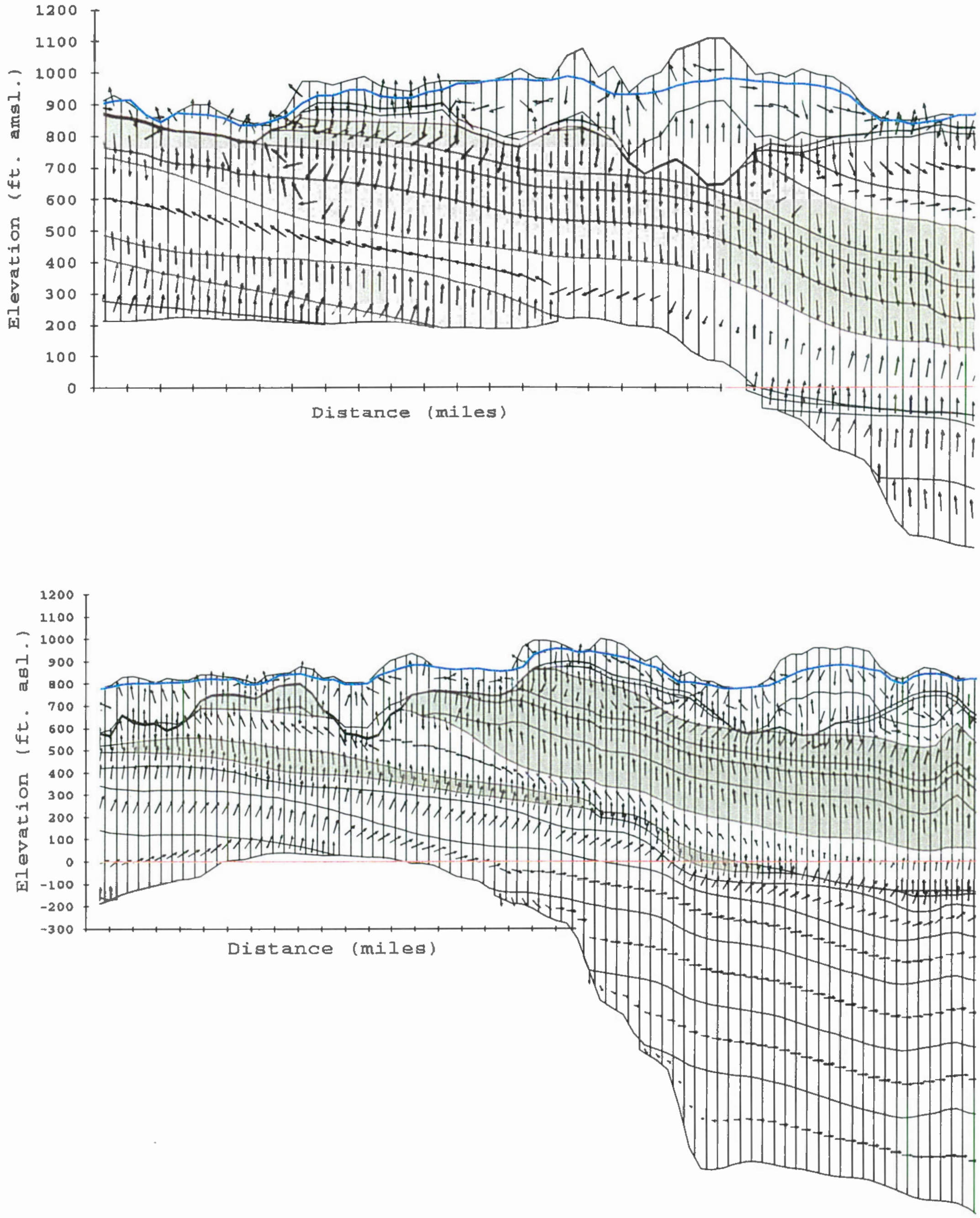

Figure 2. W-E cross-sections of southeastern Wisconsin regional model showing flow vectors under steady-state pre-development conditions. (a) Profile along row 79 in southern Washington County, (b) Profile along row 121 in southern Waukesha County. Heavy line near top is the regional water table. All layers are continuous, but thin to 1ft where hydrostratigraphic units pinch out. Gray layers (aquitards) have Kh < 1ft/d; white layers (aquifers) have Kh > 1 ft/d.

Surficial Geologic Mapping in the French Village 7.5-minute Quadrangle, Metro East St. Louis Area, Illinois

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The surficial geology of the French Village 7.5-minute Quadrangle, located in the Metro East St. Louis area, was mapped as part of a USGS funded STATEMAP project in 1999. The French Village map contains a variety of interesting and important stratigraphic units that are typical for the region. The complex assortment of thick Quaternary deposits found here (intercalated loess, paleosols, diamictons, lacustrine deposits, alluvium) presented a challenge of how to produce an easily understood and meaningful map product.

For the purposes of this one year STATEMAP project, a method for displaying subsurface geology was preferred that did not require time consuming 3D modeling or excessive manpower (only 1-2 people were working on the entire project). ***Three cross-sections*** were produced that cross various geologic terrains and intersect many key stratigraphic, engineering and water well borings as well as observed outcrops. When their locations are carefully chosen, cross-sections (here exaggerated 20 x) can provide insight into the relations between and thickness of subsurface Quaternary units as well as the depth to bedrock. ***Loess thickness contours*** (dashed on the surficial geology map), that show the total thickness of the Wisconsin Episode Peoria and Roxana Silts, were used as an additional means to efficiently portray information in the third-dimension. As much as 90 feet thick near the bluffs, these loess units decrease in thickness exponentially southeast of the Mississippi River Valley from which the silts were deflated. A third means for showing important subsurface information is the use of a ***colored striped pattern*** on the map in color to indicate the occurrence of up to 60 feet of an Illinois Episode ***lacustrine silt (Petersburg Silt) in bedrock valleys***. The diagonal stripes are colored light pink (the color of the Petersburg Silt in cross-sections) but are in a matrix of light tan – the color of the surficial loess units. These striped areas are of importance because they indicate areas that were inundated with backflooded lake sediment during Mississippi River aggradation of the penultimate glaciation. Furthermore, these mapped areas are of practical importance because they indicate low areas or valleys on the bedrock surface.

In summary, the French Village surficial geologic map displays 3 simple means of portraying subsurface information. Contours are useful for displaying the thickness of a near-surface unit, which is relatively predictable (such as loess). A colored striped pattern is useful for special units of interest, which are only sporadically preserved (e.g., lake deposits, alluvium, or old till deposits). Such patterns could also potentially be used to indicate important bedrock valleys or glacial aquifers. Cross-sections are of great importance to indicate the generally continuity, stratigraphic relationships, and thickness of various map units. These means will not replace the need for full blown 3D modeling of the subsurface geology, but are alternate ways of displaying information when resources and/or time are not available or when a simpler output is preferred for the intended map audience.

Developing a preliminary 3-D model of the quaternary geology of the Wauconda 7.5′ Quadrangle

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Background. Using data from ISGS boreholes, natural gamma logs of boreholes and water wells, water-well drillers' descriptive logs, and water-well samples, we created a preliminary 3-D model of the Quaternary geology of the Wauconda quadrangle. Because only minor deposits of postglacial sediment cover the land surface, too thin to represent on this model, only the glacial deposits are represented. The 3-D model illustrates our present understanding of relationships among Quaternary units. It also shows areas where data are sparse and future drilling, downhole geophysics, and shallow seismic reflection studies should be focused. The digital model can be easily modified as new data become available.

Regional Stratigraphy and Stratigraphic Framework. The Quaternary deposits and topography of the WaucondaQuadrangle resulted from cycles of erosion and deposition during Wisconsin Episode glaciation, between about 25,000 and 14,000 radiocarbon years ago in Illinois (Fig. 1) (Hansel and Johnson, 1992, 1996). The glacial drift ranges from about 100 to 250 feet thick and consists of three distinct till units of the Wedron Group (Wadsworth Formation, Haeger Member, and Tiskilwa Formation) that intertongue with proglacial fluvial and lacustrine sediments. These materials were deposited during three glacial phases of the Lake Michigan Lobe (Fig. 2) and form three distinct glacigenic sequences consisting predominantly of proglacial/ subglacial successions. These sequences offlap to the east–northeast in the up-ice direction.

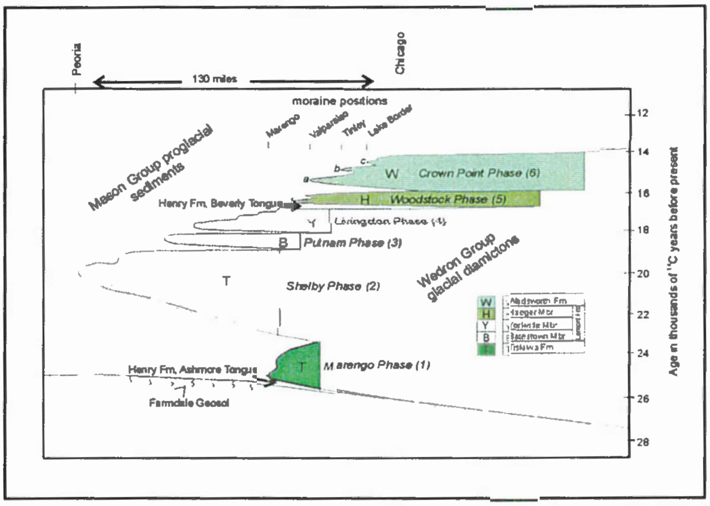

Figure 1. Time-distance diagram from Peoria to Chicago showing glacial phases and lithostratigraphic units of the Wisconsin Episode Lake Michigan Lobe in Illinois. Only phases and units in the Wauconda quadrangle are colored. After Hansel and Johnson, 1992.

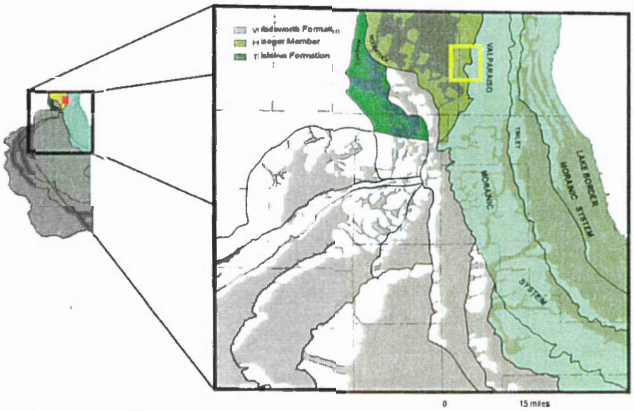

Figure 2. End moraines and ice-margin positions of major glacial phases of the Lake Michigan lobe during the Wisconsin Episode in Illinois. Quadrangle boundary shown in red on inset map. After Hansel and Johnson, 1992.

The lowermost sequence contains proglacial sediments (predominantly fluvial sand and gravel of the Ashmore Tongue, Henry Formation) and diamictons (till and ice-marginal sediments) of the Tiskilwa Formation. The Tiskilwa diamicton is buried beneath sediments of a middle sequence, which contains a thick sand and gravel unit (Beverly Tongue of the Henry Formation) and diamicton of the Haeger Member (Lemont Formation). The Haeger diamicton is exposed at the surface over much of the western two-thirds of the quadrangle. The uppermost sequence, comprising Wadsworth diamicton that overlies a discontinuous sand and gravel (unnamed tongue, Henry Formation), is present in the eastern third of the quadrangle. Locally in this area, tongues of proglacial lacustrine sediment of the Equality Formation are present, especially at the surface, but also intertongued with diamicton of the Wadsworth Formation. Because drillers often do not differentiate between lake clays and clay-rich diamictons in their logs of water wells, lacustrine sediments are probably under-represented in the model. Sand and gravel of the Henry Formation is also present locally at the surface. Figure 3 illustrates intertonguing relationships among the diamicton units of the Wedron Group and sand and gravel units of the Henry Formation. The sand and gravel units form regional and local drift aquifers. Our geologic mapping will help define these aquifers and provide information for their utilization and protection in this area where population and water demands are both growing rapidly.

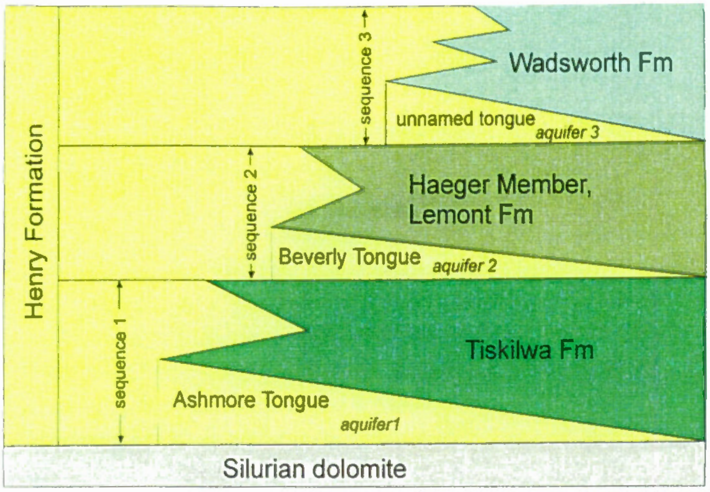

Figure 3. Intertonguing relationships among diamicton and sand and gravel units. The materials represent three major glacigenic sequences. The sand and gravel tongues form regional or local aquifers. Locally, aquifer 1 (Ashmore Tongue, Henry Formation) may be connected to the uppermost bedrock aquifer.

Data and Methodology. Because exposures are rare, the data used in the model are predominantly from descriptions of cores and drill-cuttings, natural gamma logs (some with samples), and water-well drillers' logs (some with samples). The data are of extremely varying quality. The highest quality data come from ISGS cores with associated natural gamma downhole logs. These data provide a basis for interpreting water wells in areas where previously only natural gamma logs, drill-cutting samples, or drillers' logs were available. Because we had few cores and natural gamma logs to integrate into the model, we made use of data from water-well drillers stored in the ISGS's well-log database. Drillers' descriptive logs of drill holes provide geological information that is extremely variable in quality. Most water wells are clustered on commercial properties and in subdivisions. Initially, we examined several thousand available water-well logs, but selected only the best ones for each section. We then attempted to verify their locations using tax-parcel data, street address information, and plat-books; several hundred water well locations were verified for the model. During model development, many records were eliminated either to reduce data clustering or because their descriptions could not be correlated with adjacent wells. In the end, records from 350 wells were used to construct the model. Wells located in an a buffer zone, 1 mile wide around the quadrangle, were also used to define the edges of the model more accurately.

We used RockWorks99 software to make stratigraphic picks and generate the model. The process involved constructing hundreds of cross sections to make well-to-well correlations in multiple directions. Many of the higher-quality data points were used first to model a larger area of northeastern Illinois (6-quadrangle area), which helped to put the Quaternary units in a regional perspective. In this project we elected to present our preliminary model in the RockWorks99 software because our present databases are set up to link with the software. Also, RockWorks99 was better at modeling pinch outs of units between data points. In the future, as our databases are updated, we are planning to use RockWorks2002 software to further develop the model. This software will provide us improved graphical representation and manipulation (ability to view the model from any perspective) and better vertical slicing capabilities.

Stratigraphic Model. In the model the main Quaternary lithostratigraphic units of the Wauconda quadrangle are illustrated as individual sediment layers overlying the bedrock surface (Fig. 4). The proglacial sand and gravel units of the Henry Formation constitute important drift aquifers in the region (Fig. 3). The lowermost aquifer, the Ashmore Tongue, is present locally beneath the Tiskilwa Formation and is connected to the uppermost bedrock aquifer (Silurian dolomite). In many places, the Beverly Tongue is a major regional drift aquifer; many municipal and private wells in the Wauconda quadrangle pump water from this unit. An unnamed, noncontiguous tongue of the Henry Formation lies beneath the Wadsworth Formation, and locally, where the sand is clean (well sorted), this unit is an important water-bearing unit. Because the intertonguing diamictons are not present everywhere, the aquifers may be connected.

The 3-D stratigraphic model is preliminary and further data collection and field-checking are planned. Overall, the model is less reliable with depth, because many wells are set into the first viable water-bearing unit in the drift and do not penetrate through all the Quaternary materials lying above bedrock. The top-most layers in the model are not always coincident with surficial sediments mapped within 6 feet of the ground surface in the quadrangle. The databases used to construct the model did not include detailed information collected by soil scientists, engineers and field geologists, and therefore should not be considered reliable for mapping surficial materials at small scales.

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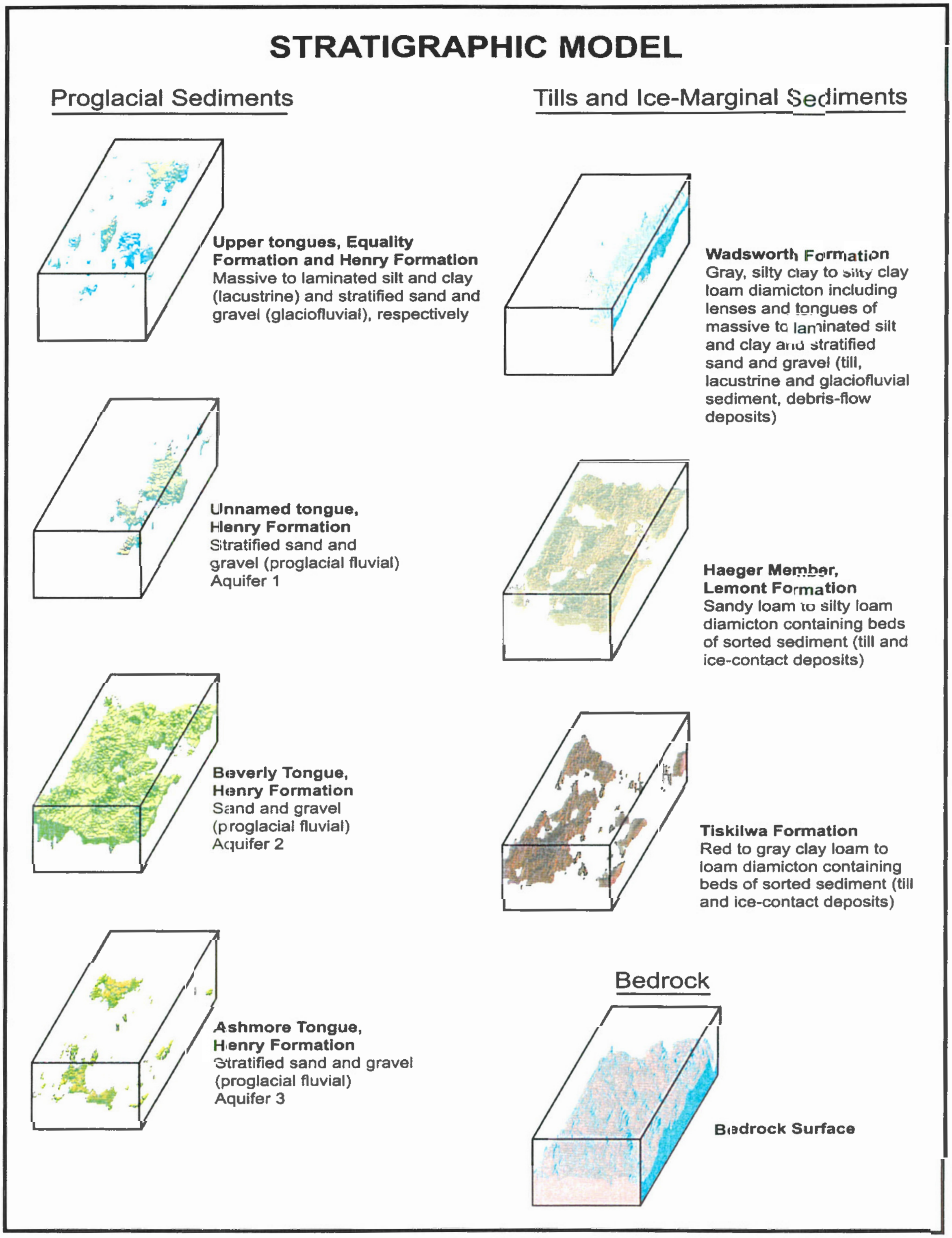

Figure 4. Individual layers representing the lithostratigraphic units in the 3-D model for the Wauconda Quadrangle.

Evaluating Uncertainty in Geologic Models from the IL29 Geologic Mapping Project

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The Illinois State Geological Survey (ISGS) has developed a three-dimensional geological model around a 24-mile (39 km) segment of Illinois Route 29. The modeled area is in north-central Illinois, and extends from Peoria County northward into Bureau County (Figure 1). The mapping area covered by the model includes about 200 mi^2 (518 km^2). The model, which is based on about 600 boreholes and outcrops, is centered on the highway and delineates unlithified materials from 50 to 300 ft (15 m to 91 m) thick overlying a bedrock surface ranging in elevation from less than 400 ft to more than 600 ft (<122 m to >183 m). The model was part of a larger mapping program conducted under a contract with the Illinois Department of Transportation (IDOT). The results from this project will support construction efforts along this section of IL29.


Figure 1. Location Map

The regional geologic framework developed in previous work included 11 lithostratigraphic units, 4 of which were glacial tills. At the completion of the study, the stratigraphic database consisted of 27 described lithostratigraphic units. Because of the limited spatial occurrence of some units and lithologic similarity of others, several stratigraphic units were combined during the modeling process. The final geologic model includes 13 units. To construct the 3-D stratigraphic model, individual surfaces of these units were modeled, corrected, and combined into a single 3-D model.

We have recently begun a separate project to characterize the uncertainty or reliability of the surface and volume models created for the IL29 project. This presentation will discuss the application of three methods we are using for this uncertainty analysis. These three methods include: (1) the area of influence analysis of the spatial distribution of the data, (2) a moving window analysis of variability in data values, and (3) cross validation for identification of anomalous data values.

The area of influence method was originally developed to evaluate exploration strategies for mining ore deposits. This data analysis technique stems from the recognition that exploratory drilling is conducted to search for specific targets (e.g., a subsurface sand and gravel). Because the target has a measurable size, there is an area around the borehole where this target could be centered and still be identified. This area corresponds to the area of influence of the borehole and is directly dependent on the size and shape of the target of interest. It follows that the spatial distribution of data points (i.e. alignment and spacing) will control the probability of detecting a target of some specific size and shape. Calculations for this method determine the probability of detecting circular or elliptical targets using any spatial distribution of boreholes. If desired, the method can calculate probabilities for scenarios where the targets are all in a preferred orientation (e.g., sand and gravel deposited in a N-S trending river valley). Output from this method can be used to create a map of the probability of detecting specific targets (Figure 2).

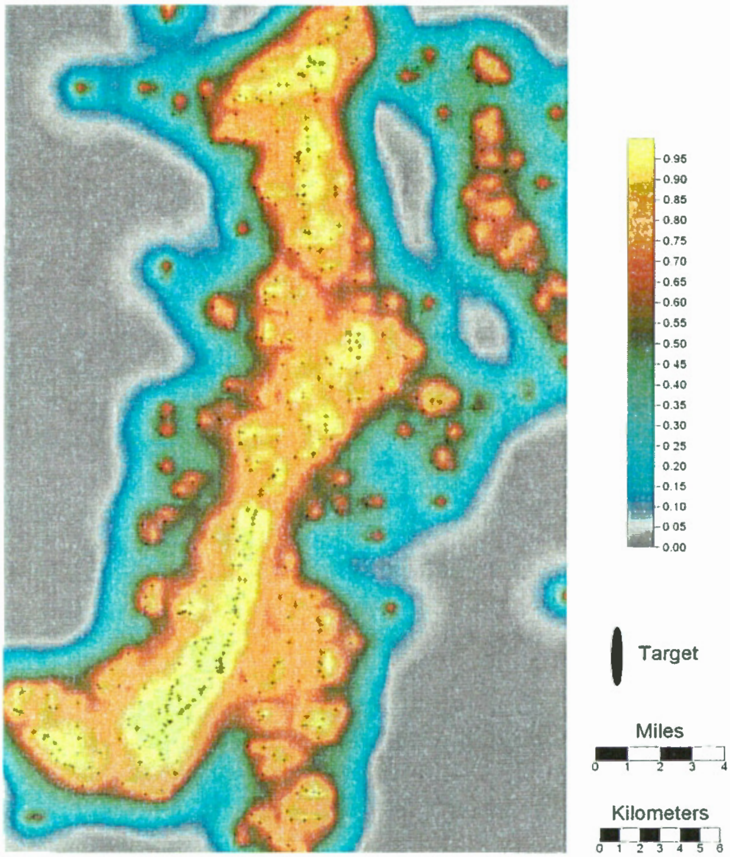

Figure 2. Probability of detecting a 10,000 ft x 1,000 ft elliptical target. The figure shows an example from a subset of the IL29 boreholes.

The area of influence method can also determine the completeness of exploration for a particular target and be expressed as the percent of the map area explored by the boreholes. Modifications to the method accommodate situations where the target cannot be identified with 100% certainty, and allow for the combination of this analysis with provenance maps that show regional probabilities of target occurrence. This method can be used for targets of various sizes and shapes, allowing the user to bracket the probabilities that a range of expected surface features would be detected. Resulting information can be used to aid in land-used decision making that is based on the distribution of geologic deposits, to prioritize locations for additional data collection, and to prioritize location-verification efforts of existing data.

In this example, the target is a fluvial sand and gravel deposit that can be approximated by an ellipse that is 10,000 ft x 1,000 ft in size. We are also assuming there is a 30% probability of not detecting the target even if it is hit. This condition is based on an estimate that approximately 30% of the deposit has a texture that is too fine for the driller to properly identify. Given the distribution of boreholes indicated by the small triangles, the resulting map shows how rapidly the probability of detection drops with distance away from the boreholes.

The uncertainty of surface maps is also affected by the local variability of the surface being modeled. The second approach, a moving window analysis, provides an evaluation of local surface characteristics using a search neighborhood. User-selected statistics are calculated for all borehole values that are located in the neighborhood. These statistics are assigned to a grid node located in the center of the neighborhood. The search neighborhood is shifted to the adjacent grid node, and statistics are recalculated. This analysis is repeated for all grid nodes using a rectangular grid. A subsequent surface model is generated that shows the variation in local surface statistic. Several statistics can provide valuable insight when used with this analysis. For example, the range (Figure 3), and the mean absolute deviation from the median can be fairly robust descriptors of local surface fluctuations. Because of the wide range in sample numbers that often occur in a moving window neighborhood, we have relied mostly on the range in observed values. This information can be used to help identify areas of greater variability (which could correspond to dissected slopes) versus less variability (which could correspond to gently sloping uplands). The information might also be helpful in identifying areas of possible measurement error or miscorrelation. Together, these evaluations can be used to test the appropriateness of conceptual models and for identifying areas of greater model uncertainty.

In the example in figure 3, a 600 ft x 600 ft grid was created by the moving window method, using a circular moving window with a 1 mile search radius. The statistic calculated was the range in values for the bottom surface of the Radnor diamicton within the search neighborhood. The resulting surface shows areas of high data range (e.g. 105 ft) in the southwestern portion of the model. Most of the model shows a range of between 5 and 25 feet.

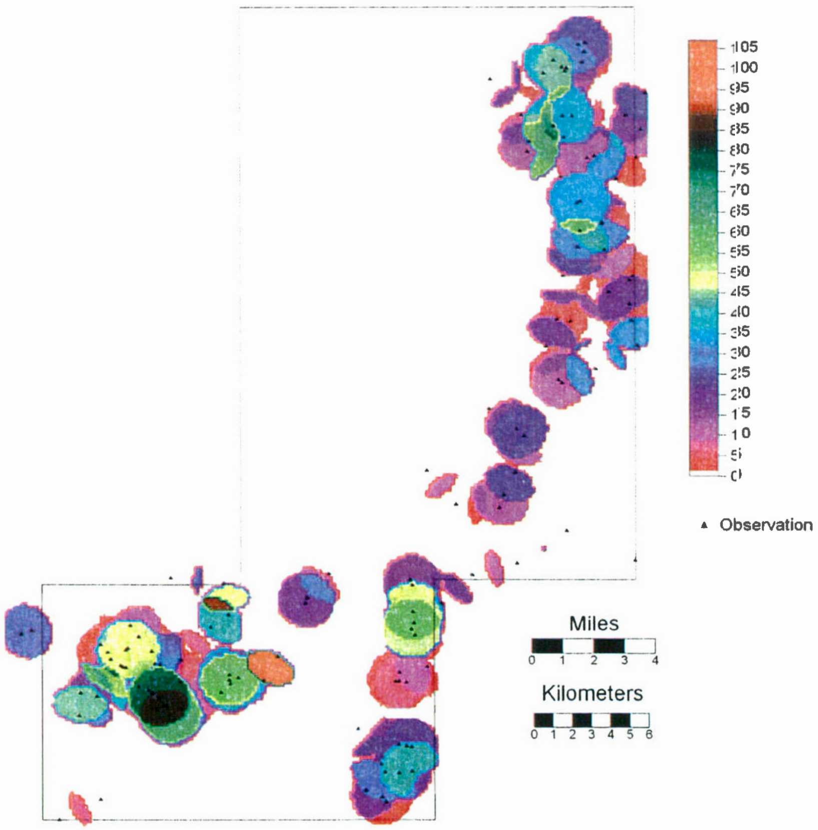

Figure 3. Moving window analysis of the range in observed values for the bottom surface of the Radnor Member of the Glasford Formation in the IL29 mapping area. Units are in feet.

The third method, cross validation, is a tool that is typically used to evaluate the predictive quality of a model. Cross validation allows for the calculation of "gridding errors", or cross validation errors, for each observation. Interpolation algorithms that produce lower cross validation errors typically are viewed as providing a higher quality fit than algorithms with larger errors. We used cross validation errors in this study, however, as a tool to identify anomalous observations and to evaluate the effect of each observation on the surface model.

To calculate the cross validation errors, an interpolation algorithm is selected and all the necessary parameters are specified. Then, the first observation is removed, and the interpolation algorithm is used with the remaining observations to calculate a value at the location of the first observation. The value of first observation is then subtracted from this calculated value to determine the cross validation error for the first observation. The first observation is then returned to the data set, and a second observation is removed. This procedure is repeated where the cross validation error for the second observation is calculated and then the second observation is returned to the data set. This process of data removal, error calculation and return of data, is repeated for n additional observations. The outcome of this cross validation procedure is a set of cross validation errors located at each of the original observations. This data set of cross validation errors can then be interpolated to produce a surface model (Figure 4).

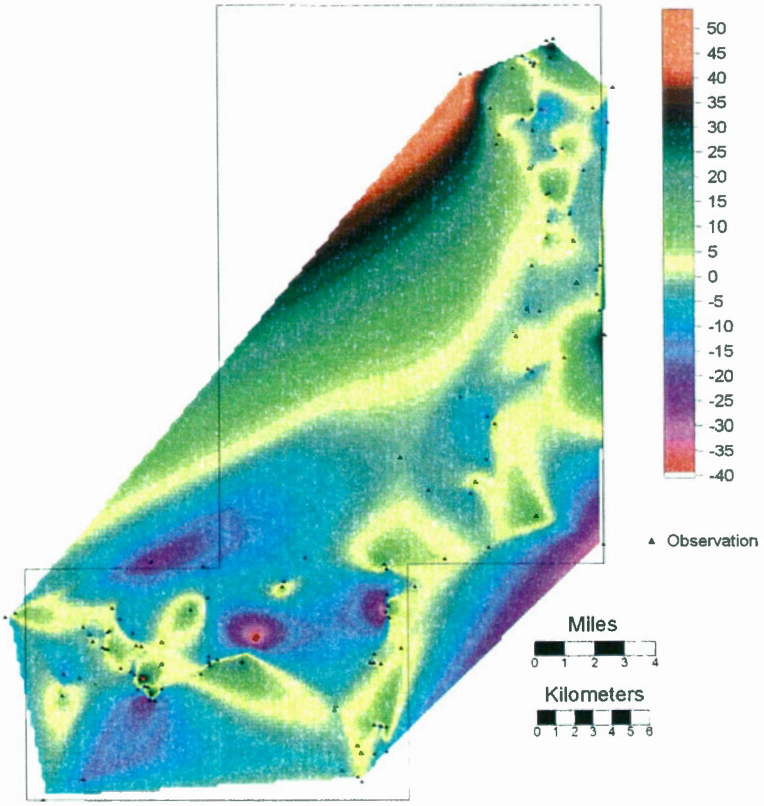

Figure 4. Cross validation errors for observations of the bottom surface of the Radnor Member of the Glasford Formation in the IL29 mapping area. A minimum curvature interpolation algorithm was used.

Large positive or negative numbers in the cross validation surface indicate that the surface model did a poor job estimating the value. This suggests that the observations at these locations are fairly anomalous relative to their neighboring observations and have a large effect on the modeled surface. In this example (Figure 4), the large positive and negative values in the northwestern and southeastern edges of the map are mostly artifacts of the minimum curvature algorithm used for interpolation. There is one point supporting these large errors in each area and the smooth trend of the algorithm projects these into areas without data. The map also indicates several points in the southern third of the map that have large negative cross validation errors. If a review of the well logs for these boreholes suggests the stratigraphic picks are correct, these cross validation errors suggest that the actual surface complexity is likely to be greater than the resultant surface model (not shown) indicates.

Together, these methods provide valuable insight to the predictive abilities of geologic maps and models. These methods also assist in the reliable use of the maps through insight to the expected level of variability in the surface throughout the map area.

Three-Dimensional Geological Modeling of Complex Glacial Deposits

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Developing three-dimensional models to represent subsurface geological conditions is inherently wrought with a large degree of uncertainty. Modelers attempt to interpolate between 'knowns' and 'unknowns' because the geological system is not fully understood nor represented with adequate data. In many instances, only a portion of a system is known through a series of carefully selected geological cross sections. Interpolations are made based on acquired knowledge of the site geology and three-dimensional relationships between geological facies from multiple depositional environments.

Extremely complex subsurface stratigraphy characterizes contaminated sites requiring remedial investigations on many Alaskan installations. Preliminary interpretations are generally derived from borehole geologic databases, geophysical studies, ground water studies, and the migration of pollutants. Yet these subsurface conditions cannot be adequately defined by drilling boreholes, nor can geophysical data be readily interpreted using existing conceptual models, especially in formerly glaciated terrains as exist beneath Fort Richardson and the Haines Fuel Terminal. Textbook models of glacial and periglacial environments are too idealized to serve as adequate analogs to interpret subsurface information at many environmental remediation sites. Textbook models are generally devised to provide an all-encompassing perspective of glacial and periglacial processes at larger scales. While these models are helpful to understand generalities, they are insufficient to provide geologic information at the scales and levels of refinement necessary for three-dimensional modeling at environmental remediation sites.

Our approach has been to merge on site investigations of the subsurface geology with investigations of modern environments representing those formerly active in developing the depositional sequences. Process studies at modern glacier locales, such as the Matanuska Glacier and Glacier Bay, allow us to apply actual field-process observations at a variety of scales to characterize site-specific stratigraphy. This work has greatly enhanced our ability to map the vertical and lateral distribution of confining layers in our investigative areas. The data and process observations are synthesized as three-dimensional models allowing us to predict the probable spatial distribution and relationships that exist among aquifers and their confining units. This approach allows us the ability to accurately develop subsurface models that are essential for ground water modeling and contaminant migration pathways identification.

Our models have been successfully applied to remedial investigations at Fort Richardson. On Fort Richardson, for example, complex end and ground moraine sequences associated with both tidewater and terrestrial glaciers are juxtaposed with glaciofluvial and glaciomarine deposits, some of which probably resulted from large magnitude outburst floods. Here, interpretation of the subsurface distribution of glacial deposits is especially complicated because ample outcroppings are not available.

The geological studies of the Poleline Road Disposal Area, Fort Richardson AK, used a combination of geophysical techniques, limited borehole geologic data, hydrological data and three-dimensional modeling techniques and conceptual interpretations gleaned from field studies at the Matanuska Glacier. The site is located about two km south of Eagle River, AK and situated in a topographic low surrounded by a wooded hill to the west, a large wetland to the south and southwest, and low wooded hills to the north and east. At this site, several glacial, glacial-marine and glacial-alluvial depositional events of Quaternary age deposited a complex system of interfingering deposits on bedrock.

These deposits are further complicated by a series of outburst floods that eroded some deposits completely while reworking others and depositing a cap of glaciofluvial materials.

Various geophysical techniques, including ground-penetrating radar, DC resistivity, and shallow seismics were used to map the vertical and lateral extent of the deposits. Ground truth data were obtained from limited deeply penetrating borehole geological logs in conjunction with hydrological data. A conceptual model of the glacial deposits was developed and integrated with field observations from the Matanuska Glacier. This modern environment defined the vertical and lateral distribution of proglacial and ice-marginal debris flows, outwash materials, supraglacial materials and basal diamictons, thereby refining the conceptual geological model.

Without these modern analogues, our conceptual models would be limited to idealized textbook examples possibly leading to erroneous interpretations that would waste funds while also misdirecting further investigations and remediation efforts. This innovative approach allows us to develop more accurate subsurface models necessary in turn to develop ground water models and identify contaminant migration pathways. Knowledge gained in studying modern glacial environments permits sound judgment and interpretations based on fundamental geologic principles

Societal Drivers for Geologic Mapping and the Value of 3-D Mapping

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Most geologic mapping carried out by the geological surveys of this Nation and others, both state and federal, have historically been for resource evaluation and exploitation. In the early history of geological surveys, the resources under consideration were generally mineral and energy related. While it is clear that both of these societal needs are still immense, the commodities emphasized within the minerals and energy fields has changed dramatically. More dramatic still is the growing need for geologic mapping to characterize aquifer architecture and ground water flow through fractured bedrock. During the last five years the proposals for geologic mapping received by all three components of the National Cooperative Geologic Mapping Program—federal, state, and university—show interesting trends. More and more geologic mapping is in direct response to regulatory concerns about protecting water supplies (e.g., well-head protection, karst delineation, agricultural runoff and stream health, and salt water intrusion). Clearly it is necessary to understand the extent and interconnectedness of our aquifer systems in order to protect them. Even in communities where geologic mapping is being conducted to address concerns about seismic or landslide hazards, ground water concerns usually takes precedence. Every land manager is facing decisions that pit one type of land-use against another. Ground water issues directly impact every other type of decision—housing development, permitting for sand and gravel operations, siting of critical facilities, grazing, forest health, surface water rights, and sustainable growth to name a few. The interconnectedness of the decision-making process for every land manager makes it vital that our geologic maps are created for multiple uses. The clever derivative products that I suspect many will talk about today can only be produced if the original geologic map database is a very robust one.

It is also clear that if our map database is to be three dimensional in a meaningful way that the information collected at the surface is augmented by other techniques such as geophysics and other forms of remote sensing and drilling. Our database must also contain data collected by others for other purposes, such as well logs and engineering reports. The challenge that lies ahead for geologic mappers is to present the information that we gather in a manner that can be easily visualized by the manager making the land-use decision. The uncertainties in our geologic map information must also be presented in a visually compelling manner as well. In other words these representations must allow the non-geologist to walk around in the earth and to examine the nature and quality of the information.

A Coupled Geologic-Hydrologic Model of a Glacial-Lacustrine Aquifer System in Northwest Indiana: Model Development and Results of a Preliminary Simulation

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As part of the U.S. EPA Great Lakes initiative, we were contracted to develop hydrogeologic models of selected surficial aquifer systems in northwestern Indiana. Our most intensive effort, which included coupling of a variably saturated three-dimensional groundwater flow model with a geologic model of a glacial-lacustrine aquifer system, was conducted in the Trail Creek watershed. The headwaters of the Trail Creek watershed are on the northern edge of the Valpariaso Moraine and the creek discharges into Lake Michigan at the harbor of Michigan City, Indiana (Figure 1).

A total of 243 edited and georeferenced well logs (mostly from water-well driller's descriptions) were available for the Trail creek area. The unconsolidated materials described in the well logs were classified into six categories of apparent hydraulic conductivity magnitude (1 for gravel … 6 for clay). A 5-foot interval was used except when a boundary was encountered. In the latter situation the length of the interval was determined by the location of the lithologic boundary. An example of a classified well log is provided in Figure 2. Those logs that contained information about the depth to bedrock were used to develop a digital elevation model (DEM) of the bedrock surface, which constituted the lower boundary of the aquifer system. A DEM of the surface topography was also obtained and was used as the upper boundary of the aquifer system. A three-dimensional representation of the aquifer system was derived by statistical kriging of the apparent conductivity logs.

A perspective view of the modeled apparent conductivity distribution indicates a highly heterogeneous aquifer system without uniform layering (Figure 3). Most of the upper surface consists of silty and clayey sediments (green to red colors), but some areas exist where sand and gravel are exposed at the surface. Those that occur in the upland areas at the head of the watershed are potential recharge areas for the main subsurface aquifer. A clearer image of the main aquifer was obtained by removing all the grid cells that had interpolated apparent conductivities greater than 2.0 (Figure 4). The sand and gravel deposits are thickest in the headwaters portion of the watershed and thin towards the watershed outlet. This distribution of aquifer materials is consistent with a fan-delta depositional system, which has been described by glacial geologists working in the area.

In an effort to simulate the flow of groundwater in this highly heterogeneous aquifer system, the interpolated apparent conductivity codes were converted into apparent conductivities (Figure 2) and output as a three dimensional array containing 49 rows (N-S dimension), 46 columns (E-W dimension), and 95 layers (vertical dimension). Since the model domain (Figure 3) in not a perfectly rectangular block, those cells that were not inside the watershed boundaries (including those that are above the ground surface in the lower watershed) were assigned a value of zero and excluded from the flow modeling exercise. The apparent conductivities were input to a numerical finite-difference model based on the three-dimensional, variably saturated model originally developed by Freeze (1971). To facilitate unsaturated flow calculations, typical values of the parameters in van Genuchten's (1980) characteristic equations for various sediment types (Schaap, et al., 2000) were input to the model. The later were used along with the modeled apparent hydraulic conductivities (which were used as saturated conductivity values) to calculate the unsaturated hydraulic conductivities and moisture contents in the unsaturated zone.

The preliminary simulation consisted of first running the model in steady-state mode to generate a set of initial conditions, and then to running the model in transient mode subject to a uniform infiltration rate of 1cm/d.

Modeled flow vectors, produced by the transient simulation, are plotted in Figure 5. Although some elements of the flow field conform to conventional theory (downward flow in the upland recharge area, lateral flow towards streams), there are apparent local flow zones in the lower portion of the watershed where the flow at depth has a strong vertical component that is not always directed upward. Such non-uniform flow could be a result of inaccurate modeling, but according to Fogg (personal communication), decoupled and seemingly random flow patterns often occur as a result of heterogeneity in complex aquifer systems. Further work will be necessary to identify all the causes of complex flow patterns (both real and artificial) in heterogeneous aquifer systems like the one presented here. Regardless of the final answers to such difficult questions, this study has demonstrated the strong affect that aquifer heterogeneity can exert on the results of flow modeling exercises.

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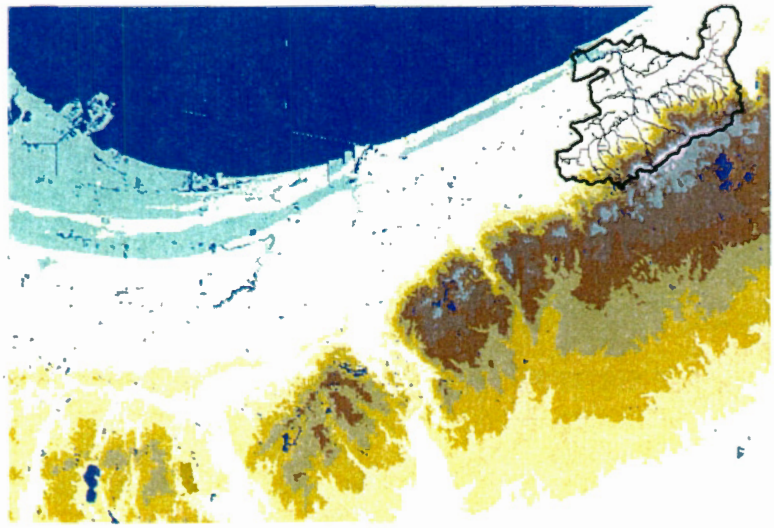

Figure 1. Shaded relief map of northwest Indiana showing the location of the Trail Creek Watershed. The watershed which drains an area of 142 km^2, has its headwaters in the Valparaiso Moraine and discharges into Lake Michigan.

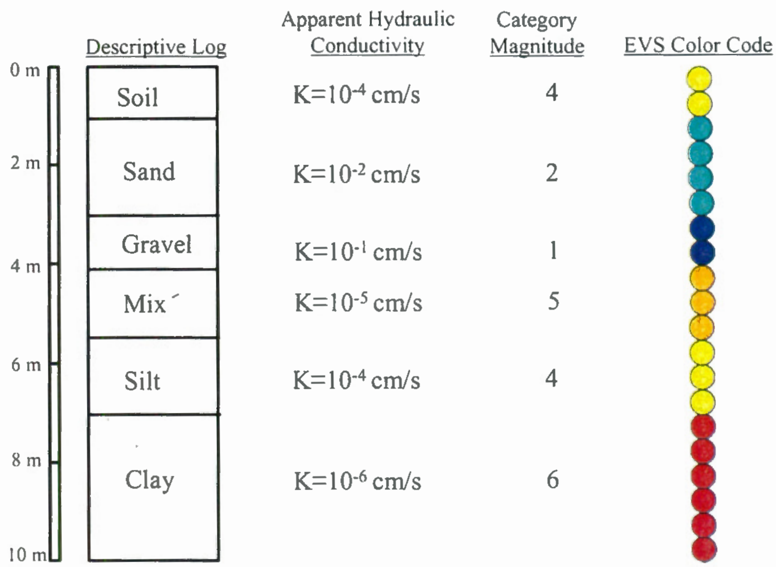

Figure 2. Example of how an edited water well log is translated into a numerical log for interpolation using statistical kriging. The material types are assigned apparent hydraulic conductivities based on look-up tables and published information about the study area. The category magnitude, which is the negative power of 10 associated with the apparent conductivity, is the variable that is input to the kriging procedure. The colors on the right are used to indicate conductivity distributions in three-dimensional visualizations of the aquifer system.

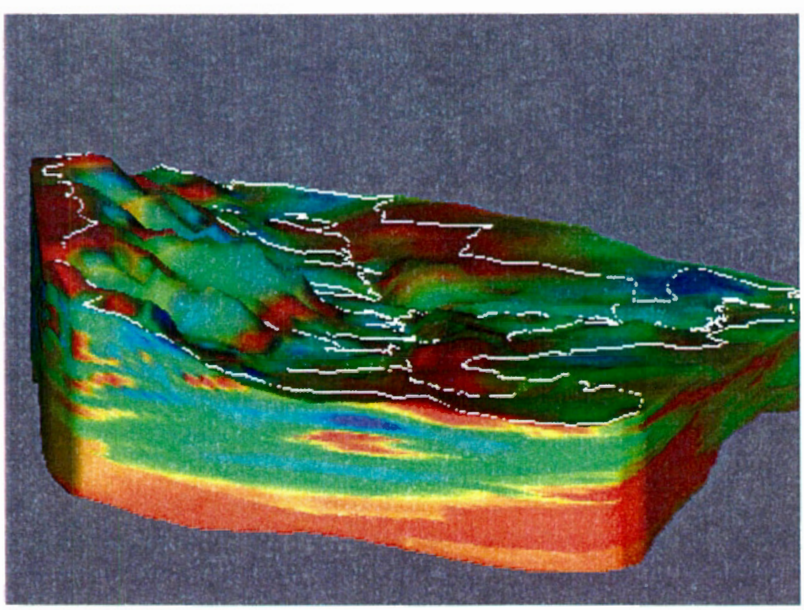

Figure 3. Perspective view of the modeled apparent conductivity distribution. Note the lack of uniform layering and the absence of a continuous capping (clay and silt) layer.

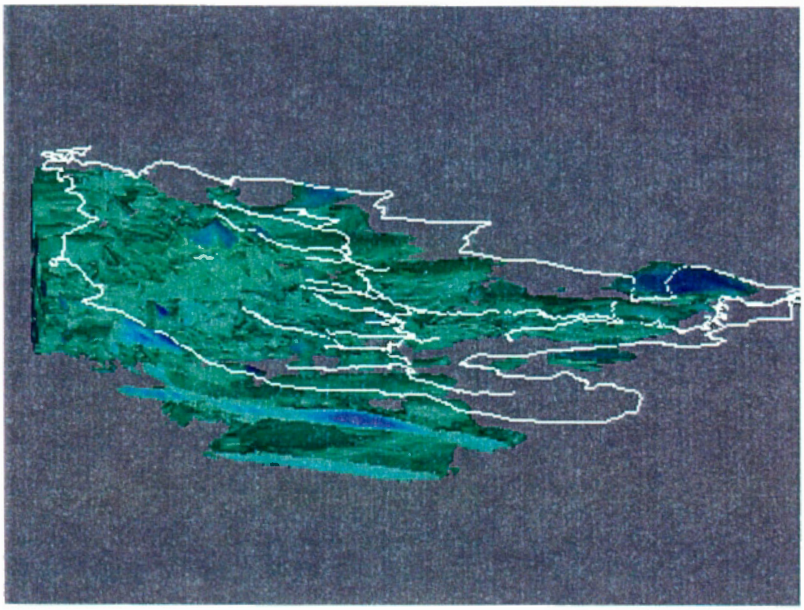

Figure 4. Perspective view of the modeled aquifer system with all cells having a category magnitude greater than 2.0 excluded from the image. The main aquifer thins toward the watershed outlet and exhibits several zones that are partially or completely isolated from the core region.

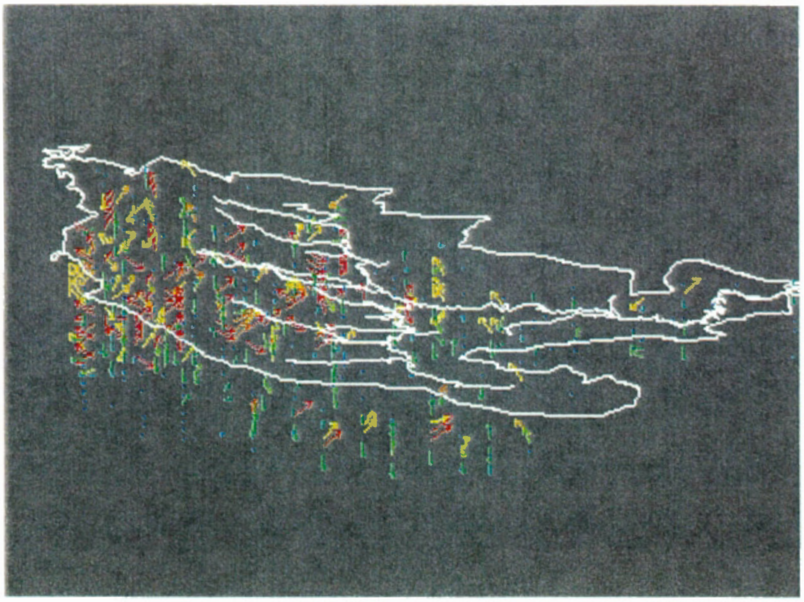

Figure 5. Flow vectors calculated using the numerical finite-difference model. Red arrows indicate areas and directions of highest flow rate and blue arrows areas and directions of lowest flow rate. To facilitate viewing, vectors were plotted for every fourth cell in the grid. Also, flow vectors in clay-rich cells do not show in the image because they are so small. Note that the main locus of flow corresponds to the recharge area and headwaters portion of the main aquifer.

Making 3-D Geologic Maps of Seattle

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Overview. The Seattle-Area Geologic Mapping Project (SGMP) was initiated in 1998 through collaboration with the U.S. Geological Survey and the City of Seattle (City) to provide comprehensive acquisition and interpretation of geologic data for the City. From that initial focus, the project has grown to include other geographic areas and a broadened range of research interests. The current goals of the project are to acquire existing geologic data and create new geologic information in the central Puget Lowland; to conduct geologic research and produce new geologic maps across this geographic area; and to support the wide variety of additional research, hazard assessments, and land-use applications of other agencies and private companies throughout the region. These goals are being met through the development of a comprehensive geologic database, published geologic maps, and construction of three-dimensional geologic maps and models.

Why 3-D mapping in Seattle. 3-D geologic mapping is being undertaken in Seattle because of the recognized need to identify, characterize, and mitigate for geologic hazards. Extensive efforts to make earthquake ground shaking maps and landslide hazard/probability maps necessitate detailed subsurface geologic information. Meetings with users' groups have also echoed the need for 3-D compilations to better delineate the hazard-susceptible geologic contacts and materials.

In addition, sufficient data are available to support a 3-D mapping effort in Seattle, providing an opportunity to evaluate whether the increased level of effort needed to produce such maps achieves a corresponding improvement in the accuracy and utility of subsequent hazard maps. Throughout the City, extensive urban development coupled with variable geology produces a wealth of subsurface data, primarily in the form of geotechnical borings. For example, the density of borehole data in downtown Seattle reaches 350 borings per ¼ section and in outlying urban areas averages 50 borings per ¼ section. Geotechnical borings are logged by geologists or engineers and are based on core samples, often enhanced by geotechnical laboratory testing. Thus each of these explorations usually contains detailed descriptions of lithology and material strength.

Project approach. Traditional geologic mapping in the Seattle area is difficult because of urban development and the resulting paucity of exposed geologic materials; however geotechnical explorations are abundant. Most of these data are poorly organized and widely scattered in building and utility departments, transportation agencies, and the archives of private consulting firms. A primary goal of the SGMP is to consolidate, organize, and standardize this information into a publicly available database. To date, geologic data and interpretations from nearly 40,000 field explorations, exposures, and excavations have been entered into a GIS-based relational database created using Oracle database software, ESRI Spatial Database Engine (SDE), and ESRI ArcView to efficiently store, manipulate, and display this existing body of Seattle-area subsurface geologic data. The downhole data is easily viewed in two or three dimensions using ArcView and custom stick-log and cross-section display tools. An initial byproduct of this digital acquisition and display of borehole data has been a streamlined process for surface map creation. Given the quantity, density, and quality of the subsurface data, we have high confidence in the resulting surface maps and can demonstrate significant improvement over prior published maps of the region. Currently, we have three maps of the Seattle area completed and two additional maps currently in preparation. The surface maps and borehole data are transferred into EVS where solid models are being developed for application to problems in groundwater flow or ground shaking analysis conducted by other scientists.

Despite the broad spatial distribution of the down-hole data, the limited depths of most borings do not facilitate either automated interpretations of the subsurface geology or spatial interpolation of material properties. Major transit and sewer projects provide excellent but very widely spaced transects of deep, high-quality borehole data for ground truthing between outcrops. Therefore, we are not modeling the contents of the database directly. We are, however, interpreting each lithologic layer in each borehole by assigning stratigraphic units that can then be mapped individually. The surface maps, in combination with their supporting information from the database, provide an excellent foundation for developing 3-D geologic maps, where the nature and location of subsurface geologic contacts are constrained by borehole interpretations and the known or inferred processes of deposition. The geologic maps of the subsurface can be attributed with the properties of the sediments with which we are familiar from surface exposures and geotechnical data. These 3-D geologic maps can subsequently be used to construct a subsurface model.

Creation of a subsurface model would be impossible without this map-making sequence, since deep borings that *could* permit direct spatial interpolation between observed localities are too widely spaced for the degree of geologic complexity. This process results in a model of the subsurface that makes full use of geologic interpretation. In the absence of our work and products, other investigators would still make models but their subsurface representations would lack the local and regional perspective that a densely populated database provides.

Lessons learned. One of the most important lessons learned thus far is that there is community-wide support for such a major undertaking. Had we the ability to predict the project's popularity and our resulting growth, we would have been well advised to start with more robust hardware and software. The project was initiated with a cost-effective mechanism for storing geologic and spatial data in a split fashion, using Microsoft Access and ESRI ArcView; this approach resulted in a data-entry and retrieval design that was flexible and programmable but limited by the rate of spatial data entry and outgrown within a few years. The financial obligations of starting a project with the hardware and high-end software necessary to overcome these problems were not apparently justifiable for our startup, but they have left a legacy that has made our expansion to current levels more difficult than originally anticipated. During this initial period, we also chose to focus primarily on acquiring data, building a user-friendly database, and developing protocols for geologic interpretation. This emphasis, while leading to better geologic maps and a more robust database, slowed the production of the initial maps; we anticipate, however, that they will expedite the production of all future maps.

Extending GIS Concepts into True 3D for Geologic and Hydrogeologic Descriptive Modeling

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Abstract. While focus in most presentations concerning 3D modeling appropriately rests on the models themselves, their creation and subsequent utility to the researcher and to scientists applying results to real world problems can be limited if tools are developed in a piecemeal fashion for each case. Discussion of some underlying concepts can help clarify our appreciation of the process and help define general goals as this technology gains greater application for water resource analysis. Geographic Information Systems (GIS by most definitions) concepts serve very well as the starting point for consideration of more rigorous 3D modeling processes, but these GIS concepts must be extended to make GIS become an ambiguous acronym. Perhaps "GIS" could also come to represent Geologic Information Systems.

Traditional GIS has organized information on the basis of geographical location, usually on the surface of the earth. More an more, GIS systems can deal with a stack of surfaces, each with attributes and phenomena related to the X,Y coordinates of those surfaces. Points, lines, polygons, surfaces, and images (and the limits of the area under study) comprise the list of geographically located entities in a GIS. Attributes attach to these entities. 3D geology requires only one more entity, a volume. In this sense, a volume is body defined by bounding surfaces. Because such a body is fully enclosed, 'airtight', as it were, it can carry attributes and be interacted with other entities. The analogy to the use of polygons in a GIS is a good one. For our geo- and hydro- purposes volumes spatially describe stratigraphic zones, fault blocks, intrusions, hydrostratigraphic units, and volumes where a 3D property (porosity, conductivity, salinity) falls within a certain range. A full set of the GIS attributes plus some new ones apply to volumes.

The poster will discuss the creation of volumes, their uses, and their interactions, and relate them to conventional GIS operations and approaches. Vector and raster-based volume entities each have their particular utility, and, as with GIS systems, a combination should yield the greatest utility.

Geologic/hydrogeologic models constructed with topologic rigor, using elements designed to represent the underlying phenomena as naturally as possible, can substantially increase the understanding of those phenomena, and make that understanding available and useful to the scientific community and to society.

Geological Mapping using Geophysics

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Mapping Techniques. Traditionally, geological mapping relies on direct observations from outcrop and borehole core analysis. Two- and 3-dimensional maps are then based on correlation of these 1-D data. As a result, complex stratigraphic relationships are poorly understood using this method of mapping. Physical and visual analysis of the sediment retrieved from the borehole, as well as eventual geological maps, is dramatically improved by geophysical observations using radioactive, resistivity, electromagnetic or acoustic properties of the sediment.

Geophysical Observations. Physical properties of sediment can be measured remotely, at or above the surface of the earth, using multi-dimensional geophysical techniques. Table 1 gives a non-exhaustive overview of various geophysical techniques.

Mapping tool	Vertical resolution	Horizontal resolution	Advantages	Disadvantages
Outcrops	Millimeter	Millimeter	-Best resolution	-Subjective observation -Limited availability
Borehole, coring	Centimeter	None	-Best grain size information	-1D, must be completed with geophysical logs - Requires many boreholes therefore expensive
Electric and Electro-magnetic	5-20 m	1-50 m	-2D and 3D porosity and grain sizes fast mapping -Covers wide areas	- Relatively low resolution
Gravity	10-30 m	30 to 100 m	-Mapping of bedrock-low density sediment interface	-Poor resolution within low density sediment
Georadar	10-30 cm	30-100 cm	-The highest resolution possible in sand and gravel	-Limited to low conductivity sediments
Seismic refraction	1- 5 m	5-30 m	-Simple processing -The least expensive of the acoustic techniques	-Must have velocity increasing as function of depth.
P-wave seismic reflection	1-5 m	5-15 m	-High resolution -Relatively easy depth conversion	-Expensive, requires experienced operators. -Very sensitive to gas in porosity.
SH-wave seismic reflection	1-3 m	5-15 m	-Maps lithologies more accurately -Simple data processing	-Requires shorter sampling interval

Table 1. Resolution of mapping techniques at a quadrangle scale

Electric – Electro-magnetic & georadar. There is a wide range of electric and electro-magnetic methods. In general these methods can map different porosity or grain sizes of near-surface sediments. These methods are still being developed and are improving, achieving higher resolutions in 2- and 3-dimensions through new techniques, instruments, and interpretation programs. Airborne techniques, already proven for mineral exploration, have a great potential in other applications, but are adversely affected by metal structures in urbanized areas.

The electro-magnetic wave used in Georadar provides the highest resolution ever achieved in geophysics. This technique unfortunately does not work well in conductive sediments (such as clay) or in some areas with a high conductive water table.

Gravity. The gravity method has shown very good results in mapping the bedrock-unconsolidated sediment interface with an estimated average error of 10-20 %. Internal structures within the unconsolidated sediments can be mapped only at a very low resolution.

Acoustic techniques. Developed for locating and mapping oil reservoirs, acoustic methods can also be used as a tool for high-resolution mapping of shallow geologic targets (Hunter et al., 1984, Steeples and Miller, 1990). Figure 1 shows a tunnel valley imaged by shallow acoustic techniques. The sand filling this valley constitutes a major regional aquifer (Pugin et al. 1999). Figure 2 shows a high-resolution seismic reflection section through near-surface faults in an area affected by earthquakes (McBride et al., in review).

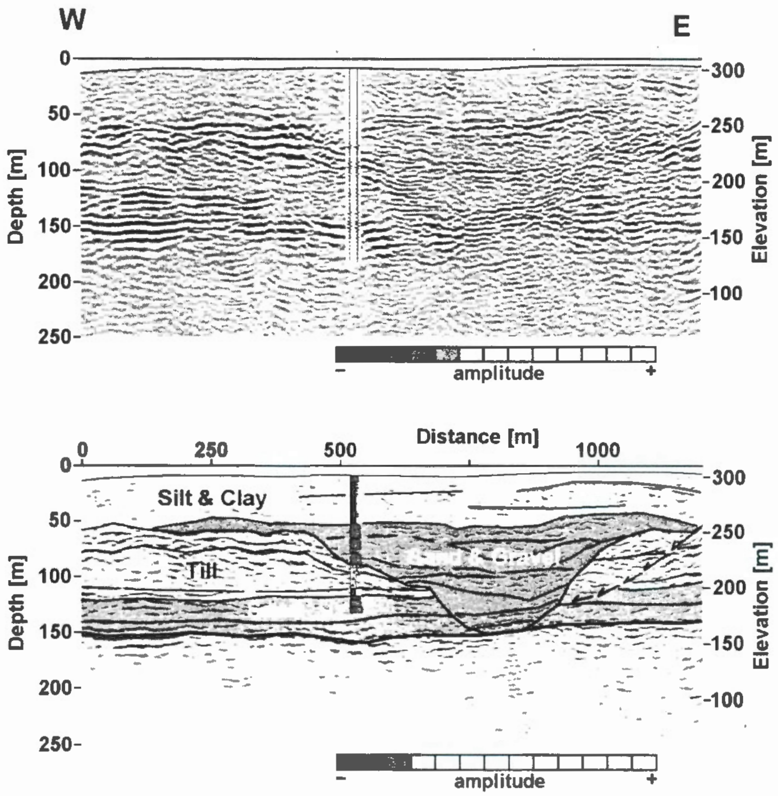

Figure 1. High resolution seismic reflection profile across a tunnel-valley, Oak Ridges Moraine, Ontario, Canada. Grey surfaces highlight sand aquifers.

Refraction. Seismic refraction surveys have been successful in mapping interfaces with large acoustic contrasts, such as the water table and the bedrock-soft sediment interface (e.g. Kempton et al. 1991). More subtle interfaces, thin layers, multiple layers, and soft sediments beneath hard ones are problematic targets for refraction surveys.

P-wave reflection. High resolution seismic reflection methods using compression waves (or P-waves) give good results when applied to mapping Quaternary sediments up to 300 m deep. Despite the high quality obtained with this technique, its use is restrained by several limitations. Where the velocity of near-surface sediments is very small, 800 m/s or less, the high frequencies required for good resolution are missing. Examples include soil with high organic matter content and areas where loess, gravel, or sand occur at the surface with a water table between 5 and 20 m deep. Near-surface water tables and tills with high velocity (1,200 to 2,500 m/s) usually provide outstanding results. A surface velocity of 1,450 m/s (velocity of pure water) gives optimum results in regard to both frequency content and signal penetration.

For most shallow studies, down to 200 m the in-hole shotgun provides the best signal penetration and the highest frequency content. However, this source is relatively expensive and labor intensive. To increase productivity, we have chosen to use a 50-kg accelerated hammer that impacts on a steel plate on a road. Using this technique, with 6-7 workers, we have acquired up to 2 km/day of high-quality information. The method requires a substantial financial investment and experienced operators for data processing.

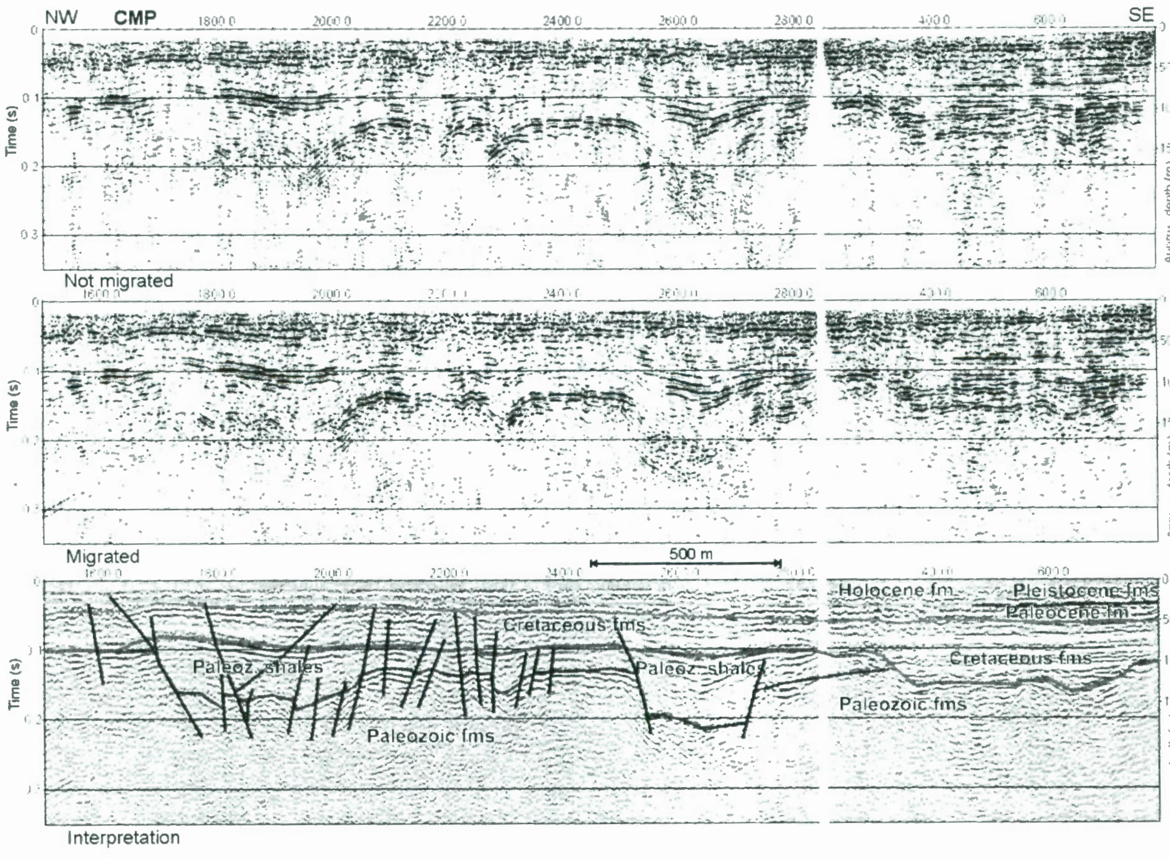

Figure 2. Shallow faults imaged near the Ohio River, along the Illinois-Kentucky border.

Horizontal shear wave (SH-wave) reflection. Because of its potential to provide high resolution images from very shallow horizons, the horizontal shear wave seismic reflection technique has gained more attention in recent years. The main disadvantage of the technique is that it requires a short receiver spacing that decreases the production rate. Typically, polarized SH-waves are generated by striking a weighted post twice, in opposite directions, further increasing the effort at each location. We are developing a land-streamer with geophones attached on sleds to increase efficiency, and lower costs by using fewer workers and less expensive equipment. Further efficiencies are realized by the use of multiple geophones instead of multiple shots to enhance the signal level of the polarized SH-waves. SH-waves are not affected by the fluids in the porosity; this means that difficulties encountered with gas content in soil and sediments while using the P-wave technique does not affect the SH-wave technique. Figure 3 shows a 1.5 km SH-wave section over an Illinois Episode tunnel-valley. Data acquisition for this image required only four people and took just two days. Drift-gas, concentrated at the base of the Wisconsin Episode till, obscured the images of the deeper sediments when using the P-wave seismic reflection technique.

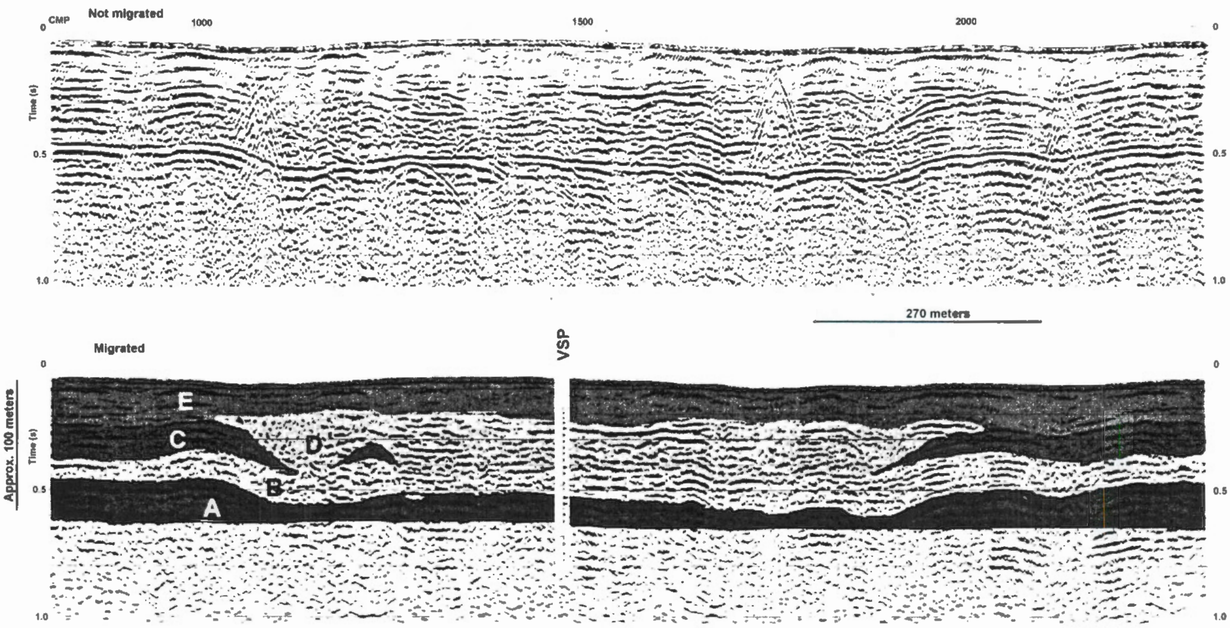

Figure 3. SH-wave seismic reflection profile through a tunnel-valley, Monticello, IL.
A: shale (bedrock); B: fluvial sand and gravel (Mahomet Sand); C: Illinois Episode till;
D: tunnel-valley fill; E: Wisconsin Episode till.

Conclusions. Geophysical methods can provide the data necessary to create high resolution maps of subsurface sediments in the absence of abundant outcrop information and to supplement data from borehole logs. A combination of surface and borehole geophysics with a good sedimentary model can provide accurate predictions of the location of subsurface geologic units at both a regional and large scale. These geophysical techniques will provide very useful data for shallow mapping applications, especially for engineers and hydrogeologists.

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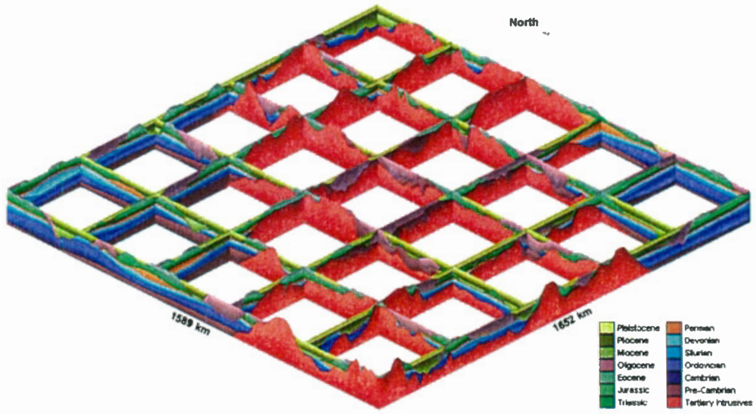
Three Dimensional Visualization of Hydrostratigraphic Data Using RockWorks/2002™ - A Hypothetical Case Study



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The stratigraphy present in the Sugob Desert, a hypothetical area located in the Northern Lacitethopyh portion of the Puedam Plate, is composed of Precambrian basement rocks overlain with near-shore and estuarine carbonates deposited during the Paleozoic and Mesozoic Eras into the early Tertiary. The area was invaded by granitic intrusives and uplifted during the early Tertiary, resulting in fluvial and gravel deposits Miocene to Pliocene in age. Surficial rocks are composed of Pleistocene lake sediments deposited in enormous pre-historic lakes associated with a regional basin and range tectonic system whose normal faulting is still active today.

The case study began with the creation of a borehole and measured-section database in which the XYZ (Easting, Northing, & Elevations) for all observed stratigraphic contacts were recorded (see Figure 1). The next step was to interpolate a series of superface (top) and subface (base) grid models for each stratigraphic unit. These grids were created within the RockWorks/2002™ program using a variety of gridding algorithms including inverse-distance, triangulation, and polynomial-regressions.

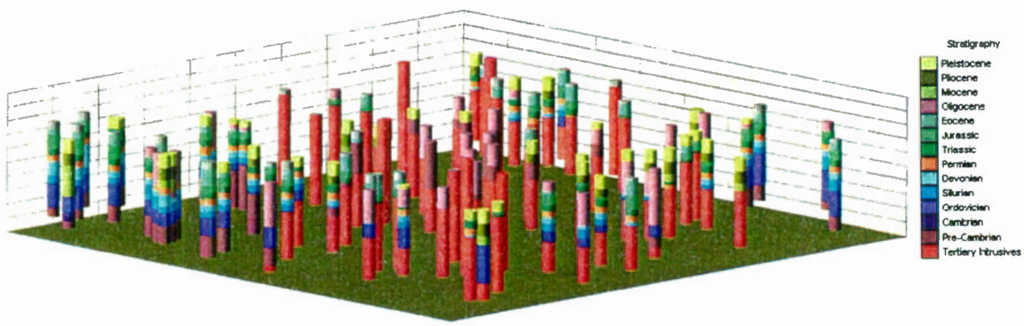

Figure 1. Stratigraphic borehole logs and measured sections.

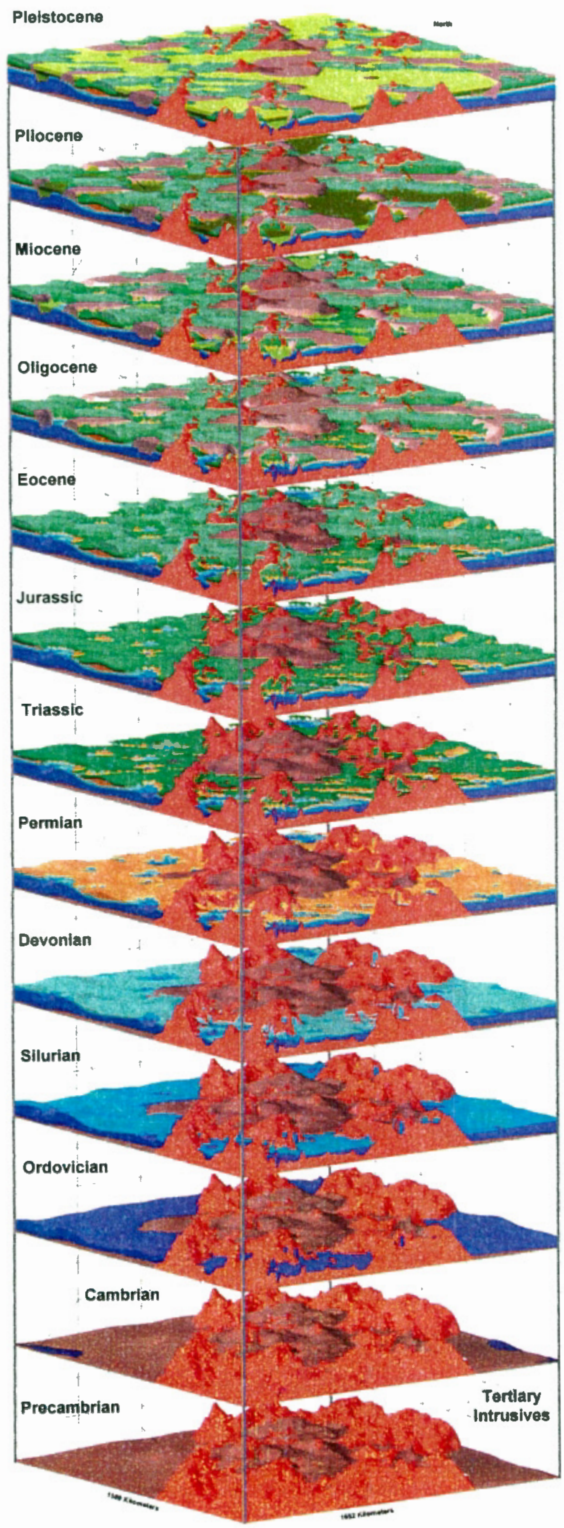

Figure 2. Stratigraphy model based on multiple grid surfaces.

The grid models that represent stratigraphic or hydrostratigraphic contacts may be; (1) interpolated from a list of XYZ control points, (2) interpolated from borehole or measured-section data, or (3) imported from other programs.

These contact models were used as the basis for a stacking operation in which the surfaces are plotted in relative order. At the same time, the program generates stratigraphic profiles along the perimeters of the stack. The final result is a stratigraphic model as depicted in Figure 2.

This type of modeling is referred to as "2½D" stratigraphic modeling. For each surface, there are two independent variables (easting and northing) and one dependent variable (elevation). As a consequence, a surface may not curve underneath itself. For any given easting and northing, there can only be one elevation. Hence the 2½D designation as opposed to true "3D".

The surfaces that define the tops and bottoms of each stratigraphic unit were truncated in a geo-chronological order via a series of grid filters. This filtering process insures that upper surfaces are set to the same elevations as the lower surfaces wherever they project below the lower surfaces.

The composite diagram depicted within Figure 2 was displayed within a 3D rendering subroutine (RockPlot/3D) that allows the viewer to manipulate the viewing angles, vertical exaggeration, lighting, etc. The user is also able to determine which stratigraphic units should be visible. This later feature was used to effectively "peel back" formations in order to gain a clear understanding of the paleo-environments.

A completely different approach to stratigraphic modeling involves the creation of a three dimensional matrix of blocks. Each of these blocks (voxels) contains a "G" (grade) value that represents the type of material at that particular point in space. The model depicted within Figure 3 was generated by using the stratigraphic surface grids as bounding filters. For example, if a voxel is bounded by the Permian superface grid and the Permian subface grid, it is assigned a G-value that represents Permian rock.

This type of modeling is considered true "3D" modeling. For any given easting, northing, and elevation, there is one dependent G-value.

Although the net result is not as aesthetically pleasing as the 2½D output, 3D models have some distinct advantages; (1) Volumetric calculations may be made simply by counting the number of voxels with a specified G-value and multiplying the result by the voxel-dimensions, (2) Non-stratigraphic data such as geochemistry, geophysics, or geotechnical observations may be modeled in a similar fashion, (3) Numeric models may be compared with each other to show correlations between material type and other geophysical parameters.

For example, resistivity and gamma models could be combined to create a "saturation" model. This model could then be combined with a lithotype model in order to generate a saturated sand model.

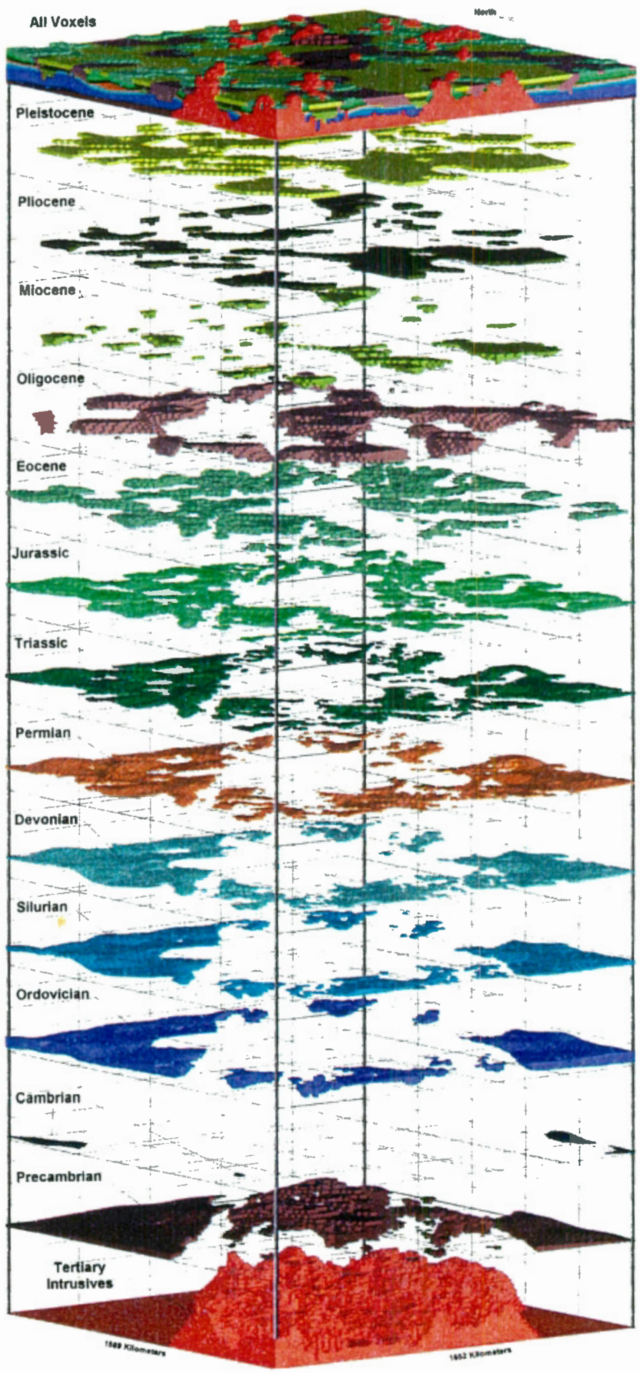

Figure 3. Solid block model.

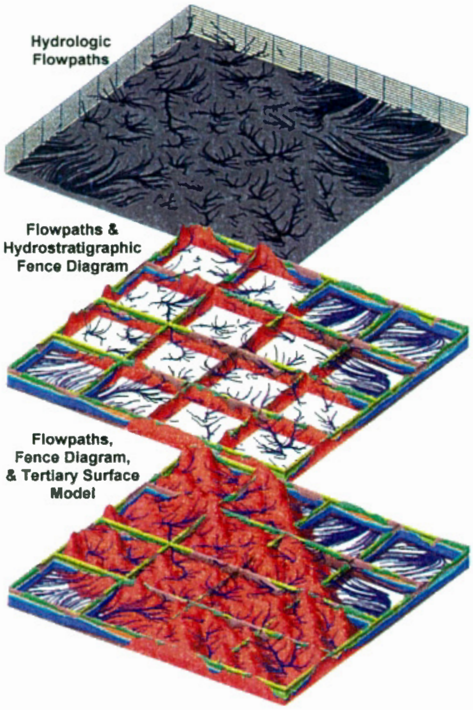

Figure 4. Flowpaths combined with hydrostratigraphic fence diagrams and Tertiary surface model.

In order to illustrate the three-dimensional relationships between groundwater flow and the hydrostratigraphy, a series of "flowpaths" were combined with the hydrostratigraphic fence diagrams and surface models (see Figure 4). These flowpaths may either be generated within RockWorks (via a simple downgradient simulator) or imported from more sophisticated particle tracking programs.

Theoretically, there is no limit to the number of "entities" that can be combined into a three dimensional diagram. Other data sets may include aerial or satellite imagery, location maps, geochemical or geophysical models, and model boundaries. In practice, the process may become very slow depending upon the number of "themes" (3-dimensional layers) open in the 3D viewer, the resolution of the models being viewed, and the speed of the processor. Figure 5 is a composite diagram depicting borehole logs, measured sections, fence diagrams, hydrostratigraphic surfaces, and flowlines.

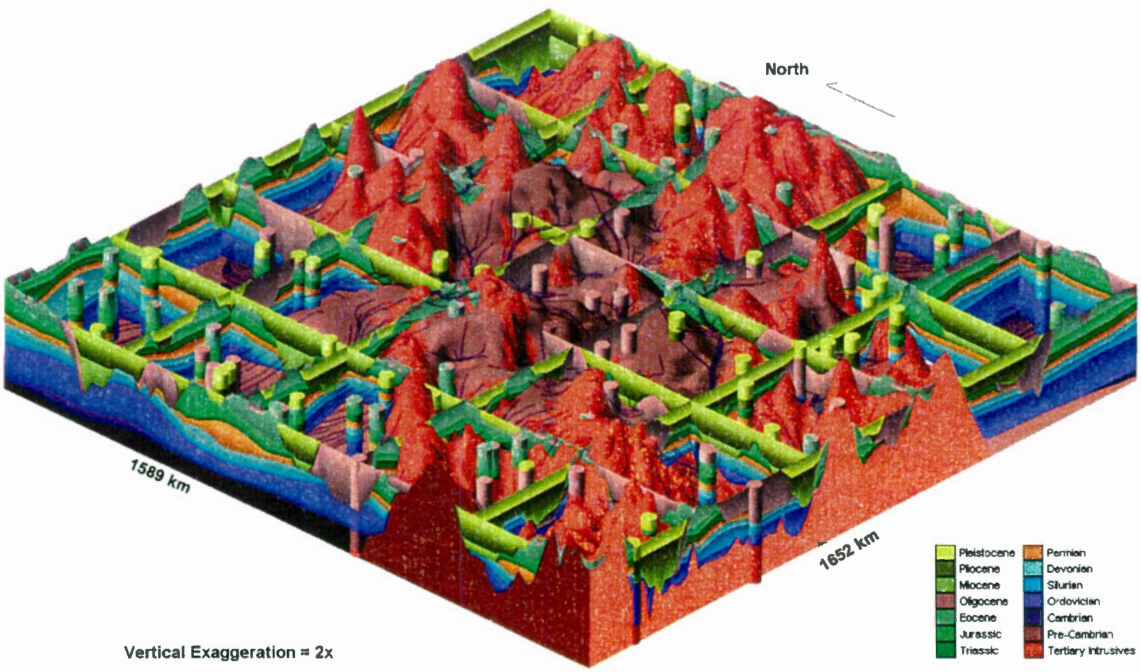

Figure 5. Composite diagram depicting borehole logs, measured sections, hydrostratigraphic surfaces, cross-sections (fence diagram), and flowlines. Note: Vertical exaggeration = 2x.

Three-Dimensional Aquifer Mapping Using Indicator Geostatistics

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The indicator geostatistics provides a method for three-dimensional aquifer mapping with quantitative aspects that are desirable in hydrogeologic application. With this method we generate maps that honor the proportions, the mean and variance in the thickness of unit types, their lateral correlation, and their three dimensional juxtapositioning relationships (cross-transition probabilities). These statistics that are honored are quantified from indictor data sets developed from borhole data. Indicator simulation algorithms generate maps on the grid required for fluid flow and transport simulations. Furthermore, many realizations of such maps can be generated that honor existing data and represent equiprobable interpretations, and thus that can be included in analyses of uncertainty in flow and transport. Here we consider application in studies of the three dimensional distribution of aquifers, and the distribution of permeability facies within aquifers, in buried-valley aquifer settings in the northern mid-continent of North America.

3D geologic framework for regional hydrogeology and land-use management; a case study from southwestern Quebec, Canada

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A 3D geologic framework which was constructed during a regional hydrogeologic survey near Montreal, Canada offers new insights into the regional Quaternary geology, the buried bedrock topography and hydrogeologic settings. The 3D model is also used to assess groundwater vulnerability to contamination. It is a knowledge-driven model using a surface modeling approach and a series of procedures which were specifically designed for regional studies in glaciated terrains. It draws on state-of-the-art technology, basin analysis techniques and a standardization/validation procedure to maximize the use of a multisource database. The model is capable of handling different complexity levels and of producing updates rapidly. Preliminary products can be generated during model construction to support ongoing investigations and modelling.

The method. The method comprises 7 iterative steps: (1) Archival data gathering and input into a database system; (2) Acquisition of new data from field surveys; (3) Mapping to feed scientific reflection and to support decision-making during ongoing investigation; (4) Data standardization and quality control that aim at classifying data according to source and establishing procedures as well as geological criteria to verify consistency (Table 1); (5) Construction of over 40 regional geologic cross sections where each cross section integrates all reliable subsurface and surface data within a 1-2 km wide strip (Fig.1); (6) Construction of discrete triangulated surfaces constrained on topographic and surficial geologic data, cross sections and the most reliable boreholes in order to represent the top of each of the main lithostratigraphic units of the Quaternary basin (Fig.2). Other local constraints are also applied at that stage to assure geological consistency such as thickness constraints to avoid surface crossovers; (7) Discontinuous surface border corrections using interactive tools and implementation of surface-to-surface constraints to bound these surfaces together along pinch-outs. The model covers an area of about 1400 km^2 (Fig.3). More than 5000 boreholes were compiled but only about half of these were used to construct the 3D model due to data declustering or quality control procedures. Interpreted geophysical data are also integrated in the model. Database management was done using the software ACCESS 97 (Microsoft), quality control was done using MapInfo 5.0 and further quality control and cross section building was carried out in the 3D graphic environment CAD system Microstation V7 (Bentley). The final 3D model was constructed using the geomodeling software gOcad 2.0.3 (T-Surf). The overall procedure was conducted over a period of three years but model construction from cross sections to the completed interlocked surfaces required about eight months, which includes the time required to learn and become familiar with the different softwares. The results have highlighted a series of advantages and limitations regarding the procedure, which can be summarized as follows:

Advantages.

1) Cross section building is not only an efficient method to construct a model with interpretation control but it is also a powerful mean of data validation. This approach considerably optimizes the use of a multisource database of highly variable quality;
2) The coherence between individual 2D sections is efficiently tested and more readily assessed if they are directly built in a georeferenced 3D environment;
3) Data standardization is helpful and simplifies the procedure of data validation and correlation

4) The procedure is particularly efficient for producing increasingly complex and consistent preliminary products in support of scientific reflection and decision-making during an ongoing investigation and this step-by-step approach provides an estimation of the surface's ability to predict stratigraphy and contact elevations at the location of new boreholes;
5) A framework made of interlocked surfaces does not require large computer power and truly helps to understand the geologic and hydrogeologic settings and can provide complex and consistent end-products as well as simplified framework for ground water flow simulation in a reasonable time frame;
6) The framework shown in Figure 3 can be modified, simplified and subsequently meshed according to any specific needs. Further discretization can also be applied directly to the complex framework in order to evaluate the spatial variability of a given property inside a geologic body or for full volume visualization.

Limitations and future development.

1) Many interactive tools are available in gOcad to construct perfectly bounded "dividing-walls" made of horizons and faults which enable the partition of the subsurface into 3D regions which describe the topological space. However, many interventions are still required to get fully satisfying results in complex settings, especially if one wants to link surfaces by low-angle pinch-outs which are so frequent in glaciated Quaternary basins;
2) Further development to implement finite element methods and other meshing algorithms currently used in hydrogeology into geomodeling systems and to provide other appropriate import/export filters would improve interactions between different specialists using the model. The visualization capabilities of geomodeling systems could thus help representing the results of groundwater flow simulation, particle tracking, etc.;
3) The method could benefit from a computer-based expert system in order to accelerate data validation and geological interpretation;
4) Polygons representing the geologic contacts were draped onto a topographic surface but corrections were needed in order to use these lines to constrain the model. Less corrections would be necessary if geological maps were constructed in a 2.5D environment;
5) Time constraints would be reduced if the basin analysis and geologic modeling were started before the onset of hydrogeologic characterization. The most complete and consistent 3D framework would thus be more readily available for process-based simulations and other uses;
6) Model reliability is limited by data quantity and quality and, since it is a knowledge-based model, by the experience of experts and the efficiency of their interaction;
7) More reliable regional geologic models could be produced if training, regulations and a standardized procedure were developed to improve the quality of water well databases.

Table 1. Boreholes database validation criterion

Reliability factor	Definition	Criterion	Data type
5	Highly reliable	Original logs and reports are available for checking procedures. Continuous and discontinuous samples are available	Stratigraphic, geotechnical and water well logs described following accepted scientific methodology
4	Reliable	Original logs and reports are available. Some wells are still accessible in the field and their location have been verified	
3	Less reliable	Original logs are not available; there is no apparent geological inconsistency with nearby reliable data	Geotechnical boreholes Water wells
2	Poorly reliable	One problem. source alt. ≠ DEM $\Delta \geq 10$ m or > 500 m from any human infrastructure or conflicting stratigraphy	Water wells
1	Unreliable	Multiple problems; altitude, lithologic description, etc.	Water wells

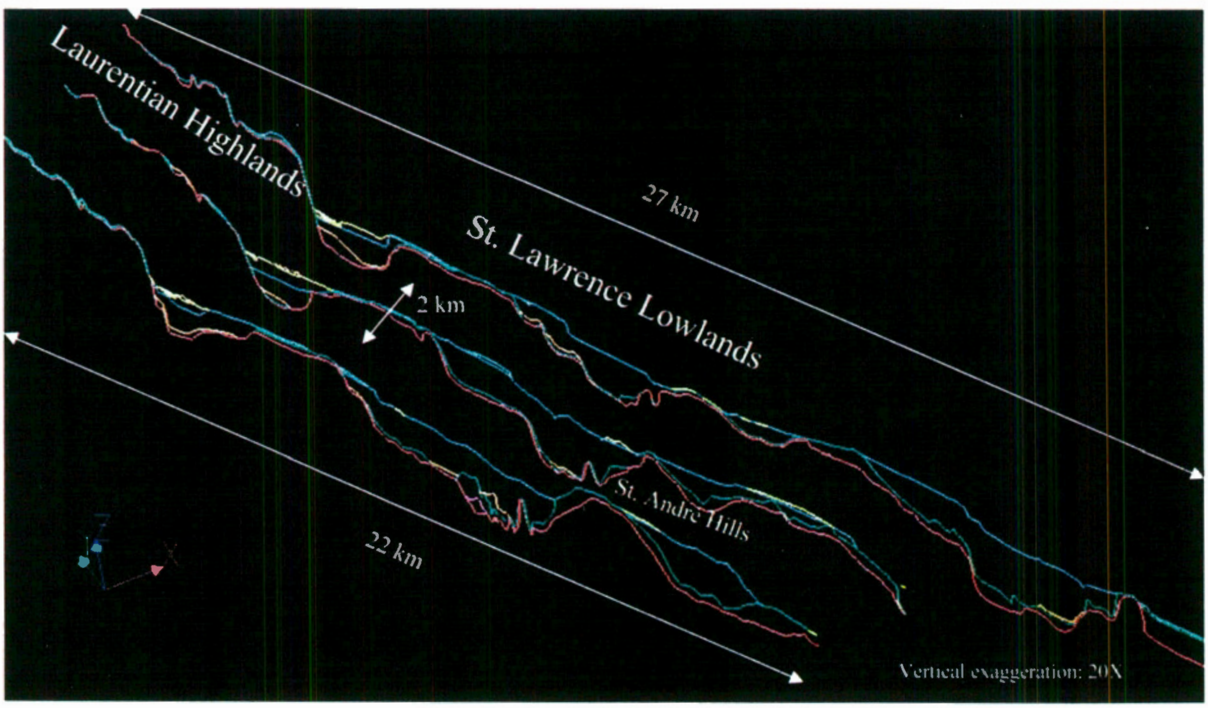

Figure 1. Example of a series of closely-spaced cross sections built in a 3D environment. The curves represent the top of bedrock and units recognized in the Quaternary basin. Ground surface and subsurface data are not shown for clarity. North is toward Y axis.

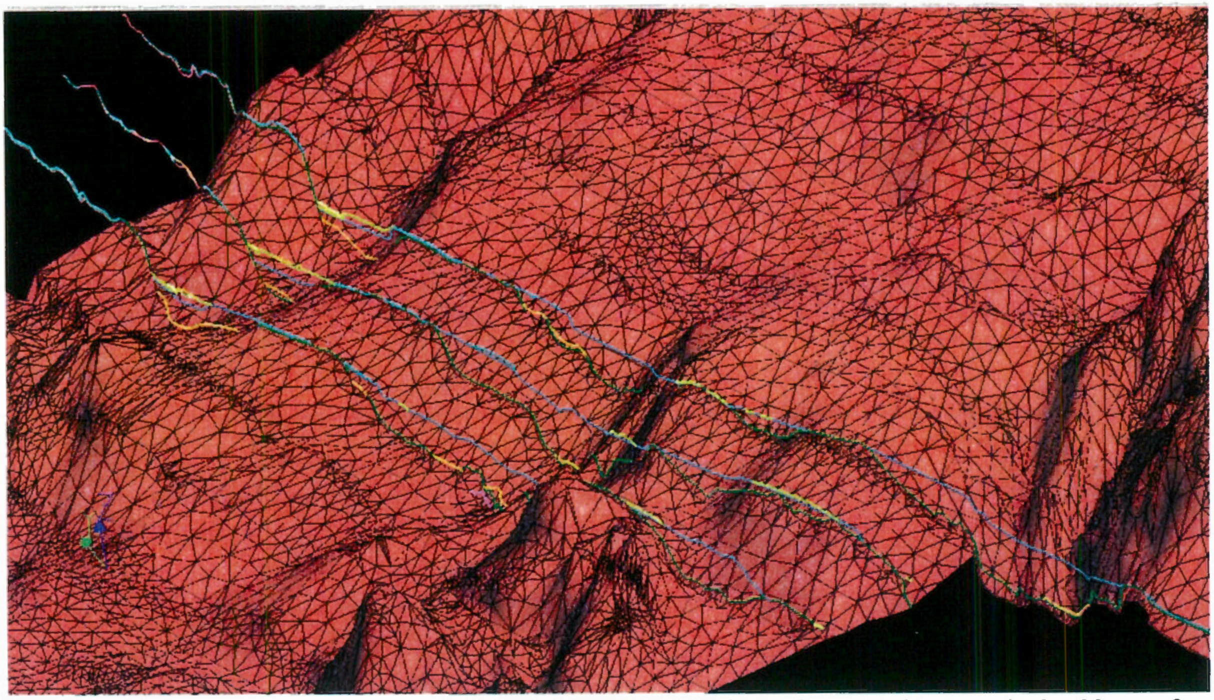

Figure 2. Same perspective view with bedrock topographic surface. Cross sections are the backbone of the model but surfaces are also constrained by reliable data between cross sections: Note the high triangular mesh density in the upper central part of the figure and elsewhere.

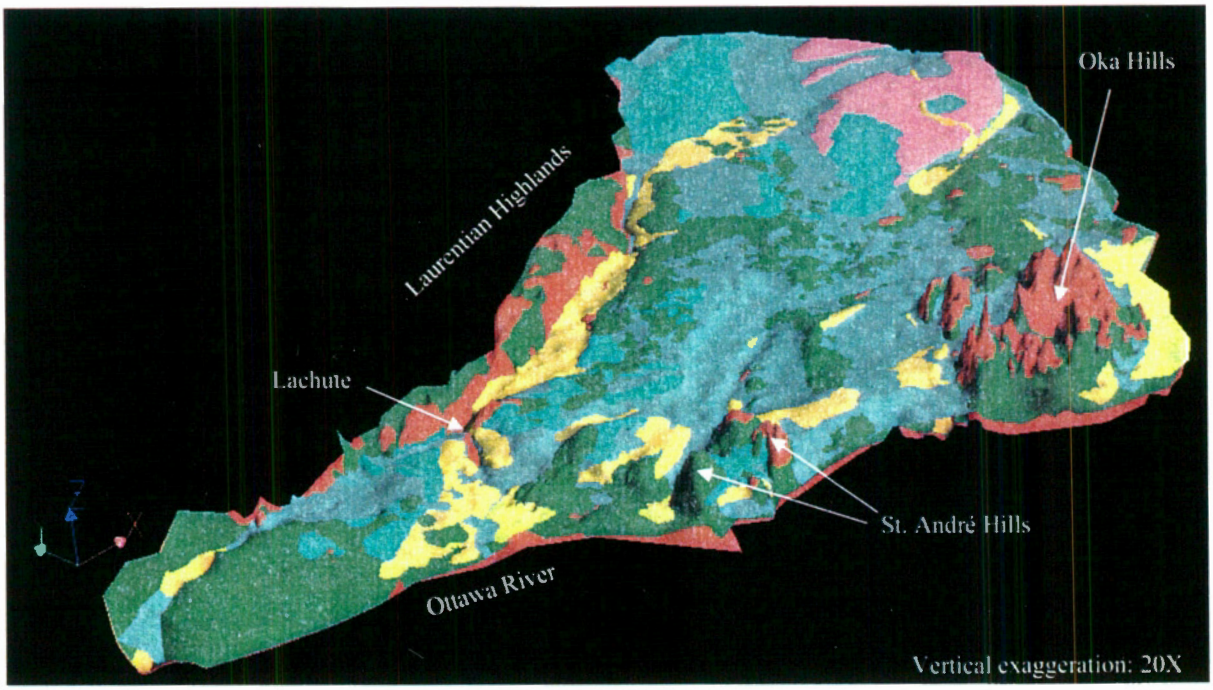

Figure 3. The 3D model is made of interlocked surfaces representing the top of the main geologic units of the Quaternary basin. 2D grid and script commands can provide a simplified conceptual framework for groundwater flow simulation by extracting data from the model. Further discretization can be applied to any part of the model in order to carry out many qualitative and quantitative analyses.

Mapping of groundwater reserves in Finland: the present status and aspects for future work

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The population of Finland relies heavily on groundwater as a source for potable water. Particularly, the rural population relies almost entirely on groundwater for their domestic water needs. About 60% of potable water distributed by communal and private water works is derived from natural or artificial groundwater. Altogether in Finland there are more than 2,300 water intake plants serving more than 10 people, and there are about 600,000 private wells usually serving one single household or a summer cottage (Korkka-Niemi 2001). The vast majority of wells are finished in unconfined, shallow, and porous gravelly and sandy surficial deposits. Geologically the aquifers are located in end moraine complexes, eskers, outwash plains or littoral beach ridges and terraces, deposited during or immediately after the deglaciation of the last Weichselian (Wisconsinan) glaciation.

There are no nation-wide databases of wells, their lithologies or hydraulic properties. However, a systematic mapping of groundwater areas was conducted in early 1990's by the Finnish Environmental Institute (Britshgi & Gustafsson 1996). This database contains files from 7,141 groundwater areas. The groundwater areas have been delineated on the basis of surficial geology, observations on the elevation of the groundwater table, and location of wells. Some of the areas include more specific additional information such as borehole logs or yield estimations based on pumping tests. This systematic mapping has been very useful because it has provided a practical tool for groundwater protection actions. More importantly, it also has indicated that groundwater is capable of supplying the national water supply in the future; at present only about 10% of the estimated total yield of the mapped groundwater reserves is in daily use.

The next phase of the survey for managing Finland's groundwater resources is presently going on. A project called VIRMA was launched three years ago in order to construct a groundwater flow model (Modflow) for at least one important aquifer at each of the 13 environmental districts of Finland. The project is being conducted in cooperation with the Finnish Environmental Institute, local environmental agencies, the Geological Survey of Finland, geology departments at the University of Turku and University of Helsinki, and local water companies. Presently, there are 10 areas that have been targeted for groundwater modeling projects and these areas represent some of the largest and best known aquifers in Finland. It has been a learning experience to construct geological models for the aquifers and to connect them with the flow models. The geological model of the Virttaankangas area (Artimo et al. 2002) is a good example of the progress that has been made in aquifer mapping.

Except for the Virttaankangas area, and for an additional half a dozen of reasonable well known groundwater reserves, the present knowledge of Finland's aquifer systems is based on traditional mapping of surficial deposits, and does not include any three-dimensional (3-D) information of aquifer thicknesses, water tables, sedimentological aspects, etc. This paper attempts to indicate this gap by comparing an independent hydrogeological data set with the existing small-scale aquifer map for Finland.

There are some characteristic geological properties common to nearly all Finnish aquifers:

1. The aquifers contain considerable variability. They normally include sediment units of very high hydraulic conductivity in close contact with units of very low permeability. In addition, the location of superconductive zones is related to core zones of eskers.

2. Esker sedimentology is controlled by deglaciation rates and a strong annual cyclicity of sedimentation, resulting in an architecture of imbricated fans (Mäkinen & Räsänen 2002). Coarse-grained proximal zones often lend themselves as the most suitable locations for water intakes. They usually are separated from each other by sequences of sandy and fine-grained sediments. The distance between individual fans depends on the rate of deglaciation being about 100 meters in the southern part of the country and about 1000 meters closer to the ice divide.

3. The bedrock surface controls groundwater flow and the location of groundwater reserves. Known fracture zones indicate the deepest bedrock depressions (Vuorela 1992), which often coincide with the largest aquifer systems.

The combination of these geological elements - esker chains (Kujansuu & Niemelä 1984), annual deglaciation rates, and location of the most prominent fracture zones - resulted in a predictive map indicating the location of potential sand and gravel aquifers. This map subsequently was compared with the map of 7,100 classified groundwater reserves. The results indicate that the mapping of national groundwater resources does reflect the general pattern of where the highest yielding sand and gravel aquifers are located. However, in areas where aquifers are not well known, particularly in areas with a high groundwater storage potential, the nationwide assessment falls short, indicating a need for further research. The VIRMA-project will answer some of the questions along with additional 3-D geological modeling and subsequent groundwater flow modeling.

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3D Hydrogeologic Characterization of the Marine Corps Air Station at Beaufort, South Carolina for Aquifer Vulnerability Analysis and Groundwater Flow and Transport Modeling

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The Earth Sciences and Resources Institute at the University of South Carolina (ESRI-USC), under contract to the U.S. Department of Defense, U.S. Marine Corps (DoD-USMC), is undertaking a three-year study of groundwater issues and development of an integrated environmental geographic information system (GIS) at the Marine Corps Air Station at Beaufort, South Carolina (MCAS-Beaufort) (Figure 1). In general, the current research is developing planning tools that will enable the Marine Corps to mark areas particularly susceptible to groundwater contamination. The project is characterizing the geology, hydrogeology, hydrology, and soils within the study area and integrating this new information with the existing knowledge base at the MCAS-Beaufort. Based on this data fusion, ESRI-USC will perform an aquifer vulnerability analysis to delineate areas with high, moderate, or low potential for allowing contaminants to enter the water table aquifer and the upper Floridan Aquifer. A significant component of the study is the development of a three-dimensional (3D) conceptual geologic model followed by development, calibration, and implementation of 3D groundwater flow and transport models covering the air station and surrounding area. The long-range goal of the project is to demonstrate to the Marine Corps and to the U.S. Department of Defense a methodology for building comprehensive, computerized environmental databases and their subsequent use for sound, well-informed decision-making regarding environmental activities (e.g., compliance monitoring, emergency response) at DoD facilities.

The Beaufort area is in the southernmost part of South Carolina. The climate is humid to subtropical with mean annual precipitation (1930 through 2000) equaling 122 cm (48.16 in). The bulk of rainfall occurs during the period June through September.

Siple (1960) reported on the geology and groundwater conditions in the Beaufort area of South Carolina. The eastern half of the area (i.e., adjacent to the Atlantic Ocean and the location of the MCAS-Beaufort) is the Sea Island section of the Atlantic Coastal Plain. It was formed by the submergence of coastal areas during post-Pleistocene time and is characterized by broad estuaries, numerous tidal flats, and islands. Much of the area is topographically between 3 m and 10 m above mean sea level.

The Coastal Plain province is typically a broad, almost level plain underlain by unconsolidated to partly consolidated sedimentary rocks that gently dip seaward. The study focuses only on the late-Tertiary to Recent deposits. Hayes (1979) and Spigner and Ransom (1979) described the geology of the Beaufort area in and around the MCAS-Beaufort. Underlying the study area, that encompasses roughly 22 km^2, is an artesian aquifer composed of a series of limestones of upper Eocene age. This regional aquifer system stretches from South Carolina to southeastern Georgia, to Florida, and into adjacent parts of Alabama. It is variously called the Ocala, the principal artesian aquifer, and the Floridan Aquifer. We refer to this regional groundwater system by the most commonly used term, the Floridan Aquifer system. In South Carolina, the Floridan Aquifer is composed of Ocala Limestone that is divided into a lower, a middle, and an upper unit on the basis of geophysical logs, lithologic logs, and hydraulic properties (Hayes, 1979). The upper unit of the Ocala Limestone equates to the upper Floridan Aquifer and occurs at roughly 10 m below land surface throughout the study area. The upper Floridan Aquifer is lithologically a white to

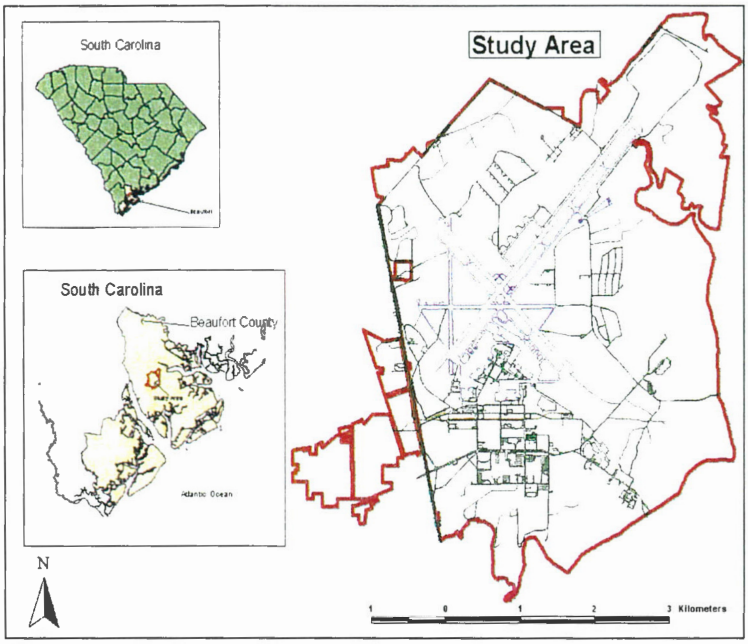

Figure 1. Maps showing location of Beaufort County, the study area, and the configuration of MCAS-Beaufort.

light-gray, calcitized, abundantly fossilferous, indurated limestone. The upper Floridan Aquifer is a major groundwater resource all along the Atlantic Coastal Plain. It is capable of yielding large quantities of good quality water.

Within the study area the Hawthorn Formation, where present, overlies the upper Floridan Aquifer. Miocene in age, the Hawthorn Formation consists of phosphatic, clayey sand to sandy clay. From recent characterization work at the MCAS-Beaufort, we have determined that the Hawthorn Formation is relatively thin (1 to 2 m) and is not continuous throughout the study area. Where it is present it functions as a semi-confining bed (Hayes, 1979).

Pleistocene to Holocene sediments overlie the Ocala Limestone, or Hawthorn Formation where present, and give rise to a thin surficial unconfined aquifer supported by local precipitation. The water table typically occurs within 2 to 3 m of land surface. Here, the soils are old and weathered. There is a clay-rich B-horizon in the MCAS-Beaufort soils that is particularly well developed in the eastern portion of the study area. Clays and organic materials leached from the surface in mostly poorer drained areas have resulted in discontinuous, but distinct, clay beds less than a meter below land surface. The better drained soils occurring primarily in the western part of the study area have a thicker leached horizon with translocated organic matter and iron sometimes fairly deep in the profile. Due to the old and well-weathered nature of the soils at the MCAS-Beaufort and the thin vadose zone, there is very little leaching or soil-water interaction during the brief time a recharge event is in the vadose.

To date, there has been significant field data collection and associated analyses at the MCAS-Beaufort. ESRI-USC has recorded over 7,500 m of high resolution reflection seismic survey lines. Among other results, the analysis and interpretation of the seismic data indicate that in several locations there are channel-like erosional features that cut down into the surface of the Ocala Limestone; and that the Hawthorn Formation varies significantly in presence and thickness.

The initial seismic investigation was the basis for the first round of soil borings via Geoprobe® technology to core the surficial (i.e., water table) aquifer and construct monitoring wells in key locations throughout the study area. A total of 25 boreholes were drilled during the first round of coring and over 100 m of core were obtained. Electrical conductivity logs were collected in each borehole during the Geoprobe® investigation. These logs are very useful in differentiating sand and clay throughout the vertical extent of the borehole. Laboratory analysis of the collected core samples (including grain size analysis) began in early 2002 and will continue through the end of 2002. Five hydrostratigraphic units have been identified within the study area, from land surface downward they are:

- shallow coastal sand unit
- lenticular (fluvial/deltaic) clay unit
- coarse to medium sand basal channel unit
- Hawthorn Formation
- Ocala Limestone - upper Floridan Aquifer

Not all units are present at all locations.

Ten of the Geoprobe® borings had 2" Schedule 40 PVC monitoring wells with 1.52 m (5 ft) screens installed in them. At several locations the monitoring wells are clustered with one screened interval above the lenticular clay unit and the adjacent screened interval below the lenticular clay unit. At locations where the shallow clay unit is absent, the screened interval is placed near the mid-section of the shallow aquifer. All of the Geoprobe® wells were installed in the shallow water table aquifer. These wells, along with other existing wells at the MCAS-Beaufort have been instrumented with automatic water level recording devices that sample water levels hourly.

Following completion of the Geoprobe® investigation, Rotosonic® borings into the Ocala Limestone (i.e., upper Floridan Aquifer) were completed at the locations of the previous Geoprobe® borings, as well as at other locations throughout the study area. Several hundred meters of core were obtained from the Rotosonic® drilling. In 16 of the Rotosonic® borings, 2" Schedule 40 PVC monitoring wells were constructed at the top of the Ocala Limestone, but isolated from the overlying materials. These wells have 1.52 m (5 ft) of screened interval in the upper Floridan Aquifer. Most of these wells have also been instrumented with automatic water level recording devices.

The results of the geological and geophysical characterization are being used to define and establish the geometry of a fully 3D numerical groundwater flow model of MCAS-Beaufort which, in turn, will provide the foundation for solute transport modeling across the study area. The three-dimensional structure of the model is directly relatable to the construction of a stack-unit map (Berg and Kempton, 1988) of the study area (Figure 2).

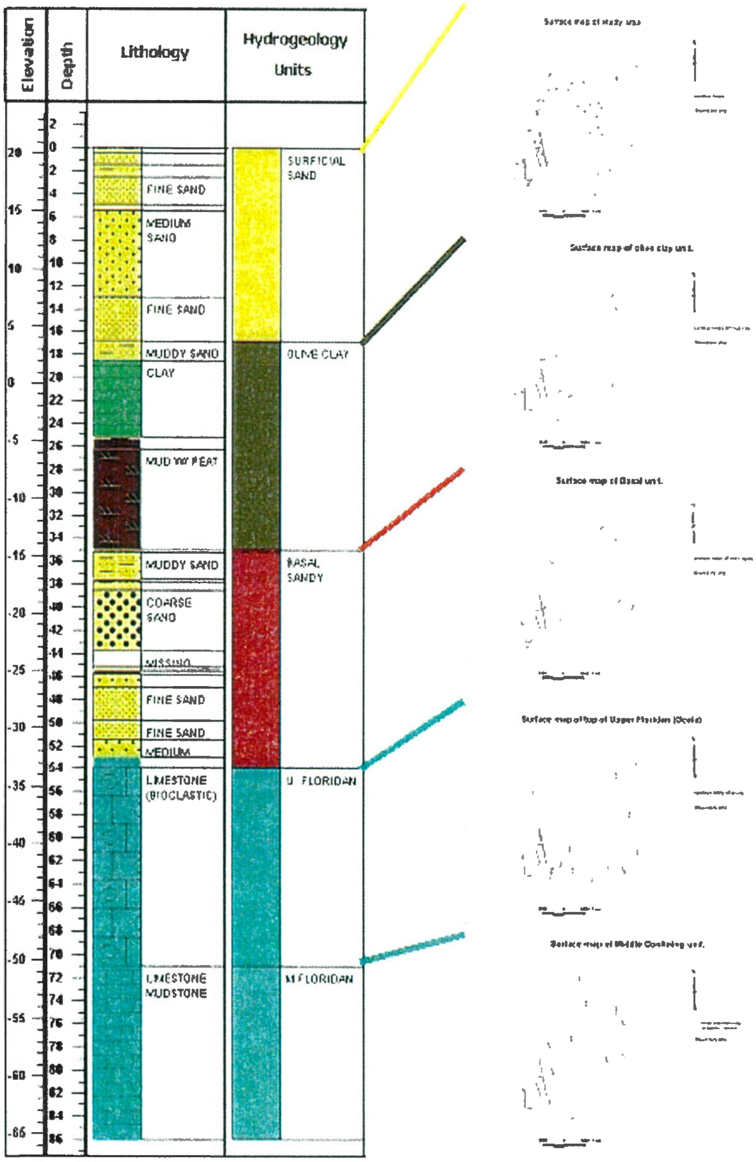

Figure 2. Hydrostratigraphic unit surface elevations used to construct stack-unit map and groundwater model domain.

Slug tests have been performed in most of the newly constructed wells. The resulting estimates of hydraulic conductivity along with those provided through grain-size analysis will be used to establish the hydrogeologic properties of the hydrostrigraphic units incorporated in the 3D numerical groundwater flow and transport models of the MCAS-Beaufort. The results of water level monitoring are being used to establish boundary conditions throughout the model domain.

Figure 3 shows the 3D configuration of the preliminary groundwater flow model encompassing the study area and vicinity. The model geometry is consistent with the hydrostrigraphic surfaces shown in Figure 2. There are several locations throughout the model domain where particular hydrostratigraphic units are absent. Within the model domain these are locations where the model layer thickness is less than 0.08 m (0.25 foot) as the modeling convention will not tolerate the physical absence of a layer. However, to simulate the physical absence of a hydrostrigraphic unit, the hydrogeologic properties for the thin layer are equated to the those of the adjacent (i.e., above or below) layer that is thicker.

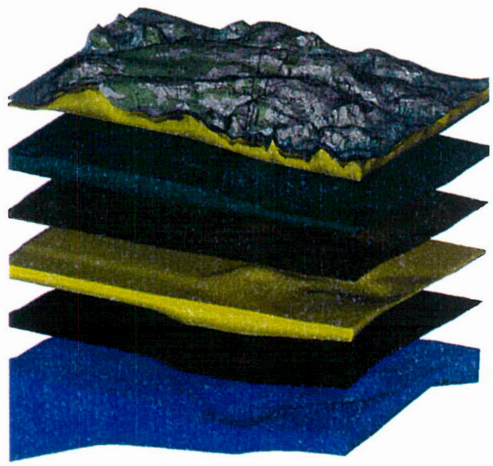

Figure 3. MCAS-Beaufort groundwater model structure.

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The Need for Basin Analysis in Regional Hydrogeological Studies: Oak Ridges Moraine, Southern Ontario[1]

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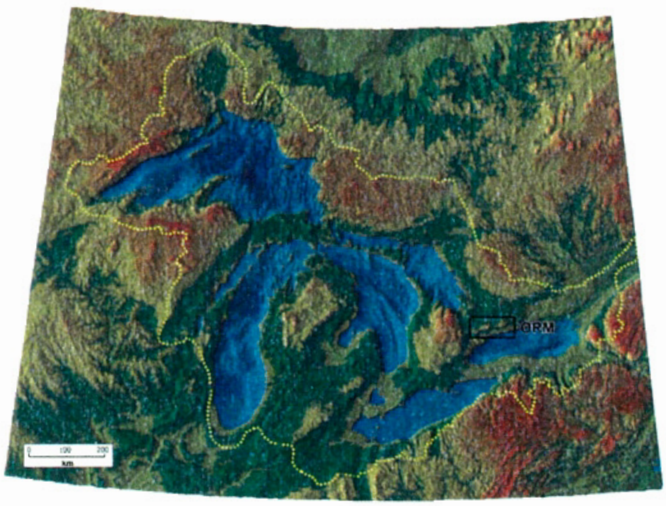
To manage North America's groundwater resources in a sustainable way there is a need for regional knowledge of aquifer systems. Improving regional knowledge, in light of scant hydrogeological data, requires a multidisciplinary approach that advances the geological understanding of a basin. Basin analysis - mapping and characterizing the reservoir potential of sedimentary basins as applied in petroleum exploration - provides an approach that is directly applicable to regional hydrogeology studies and related land use planning. This presentation applies basin analysis to a glaciated terrain by integrating data from a variety of sources and scales of investigations to develop a 3-dimensional (3-D) hydrogeological model of the Oak Ridges Moraine Area (ORM), southern Ontario (Fig. 1).



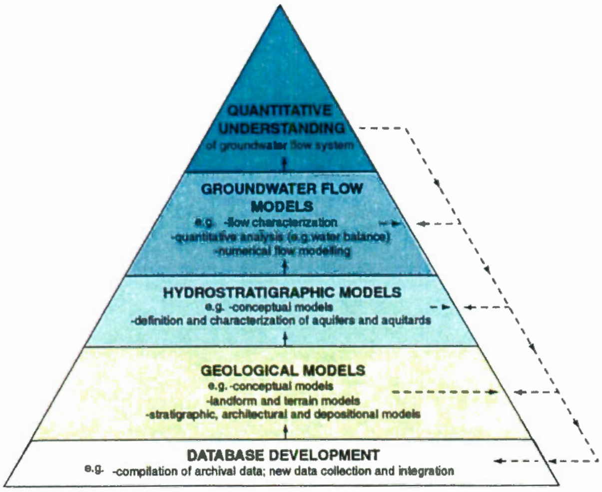
ORM study within the Great Lakes Basin

Figure 1. A digital elevation model (DEM) of the Great Lakes basin highlights the location of the ORM regional study within the broader topographic and geological basin.

Basin analysis supports the progression from data compilation and geological conceptualization to model development, and ultimately, towards quantitative flow system analysis (Fig. 2). This progression is achieved notably by developing primary geological models of the stratigraphy, sedimentary architecture and origin of deposits of the ORM area (Fig. 3). In this study, the analysis outlines two regional elements, or hydrogeological settings, highly significant to groundwater flow in the area: i) regional till uplands that form the principal aquitard, and ii) channels that breach the till and form hydraulic windows and important channel-fill aquifers (Fig. 4). The widespread channel aquifer setting had not been previously recognized because its identification required a 3-D geological framework based on high-quality topographic, geological and geophysical data. Development of the regional geological knowledge would not have been possible using relatively poor-quality water well records alone. A conceptual numerical model is used to illustrate that vertical flow through channels can be of greater magnitude than that across the regional aquitard (Fig. 5). However, other potentially important controls on vertical groundwater flow, through both channel

[1] This is a précis of a paper in Geoscience Canada published in v. 29: 1, 2002 by the same authers; full paper is available as a pdf file at the Oak Ridges Moraine website: http://sts.gsc.nrcan.gc.ca/orm/index.asp

windows and the regional aquitard, are the horizontal continuity and transmissivity of Lower sediment aquifers (Fig. 5). These controls are directly related to the basin attributes of stratigraphic architecture and sediment facies variability (Fig. 3c), and need to be taken into account for improved numerical analysis.



Basin Analysis Approach

Figure 2. Simplified basin analysis approach used in the regional hydrogeology analysis of the ORM area. The approach leads progressively from data base development early in a study (base) to quantitative understanding of groundwater flow systems as the study matures (at the top).

Development of Geological Models

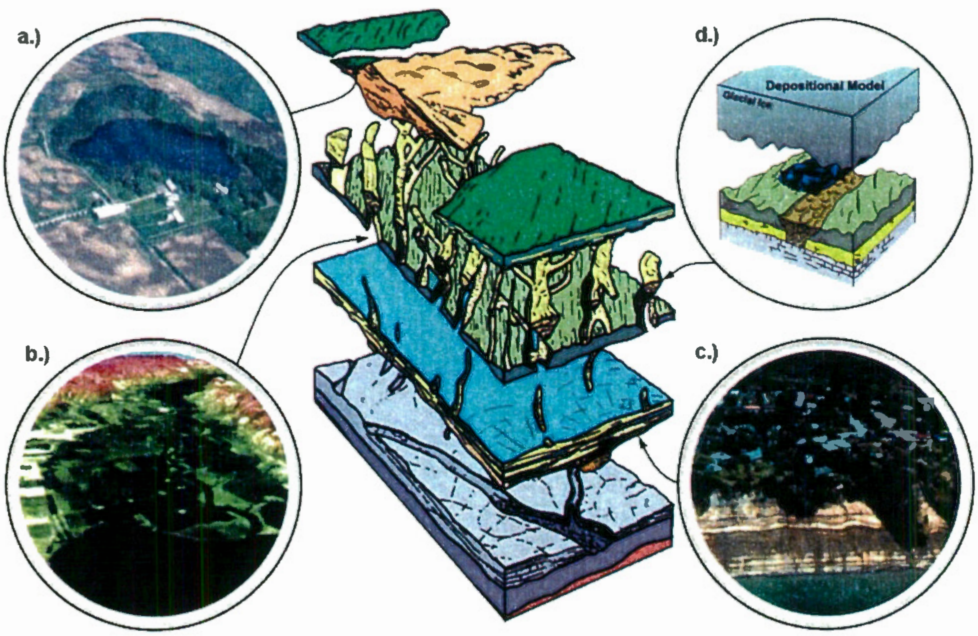


Figure 3. Development of geological models was central to the ORM basin analysis study. The ORM stratigraphic architectural model consists of five stratigraphic units (Paleozoic bedrock, lower sediment, regional till, moraine and channel sediment, and, upper till). Elements of model development are illustrated: a) terrain analysis of surface strata shows the importance of hummocky topography and internally-draining lakes to recharge; b) DEM highlights a major channel feature that may be a significant discharge area, or where buried, could be significant to regional flow; c) exposed lake bluffs reveal the broad tabular sedimentary architecture of the widespread lower sediment strata that help contribute to regional groundwater flow (see figure 5); d) depositional models form key analytical tools to gain regional understanding of the heterogeneity of hydrostratigraphic units. (A channel fill model is shown and used in figures 4b and 5).

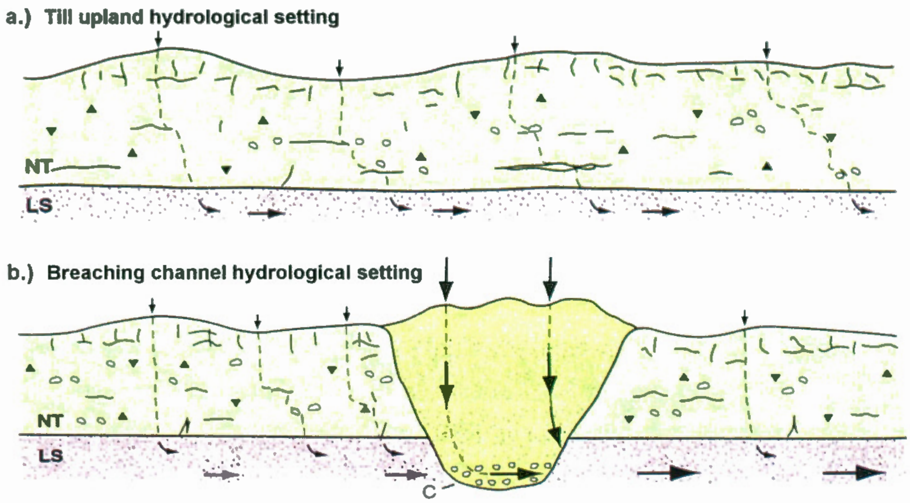


Figure 4. Hydrogeological terrains: a) continuous aquitard setting: till upland; b) breached aquitard setting with coarse channel sediment. Arrows indicate generalized groundwater flux. NT=Newmarket Till; C=channel; LS=lower sediment aquifer.

The concept of watershed with surface water and groundwater interaction, that is embodied in basin analysis, effectively enhances communication of 3-D concepts and understanding between geoscientists, and engineers, planners and other scientists. Better understanding of regional 3-D hydrogeological settings also will improve the scientific basis for land use planning at all scales, as the key identified settings are scaled up from site, to watershed, to regional scales within the basin framework. Site remediation or development proposals generally rely on site-specific (~1-10 km^2) data and analysis, often restricted to shallow depths and predominantly for the purpose of site design. Such studies will benefit from regional knowledge of hydrogeological settings and of the extent of flow systems beyond the site to watershed or basin scales. Accordingly, the presentation advocates investment in both high-quality data and the requirement for regional understanding of the geological system that underlies basin analysis; and this, permits a much more reliable assessment of groundwater systems in complex hydrogeological settings across North America.

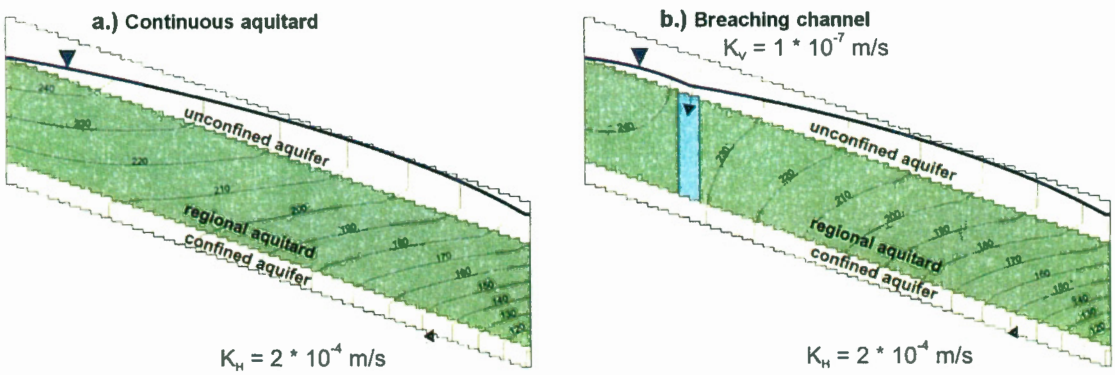


Figure 5. Steady-state visual MODFLOW groundwater flow simulations illustrate the effect of vertical flow through a regional aquitard and a breaching channel with modest vertical conductivity in a generalized 2-D cross-section of 1 km width. a) Continuous aquitard (no breach). b) Breaching channel in aquitard: 1 km channel (vertical hydraulic conductivity (Kv) of $1*10^{-7}$ m/s) breaches the regional aquitard and transmits ~37% of flow with modest Kv--Kv may be up to 100 times higher. Note: Horizontal hydraulic conductivity (Kh) is $2*10^{-4}$ m/s (Transmissivity, T=173 m^2/d) in the confined aquifer is set relatively high to demonstrate the effect of a non-restricting horizontal flow. Thick line is the phreatic surface of the unconfined aquifer.

Developing a standard geologic data model to incorporate 3-D information

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When preparing a geologic map, whether in analog or digital format, the author manages the basic information and interpretations within some organizational framework. This framework can be both scientific (e.g., a set of guiding principles for the regional stratigraphy) and physical (e.g., putting the information into field notebooks, spreadsheets, databases, or a GIS). Commonly, geologists are not consciously aware of this framework – they just use it. This is especially true in GIS, where users (whether geologist-authors or GIS professionals) traditionally have either used the data structure, or data model, provided by the software (e.g., ArcInfo) or have modified it slightly according to project or agency needs. As a result, there has evolved a wide variety of data models. Because digital data offers vast potential for sharing, integration, and reinterpretation of information, many geologists have concluded that some standardization would be beneficial. Development of standard science language (e.g., to describe rock lithologies) and/or a strategy for correlating among local or regional science languages has become essential.

In the United States, the Geologic Mapping Act of 1992 and its subsequent reauthorizations stipulate the development of a National Geologic Map Database (NGMDB) and the standards necessary to support it. In 1996, the Association of American State Geologists, the Geological Survey of Canada, and the U.S. Geological Survey agreed to collaborate on development of a standard data model and science language. This work was begun through a newly-formed committee, the Data Model Working Group, which developed a draft data model. Beginning in about 1998, this data model was informally evaluated by many agencies. In 1999, the North American Data Model Steering Committee (NADMSC) was formed, to supercede the Working Group and to continue the data model development.

Currently the NADMSC is redesigning the draft standard model based on test-implementations by the various agencies, and is developing standard science language. Because of the difficulties in designing a data model and a standard science language that can be uniformly implemented by many agencies, the NADMSC's current philosophy accepts the need for (and the reality of) local-agency deviations from the standard, and is focusing on two things: 1) a high-level conceptual data model that would specify the concepts necessary to adequately describe geologic map information, and 2) a universal translator (possibly using XML) that would serve as a bridge between the various implementations. For such a translator to be feasible, each agency would standardize its data model and science language, and be capable of writing their information to the NADMSC standard via the translator. Further information is available at <http://geology.usgs.gov/dm> and <http://ncgmp.usgs.gov/ngmdbproject>.

At present, this data model addresses two-dimensional geologic data. However, the developers understand the need to incorporate into the model the detailed 3D information that decisionmakers and scientific researchers require. In the central Great Lakes area, where 3D information on surficial deposits has been widely developed, the NGMDB has approached the Central Great Lakes Geologic Mapping Coalition with an offer to collaborate on a prototype project to extend the conceptual data model so that it can manage the 3D map information gathered by the agency members of the Coalition (the geological surveys of Illinois, Indiana, Ohio, and Michigan, and the USGS). It is hoped that a prototype can be pursued in the coming years.

If the data model is extended to incorporate 3D information, in what form will that information be available? Will it be a series of "stack-unit" maps that show the topography of each significant buried surface and, by comparison of surfaces, also show the geometry (i.e., the thickness) of each geologic unit? In stack-unit mapping, physical attributes such as lithology are assigned to each unit; although it is well known that units are not homogenous, this style of mapping must inherently apply an attribute uniformly across a unit. In contrast, might geologists develop 3D maps where each location in 3D space (i.e., each volume pixel or voxel) possesses a uniquely-defined set of attributes. This, for the purposes of detailed analysis is the ideal data set, but is it a reasonable and attainable goal for the geological surveys? Through continued discussions among mappers, GIS and computer professionals, and agency managers, the geoscience community will face these questions and develop strategies to deliver high-quality, useful 3D data to decision makers and researchers.

Glacial geology mapping in Berrien County, Michigan: Resolving the third dimension for increasing the accuracy of resource assessment

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In Michigan, 92% of the state's glacial geology remains unmapped at a scale useful for resource planning, which we consider a scale of at least 1:50,000. Virtually every hydrogeologic report, environmental assessment, and remedial investigation contains a section on the geologic setting of the site being studied. For most of Michigan, this means the glacial geology of the site. The only map available for the entire state is the "Quaternary Geology of Michigan", published by the Geological Survey Division in 1982. This map, at a scale of 1:500,000, was never meant to be used for detailed investigations. In the absence of anything better, it is commonly used as a guide to the stratigraphy that can be expected for site investigations. At scales typically around 1:1,200, these sites are barely a pinprick on the state map. It should come as no surprise when the state map doesn't correlate well with the site map. Michigan has a reputation for plentiful water resources. According to the National Ground Water Association, Michigan has more water wells that any other state (about 1.2 million). About half of these wells are in glacial aquifers, and the majority of bedrock aquifers are recharged though glacial materials. Yet, these deposits have not been adequately mapped at a scale that enables planners to predict where the water-bearing formations exist, let alone estimate their potential for water production. Without this information it is not possible to determine safe yields for these formations or to delineate sole-source aquifers, let alone perform the source-water assessments currently required by the EPA.

The fact is that glacial sediments dominate the geology of Michigan. There are many ways this fact affects our daily lives. Soil fertility, erosion potential, runoff/infiltration, load-bearing capacity and suitability for construction materials all depend on the sediments that glaciers left behind. Regarding hydrogeologic impacts for instance:

- All of our ground water for drinking and irrigation either filters through or is stored within glacial deposits.
- Strategies for environmental cleanup must take into account the glacial stratigraphy for cost-effective planning.
- Source-water assessments should be done considering aquifers as glacial-hydrostratigraphic units.

Mapping Pleistocene deposits has the advantage that, due to their recent deposition, they retain much of the original topography. Hence, morphology has played a role in the development of glacial theory. This has been a bane as well, since one of the problems plaguing glacial geology is our historic legacy of using morphology as a proxy for sedimentology. Leverett and Taylor (1915) described the internal characteristics of the glacial deposits of Michigan and Indiana only in the few areas where such data was available. Out of necessity, they relied on morphology to make conclusions about landform genesis. Based on his literature survey, Flint (1957) defined moraine as "an accumulation of drift having a constructional topographic expression … independent of the surface underneath it, and having been built by the direct action of the ice." The use of a largely topographic classification led Leverett and Taylor (1915) and many others to misclassify as moraines landforms we now know to be fluvial deposits.

Jahns' (1941 and 1953) mapping efforts in Massachusetts led him to recognize that glacial landforms appeared associated together in a genetic series. Jahns called these associations of features

"sequences" (Jahns, 1941, p. 1910), in the sense that landforms could be traced from sub-glacial to sub-aerial ice-contact to proglacial types. Ice-front positions were determined by mapping the locations of "...ice-contact meltwater deposits, such as eskers or ice-channels fillings, kames, kame terraces [and] kame plains..." (Koteff, 1974, p. 122). The terminology choice of "sequence" by Jahns (1941, p. 1910) was "unfortunate" (Koteff, 1974, p.122), due to the extant use of the word in a time-transgressive manner. Jahns intent was to use the term to mean deposits being formed contemporaneously. Koteff and Pessl (1981) subsequently renamed the term "morphosequence" (as a combination of morphologic and sequence) both to eliminate the confusion with the time connotation and to add the geomorphology component of the mapping technique. Morphosequence analysis is not just a morphologic examination of topography. It must also include the distribution of texture and sedimentary structures and reconstruct the grade and base level relationships of the entire depositional sequence.
Koteff's (1974) own fieldwork as well as a review of his colleagues' mapping led him to recognize eight morphosequence types:

A. Fluvial ice-contact sequence
B. Fluvial non-ice-contact sequence
C. Lacustrine ice-contact sequence
D. Fluvial-lacustrine ice-contact sequence
E. Fluvial-lacustrine non-ice-contact sequence
F. Lacustrine-fluvial ice-contact sequence
G. End moraine and associated outwash
H. Glaciomarine

As can be deduced from the nomenclature, the key features of the idealized sequences (Figure 1) are whether it begins in contact with the ice and the existence and distribution of fluvial and lacustrine units. Of lesser importance are moraines and coastal influences. Jahns (1941) suggested that drawing profiles of outwash plains at a vertical exaggeration of 20x would readily illustrate the form of the sequences and show the position of former ice margins (Figure 2). These can then aid in restoring the collapsed outwash plain to its original form.

Koteff (1974) and Koteff and Pessl (1981) believed that basal shearing was responsible for sediment transfer from ice entrainment to the fluvial system. Gustafson and Boothroyd (1987) showed this to be incorrect, that the main source of water and sediment transfer from the glacier is from subglacial drainage. This does not alter the utility of the morphosequence concept.

The Valparaiso morainic system in eastern Berrien County, southwestern Michigan, is a 10-18 km-wide continuous belt of collapsed glacial landforms. Previously, the composition of the moraine belt was inferred to be of unsorted materials, including coarse- to fine-textured tills, and some stratified deposits. The moraine boundary was defined primarily on classical geomorphic evidence of relative high elevation, "kettled" or "swell & sag" topography, presence of boulders at the surface, steep ice-contact face, etc. Recent geologic mapping using more than 25,000 water-well and engineering boring records, airborne and down-hole geophysical data, and test drilling has revealed the three-dimensional deltaic structure of deposits composing the Valparaiso morainic system in eastern Berrien County, southwestern Michigan (Figure 2). The deposits include over 50 glaciodeltaic morphosequences, mostly ice-marginal deltas that are graded to proglacial Lakes Madron and Dowagiac. Correlating the elevations of the heads of deltas and the fluvial/lacustrine interface allowed us to group glaciodeltaic morphosequences by outlet/proglacial lake level and therefore, infer the location of nine ice margins at various stages during construction of the Valparaiso Moraine. The resulting geologic map shows shingled deposits from a highly undulating ice margin, rather than the single, linear margin shown on older maps.

Each delta grades from ice-contact landforms underlain by coarse-grained facies at its head to non-collapsed landforms underlain distally by fine-grained facies. Proximal deltaic deposits are coarse grained, locally containing boulders and lenses of poorly sorted flowtill with zones of collapsed bedding along ice-contact slopes. A gravel-pit exposure extended by a drill hole in the middle of our characteristic delta on Rangeline Road, showed, from top to bottom: 20 ft glaciofluvial sand and gravel; 15 ft deltaic foreset sand, silt, and gravel, dipping 10° SSE; 30 ft pebbly sand; 35 ft coarse to medium sand; 26 ft medium to very fine sand and silt at the base; overlying 5.5 ft of gray silty (Saugatuck?) till. Comparable proximal and distal sections are derived from water-well data in this deposit.. Predictive vertical sections down gradient and across the gradient show the 3-D distribution of sedimentary facies within this deposit, based in part on other deep exposures in Michigan, and in modern glacial environments at the Bering Glacier, Alaska. This example demonstrates the relationship between sedimentary and hydrogeologic facies, which requires reliable subsurface data, and a modern understanding of glacial lake levels and ice-marginal processes that distribute the facies in repetitive and predictable motifs.

deposits/basin… proximity to ice… base level control

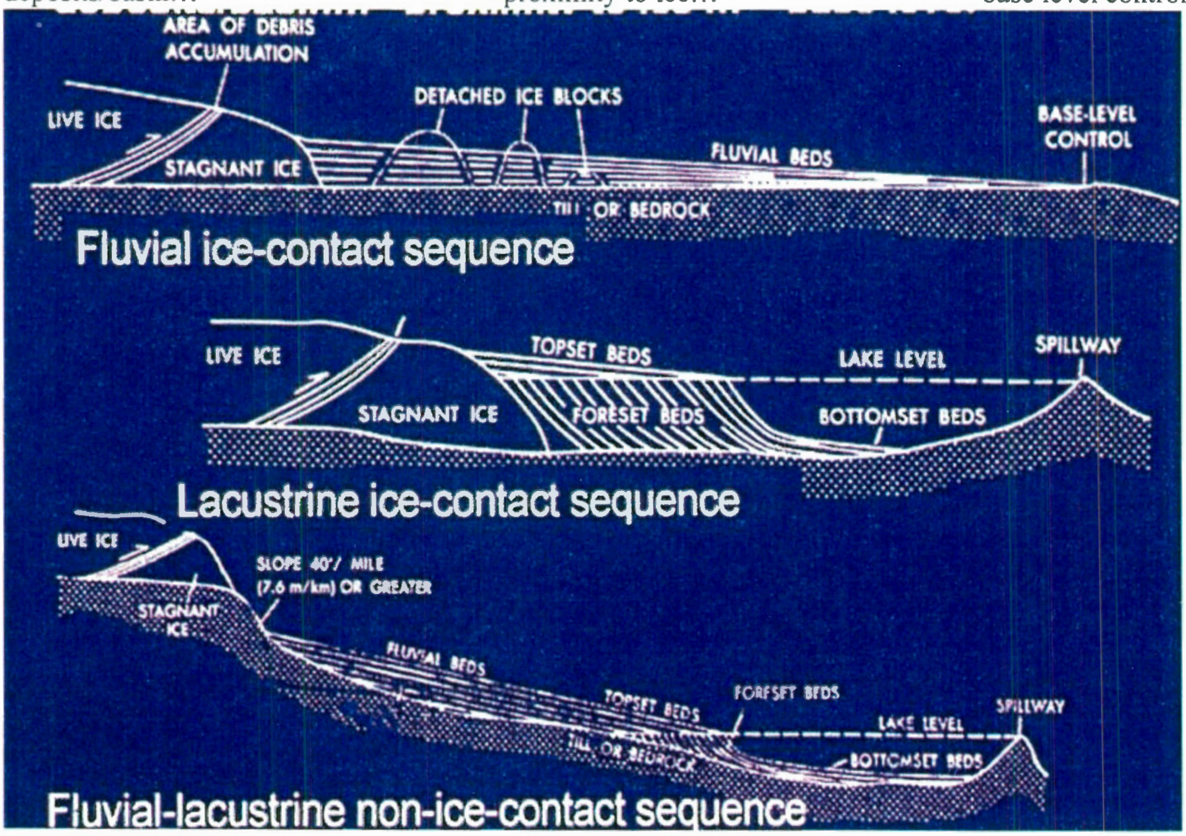

Figure 1. Morphosequence classification

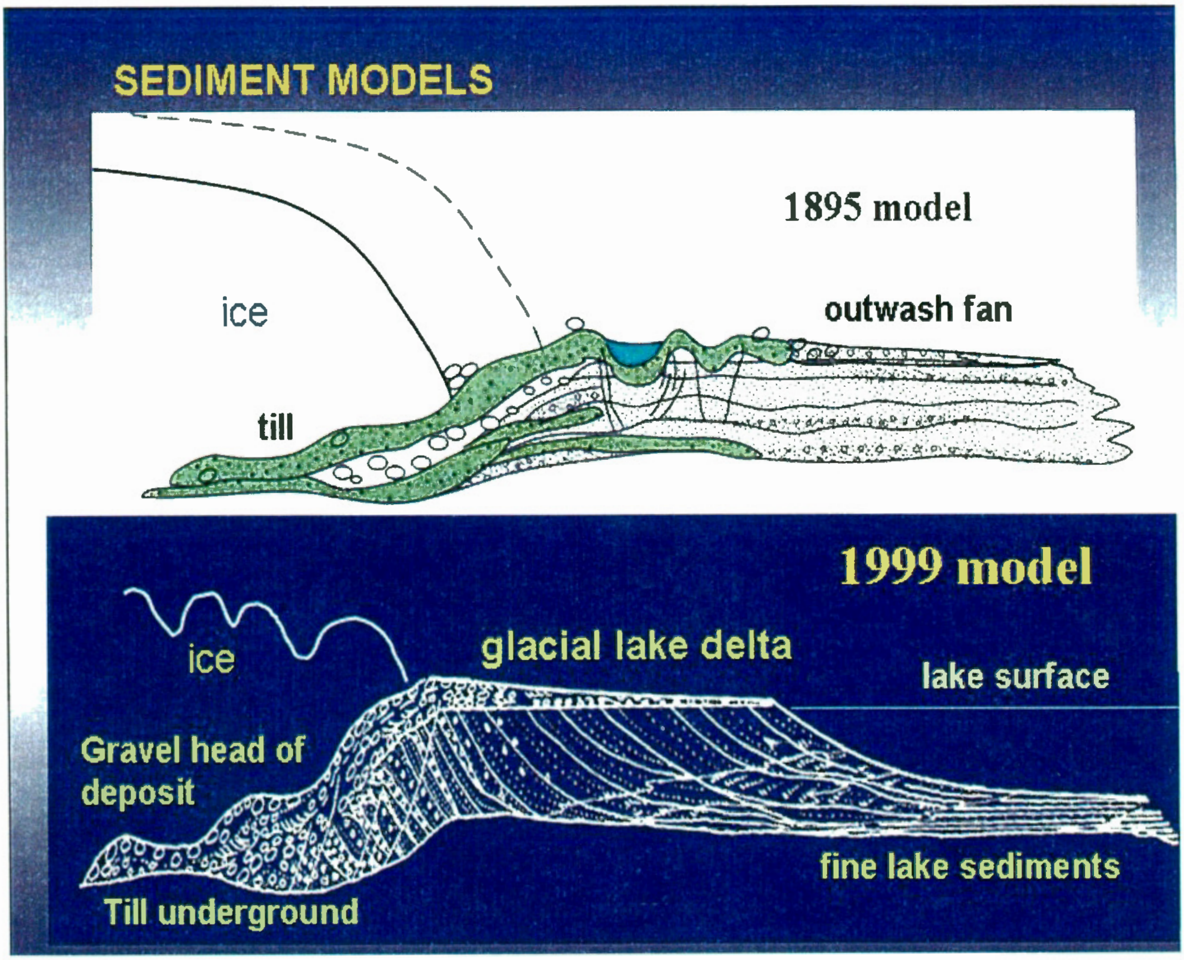

Figure 2. Early 20th Century glacial depositional model vs. model developed by recent mapping.

Hydrogeologic Framework Construction, Using An Example from the Death Valley Ground-Water Flow System, Nevada And California, USA

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An understanding of ground-water flow requires the formulation of conceptual and digital models that characterize the three-dimensional (3D) hydrogeologic framework within which the water moves. One such digital model is a hydrogeologic framework model (HFM), a computer-based volumetric model that provides a description of the geometry, composition, and hydraulic properties of the hydrostratigraphic units and structures in a ground-water flow system. This paper will discuss the general process of understanding the hydrogeologic framework and constructing a HFM based on experience in the Death Valley region.

The U.S. Geological Survey has developed a HFM as part of numerical simulation of ground-water flow of the Death Valley regional ground-water flow system (DVRFS), which encompasses approximately 100,000 km^2 in southern Nevada and eastern California. Flow models have been constructed in part to evaluate the potential transport of radionuclides from underground nuclear weapon testing areas at the Nevada Test Site and possible future effects of the potential high-level nuclear waste repository at Yucca Mountain, Nevada.

Regional geologic elements in the DVRFS that change both laterally and vertically and exert considerable influence on the ground-water flow include: a) facies transitions in a Paleozoic miogeoclinal sequence; b) welding transitions and alteration zones in Tertiary volcanic rocks of the southwestern Nevada volcanic field; c) juxtaposition of clastic confining units and the regional Paleozoic carbonate aquifer during Mesozoic thrusting and further structural disruption by Tertiary extensional and strike-slip faults; d) faults that may themselves act as barriers or conduits to fluid flow; and e) presence of complex stratigraphic variations in Tertiary basins. To understand the ground-water flow in this system, it is necessary to reproduce the geologic complexity of this region using a relatively sophisticated digital HFM.

Every geologist uses and constructs three-dimensional models, at least mentally. Cross sections, fence diagrams, and block diagrams are traditional tools that geologists use to portray 3D relationships of geologic units and develop a conceptual understanding of the system to be modeled. Acquired field data are a mixture of quantitative and qualitative information and include: 1) the geometry of stratigraphic units and structures in two and three dimensions; 2) the 3D distribution of material properties; and 3) time-related data, such as the sequence of events, unit superposition, or hierarchy of faulting.

Data gathered for subsurface modeling of the DVRFS include geologic maps and cross sections, regional structural and lithostratigraphic facies analyses, geophysical investigations and lithologic data from boreholes. Derivative interpretive geologic products, such as maps of unit extents, stratigraphic and structural hierarchy, and zone maps of material properties, provide additional information for the construction of the HFM and bridge the gap between basic geologic data input and the needs of framework and ground-water flow models.

A three-dimensional HFM serves as means to quantify, analyze and visualize a conceptual model of a natural system, integrate and extrapolate field data, and feed 3D spatial and property information into a process model. 3D geologic modeling software combines the elements geologists need to construct and analyze a three-dimensional model: a spatial 3D database, analytical capability, and mapping and graphic display. Conceptual and digital models of the hydrogeologic framework must describe, in simplified form, the surficial and subsurface stratigraphy, lithology, structural geometry, heterogeneity, and fabric.

The DVRFS HFM is used to integrate, manage, and store hydrogeologic data for a numerical ground-water flow model being developed for the region. The 3D HFM for the DVRFS was constructed using mixtures of quantitative geologic data, interpretations based on quantitative data, and qualitative, tacit geologic knowledge. Interpolated surfaces are created from these "data" and then "stacked" in geologic or stratigraphic modeling software to create volumetric units (figure 1). Attributes stored in these units include lithology, unit properties (such as facies zones), unit top elevation, and unit thickness. From these attributes, users can develop flow model input arrays describing the geometry of the hydrogeologic units.

Successive iterations of framework improvements bring the digital product closer to the conceptual model. This has been achieved primarily through improved data inputs and increased number of hydrogeologic units. Improved data inputs included the construction of regional-scale geologic cross sections specifically commissioned for this work using a consistent set of geologic and hydrogeologic units and a consistent structural style. Often more than one geologic conceptual model may honor all available data. Because the task of building a digital 3D framework model is labor-intensive and technically difficult, it is usually not possible to construct 3D frameworks to test all possible conceptual models.

The results of a first-generation flow model for the DVRFS guided construction and modifications to the HFM. The HFM was re-examined in areas where differences between measured and simulated water levels were great. In several cases, problems in the flow model identified places where modifications to the geologist's conceptual model and to the HFM would aid in flow model calibration. For example, a geologic barrier to flow was necessary to calibrate the flow model in an area of steep hydraulic gradient. The HFM initially contained only a partial barrier to flow. Geologic data were re-examined and found to allow a modification to the HFM that increased the effectiveness of the barrier. Modifications to the HFM were made on the basis of geologic data; arbitrary changes to simply allow flow model calibration were not made. A flow model that reasonably simulates the hydrology of the region suggests that the geometry and properties depicted within the HFM are consistent with another external dataset not used in framework model construction. In this way, the flow model partially validates the HFM.

In general, the HFM successfully depicts a highly complex system that meets the needs of a variety of user groups such as the Department of Energy (for both the Nevada Test Site and Yucca Mountain), the National Park Service, and growing urban areas within the study area. The HFM, however, is not a perfect representation. The HFM was built to serve the needs of the regional groundwater flow model. As a result, the relatively coarse discretization (1500-meter cells) misses thin and small units and structures. Because faults could not be explicitly represented in the flow model, they were not depicted explicitly as surfaces in the HFM. Instead, faults in the HFM appear as abrupt elevation changes in the gridded surfaces that represented the tops of the offset hydrogeologic units; barriers to flow were added separately to the groundwater flow model.

In any modeling effort, we must meet the requirements of the users and the planned end use. In cases such as the DVRFS, accurate simulation of a highly complex system required expensive, sophisticated programs. In other applications, or where less complex systems are being simulated, the techniques of quantifying a conceptual model (necessary for flow modeling) and integrating field data (both real and tacit) are available with less sophisticated software that are appropriate for the task (figure

2). The techniques used to build the DVRFS HFM can be adapted to build definitions of the hydrogeologic framework that serve as a means to analyze the conceptual model, integrate data, and feed information into a process model.

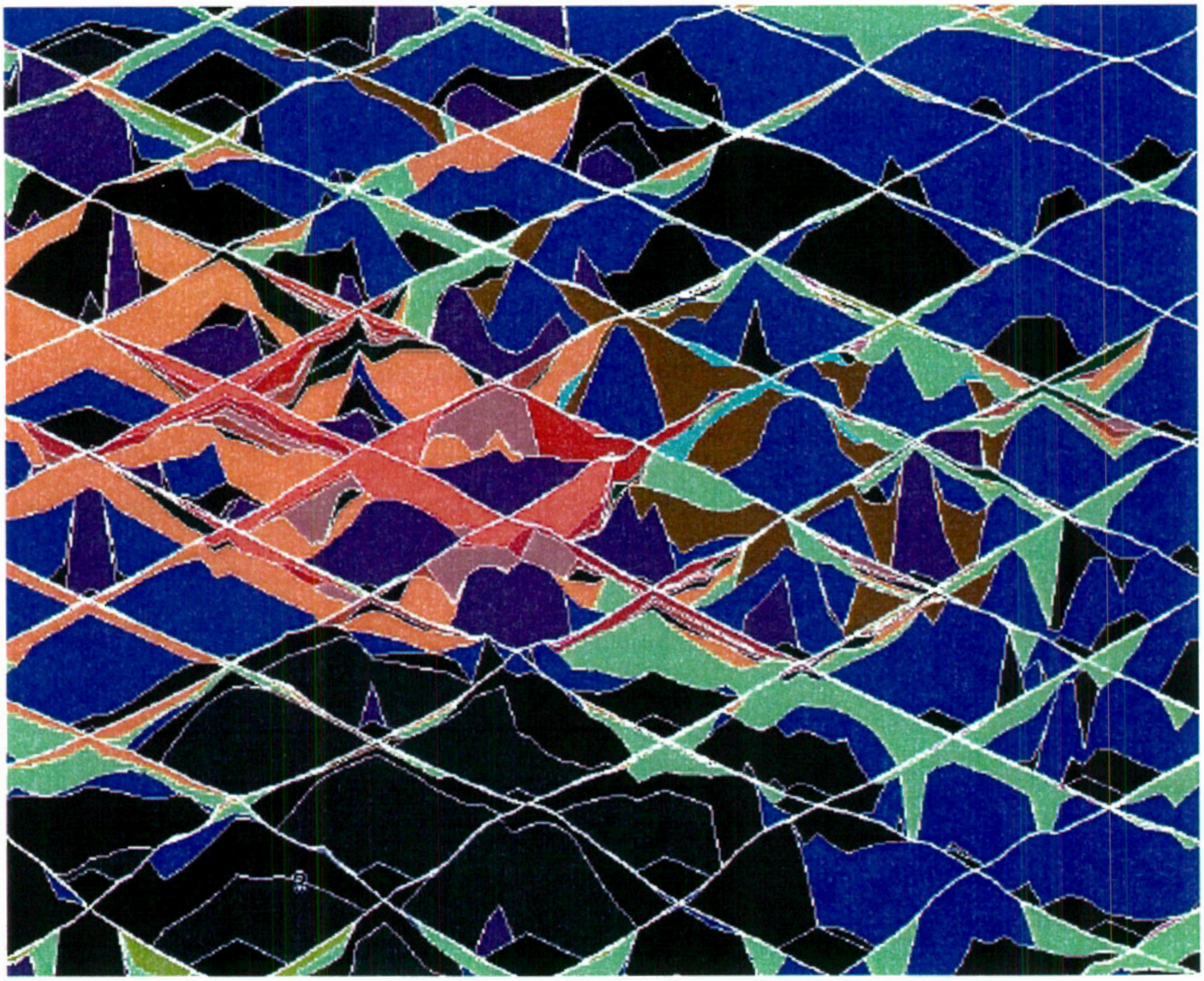

Figure 1. Vertical north-south and east-west slices through the three-dimensional hydrogeologic framework model of the Death Valley regional flow system. North is to the upper left corner of the figure. Slices are spaced every 15 km and extend to a depth of 4 km below sea level. Vertical exaggeration is approximately 4:1. Orange and red colors represent volcanic rocks, light green represent Tertiary basin-filling sedimentary rocks, blues represent Paleozoic carbonate rocks, dark colors represent Paleozoic and older siliciclastic and metamorphic rocks.

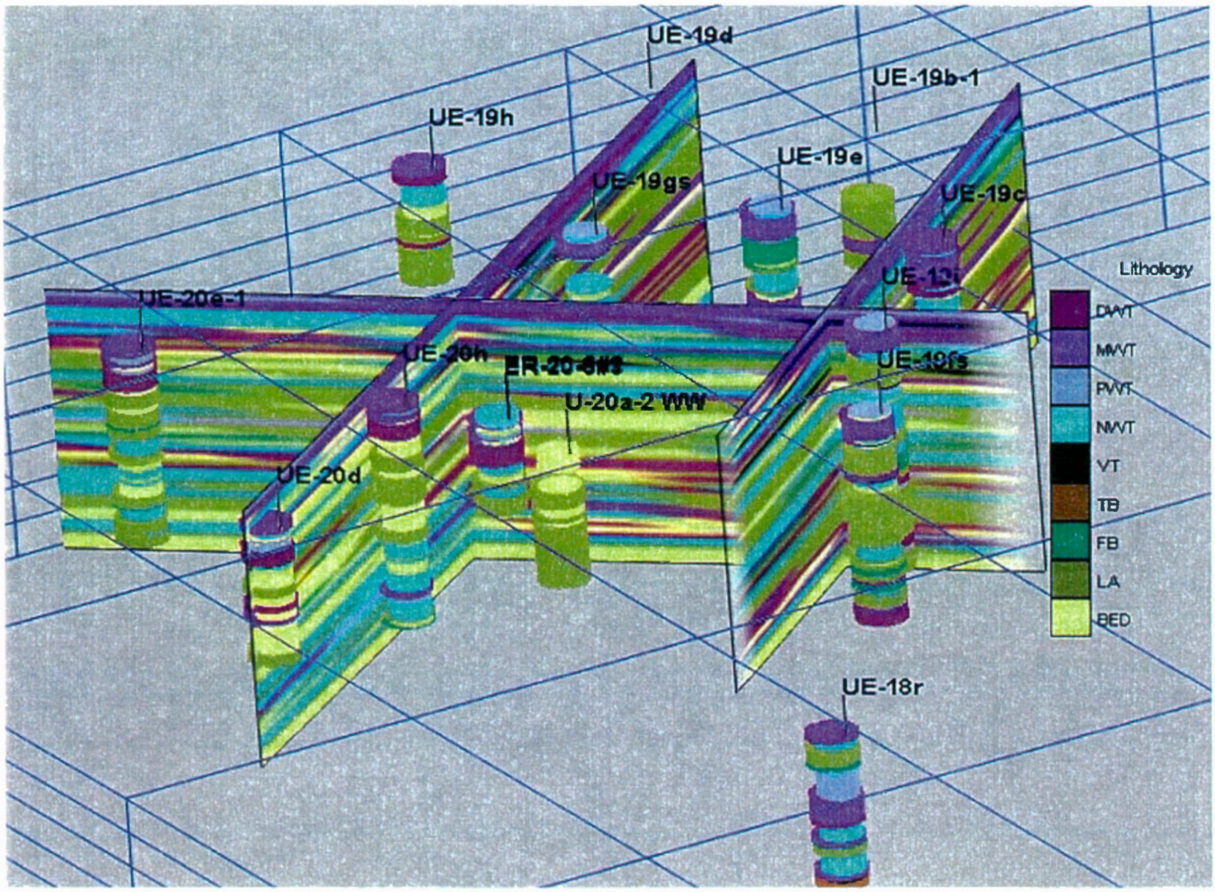

Figure 2. Example of 3D properties distribution created with inexpensive software. Vertical panels are slices through a three-dimensional rock properties model of volcanic rocks in a portion of the Death Valley regional flow system. Borehole data from which model was created are shown. Thin blue lines are oriented parallel to north-south, east-west and horizontal; north is to the upper left corner of the figure. The northwest-southeast section is 18 km long; vertical exaggeration is about 1.5:1. Colors represent lithologic and welding variations in the Tertiary volcanic rocks of Pahute Mesa, Nevada: DWT, densely welded tuff; MWT, moderately welded tuff; PWT, partially welded tuff; NWT, nonwelded tuff; VT, vitric tuff; TB, tuff breccia; FB, flow breccia; LA, lava flow; BED, bedded tuff.

Construction of a geological model for southern Manitoba for groundwater modelling

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Most of the one million inhabitants of Manitoba, Canada, live in the 400-km x 700-km area of Phanerozoic terrane adjacent to North Dakota and Minnesota, and the majority live in the Winnipeg area, a 200 km x 230 km area in the southeastern corner of the province. The City of Winnipeg obtains water from Shoal Lake, but the 200,000 residents of surrounding areas rely on groundwater from bedrock aquifers. Fresh water in these aquifers consists of modern recharge and relict subglacial recharge, but a saline water system recharged in South Dakota and Montana discharges to the western Red River valley. Research on the long-term sustainability of the fresh groundwater resource is addressing protection of recharge, and ensuring that excessive pumping does not lead to unacceptable lateral migration of the saline waters. Groundwater modelling is a key element of this strategy. The first phase of work involved construction of a pilot model for the Winnipeg area, and the geological model for this area has now been successfully used for groundwater flow modelling by P. Kennedy, under the supervision of A. Woodbury (Kennedy, P. L. 2002: Groundwater flow and transport model of the Red River/Interlake area in southern Manitoba; University of Manitoba Ph.D. thesis, 273 pp). Having completed the pilot model, work is now underway to build a 3D geological model of the entire Phanerozoic succession of southern Manitoba, including reconciliation with the stratigraphy of Saskatchewan, North Dakota, Minnesota, and Ontario. Having found readily available digital elevation models (DEMs) to be inadequate, a new digital elevation model was constructed by the authors, largely from Provincial legal survey data*. The resulting model has a grid resolution of 100 m, absolute vertical accuracy of about +/- 3 m, and relative accuracy of less than a metre. The DEM has been used to position drillholes vertically, the geological model hangs from the topography, and the DEM has provided insight into previously unrecognized geological features. Large lakes occur in the area, including Lake Winnipeg, which is 25% larger than Lake Ontario. These are key features in the hydrological landscape, and lake-bottom features provide insights into geology. Soundings from 22 hydrographic charts therefore were digitized and a database containing 31,607 digitized bathymetry points was created. These were gridded with shoreline data and locations of shoals, at a grid resolution of 100 m. Offshore geology of Lake Winnipeg is being interpreted from geophysical and coring data collected during two one-month cruises. Surficial geological maps are being digitised and reconciled as a guide to 3D modelling of the uppermost strata, and efforts are underway to better utilize soil mapping. The subsurface geological model is not directly linked to the surficial map polygons, due to the greater detail of the surficial geological mapping. Key inputs to the 3D model of the sediments were cored holes logged by geologists, and geophysical surveys. These high-quality results were extrapolated laterally using water well data from 80,000 sites (Figure 1; Figure 2). The 200 km x 230 km Winnipeg pilot area was divided into 46 transects each 5 km wide, and a large colour chart was printed for each transect, showing all drillhole data, surficial geology, and surface elevation. The drillhole data were correlated lithologically (Figure 3) and the correlation was digitised as predicted stratigraphy points at a 5-km spacing, which were then gridded. A new set of 1:1 million bedrock polygons for the Phanerozoic units was constructed, linking outcrop to subcrop, to produce stacked polygons. Structure contours for each Phanerozoic unit were then gridded. Experimentation presently underway is meant to optimize methods for model construction, verification, and communication.

*http://www.gov.mb.ca/itm/mrd/geo/demsm/index.html

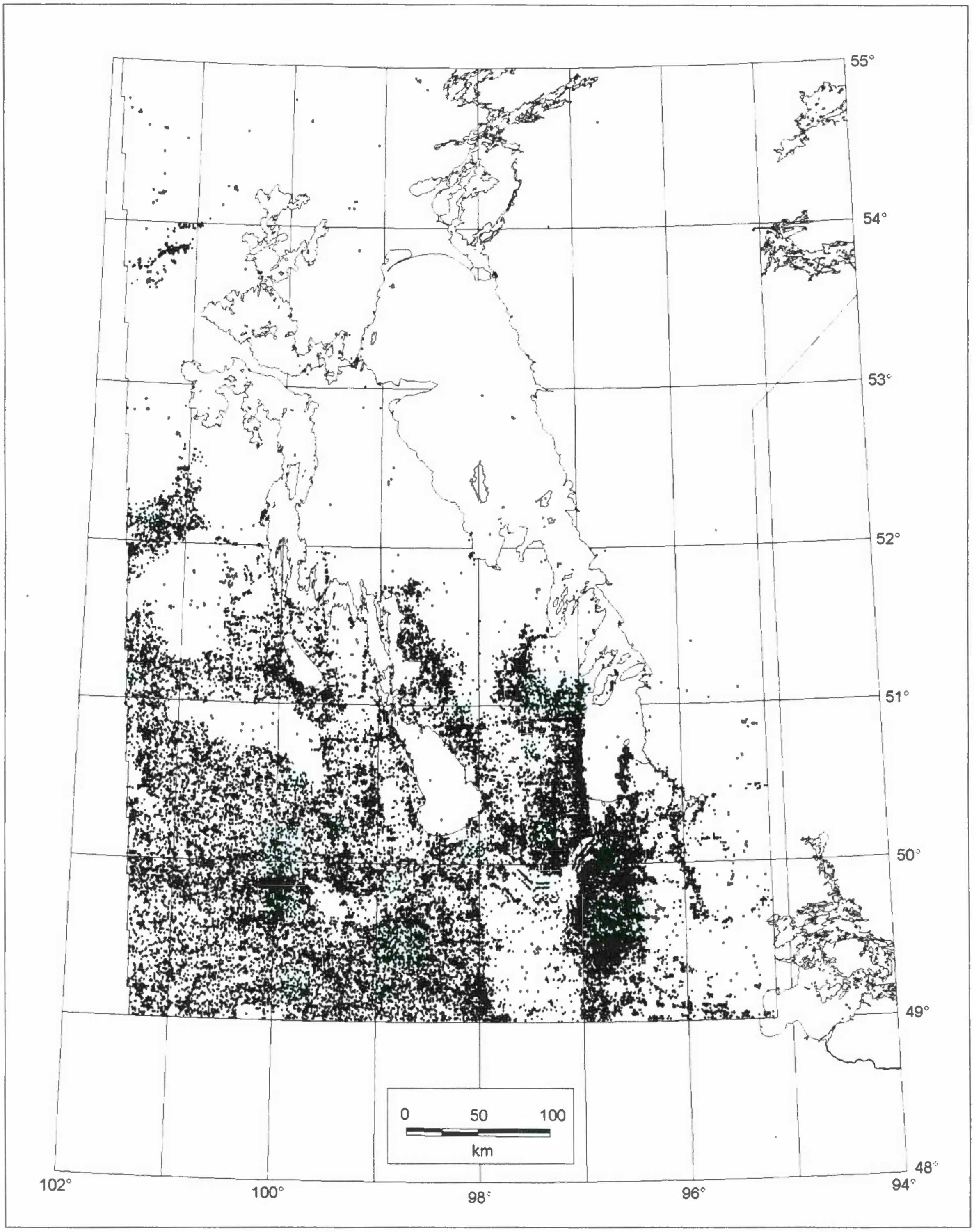

Figure 1. Location of water well data in southern Manitoba.

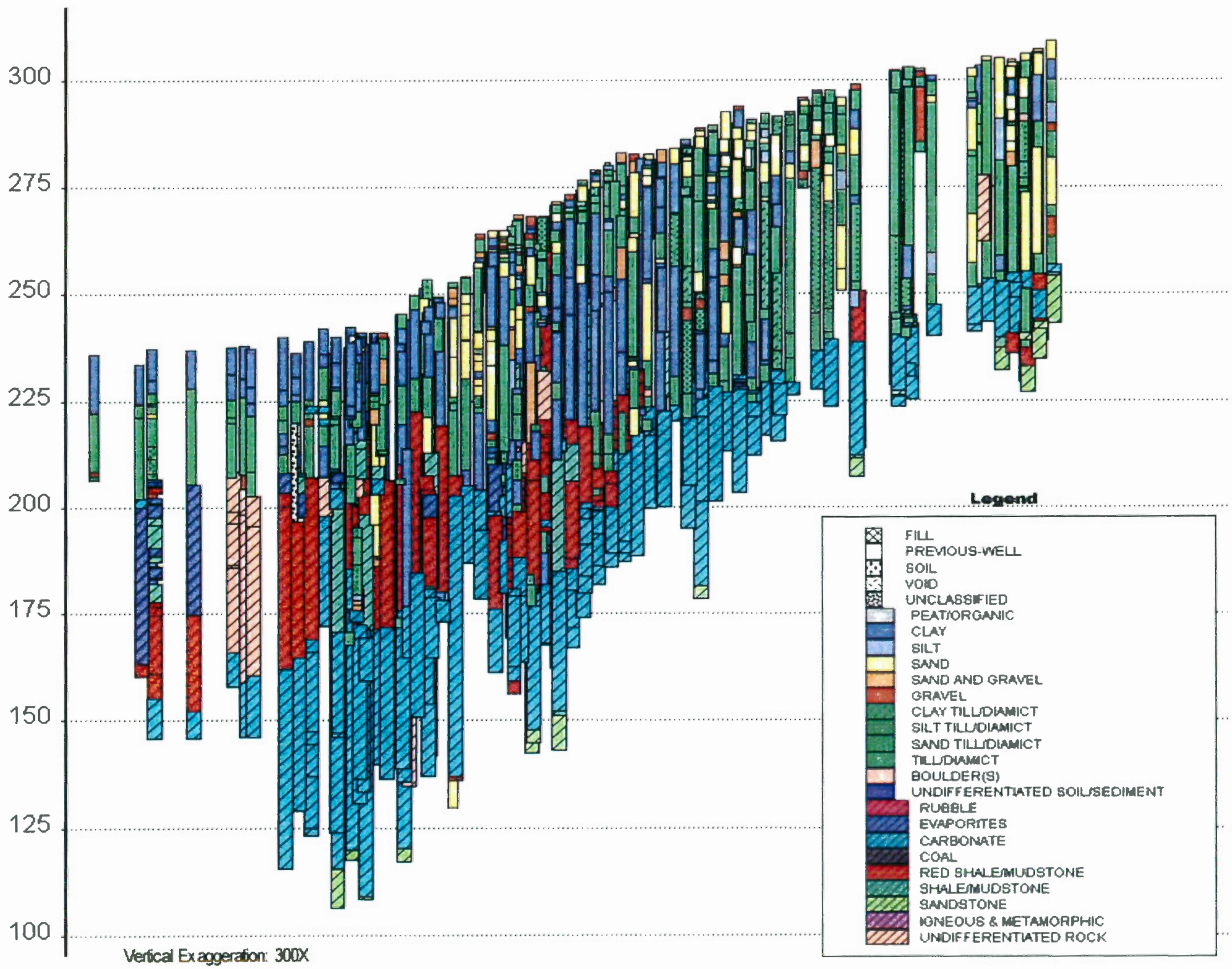

Figure 2. A portion of the drillhole data scatterplot for the 5 km swath shown in Figure 3; vertical scale in m asl, horizontal scale 75 km.

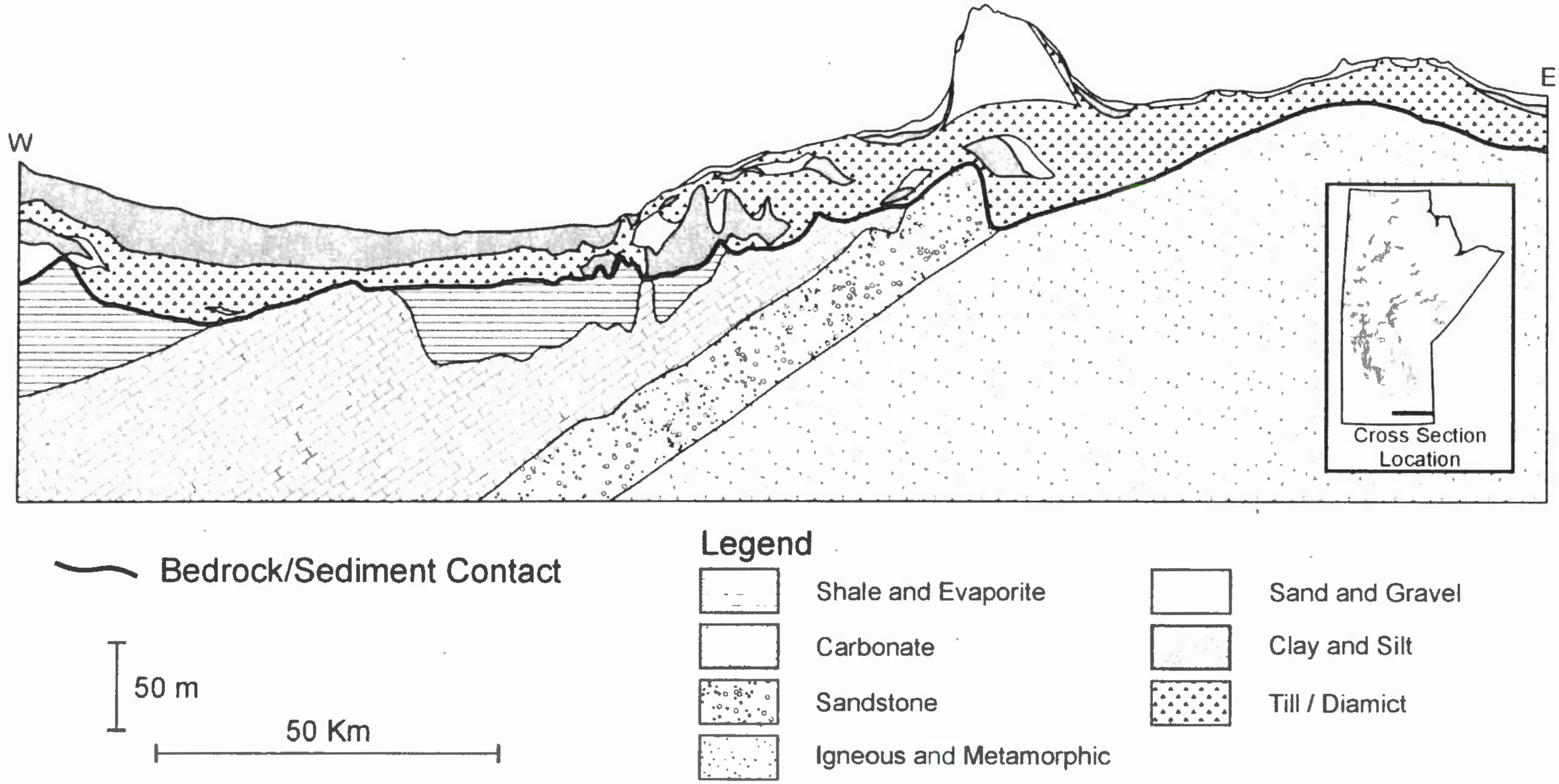

Figure 3. One of the 46 interpreted sections for the Winnipeg pilot area.

A geophysical investigation into the lithology and stratigraphy of the Mahomet Buried Valley, Piatt County, IL

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P-wave profiles, S-H wave profiles, vertical seismic profiles (VSP), gamma logs, well logs, and borehole cores were compiled to produce a complete stratigraphic section of the buried Mahomet Valley aquifer system in Piatt County, IL. The Illinois Board of Higher Education supported this collaborative project between scientists from Illinois State Geologic Survey (ISGS) and faculty and students at Illinois State University (ISU).

Preliminary results from a series of six shear wave and five P-wave seismic profiles, two borehole cores, and well log data support the results of earlier investigations of the Quaternary glacial stratigraphy of the area. Wisconsinan and Illinoian tills overlie pre- or early-Illinoian sands and gravels. The sands and gravels present within the valley and its major tributaries compose the Mahomet aquifer and are part of the Mahomet Member, Banner Formation. The Mahomet Member overlies Pennsylvanian strata. The availability of borehole logs directly along geophysical lines enables a "ground-truth" of geophysical interpretations.

Allerton 3 (Figure 2) was drilled to a depth of approximately 59 meters and was terminated in the Mahomet Sand Member. The first lithological unit encountered is approximately 18 meters thick and is composed of gray to brown diamicton. A mottled dark organic layer, which is 15 centimeters thick, is present at a depth of 20 meters. Below this dark organic layer 4.9 meters of dark gray diamicton is present. This small interval of diamicton is lithologically very similar to the overlying gray diamicton. Below this unit three closely spaced layers of dark organic material and green organic material are present. The thickest is 15 centimeters in thickness. The till below this interval is brown to gray and is less massive than the overlying diamicton. The lower 22 meters of till contains abundant wood fragments. At approximately 29 meters, a dark brown silt-clay contains small shell fragments. Below this less massive diamicton lies (depth of 53 meters) a brown, medium to fine grained, well-sorted sand.

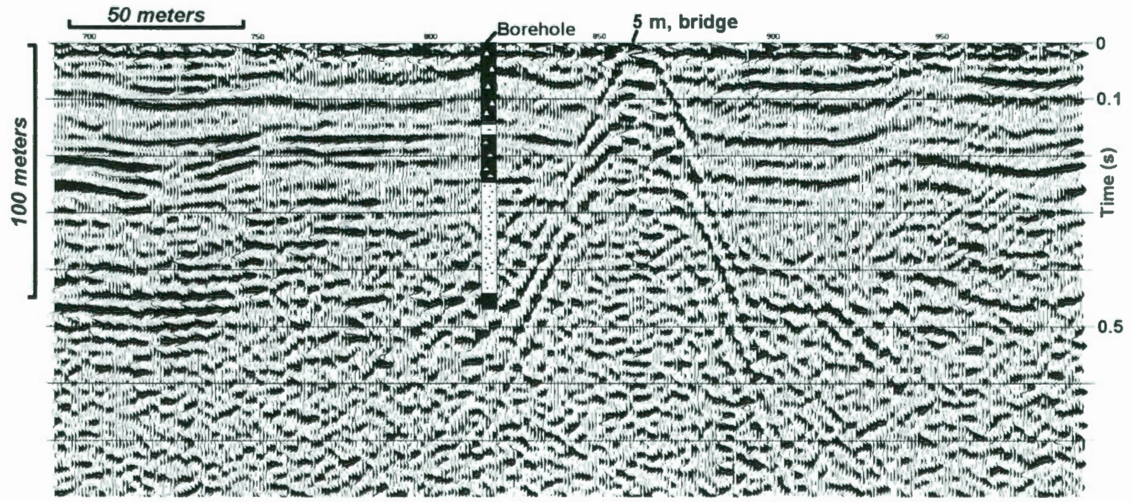
Allerton 4 (figure 3) was drilled to a depth of 99.5 meters and was terminated in a greenish gray mudstone. The lithology of the diamicton units in Allerton 4 is very similar to Allerton 3. Three major lithological differences can be identified from Allerton 4 in comparison to Allerton 3. These include the presence of a thick silt bed, a thin peat bed, and a complete sand unit. A gray silt occurs at a depth of 24 meters. This silt is at least 0.6 meters thick but could be as much as 0.9 meters thick. A 15-centimeter bed of peat, which was not found in Allerton 3, lies within the upper portion of the gray diamicton unit. The sand is approximately 45 meters thick (complete thickness) and contains sand with interbedded gravel deposits. The sand varies from fine to coarse grained, poorly to well sorted, and in angular to well rounded. At a depth of approximately 98 meters a silt-clay bed (0.8 meters thick) contains shell fragments and may indicate a fluvial deposit.

The Wedron Group is the uppermost unit formation in the area and consists of diamicton interbedded with minor sand and gravel layers. The Wedron ranges from 20-30 meters in thickness and extends laterally over the entire area except for portions of the Sangamon River floodplain. The diamicton varies in color from brown to gray and may include dark organic layers near its base. A dark brown to black clay (Robein or Roxana Loess) layer is underlain by green clay (Sangamon Soil Horizon) and distinguishes the Wisconsinan from the underlying Illinoian strata. The green clay and the loess are present in some areas. The heterogeneity of the contact is reflected in borehole logs (Figures 2 and 3).

The Illinoian sediments, which are approximately ranges from 18-33 meters in thickness, consists of gray diamicton interbedded with gravel, sand, and silt layers. Organic matter including wood and shells are also present in some intervals.

The pre- or early-Illinoian Mahomet Sand Member, (0-50 meters thick), consists of fine to coarse-grained lithic sand with interbedded with pebbles and gravel. The sand, pebbles, and gravel are all sub-rounded to rounded and vary from poorly sorted to well sorted. The Mahomet Sand Member is thickest in the center of the channel and thins along its margins into the tributaries.

The contact between the Wisconsinan and Illinoian units is difficult to pick using only one borehole log. By correlating the two boreholes along with geophysical data (Figure 1), a more confident interpretation can be made. Allerton 4 was used to correlate the geophysical record to the borehole data. This borehole was drilled almost directly on the line itself. Close inspection shows strong reflections along the horizons that were picked between the Wisconsinan till and Illinoian till, as well as between the Illinoian till and the Mahomet Sand Member. The division between the Mahomet Sand and bedrock is not as apparent, however the bedrock is composed of shale and the loss of reflection is an indicator of bedrock penetration.



SH-wave section, Mahomet buried valley, Allerton Park, Illinois

Figure 1.

Allerton 3

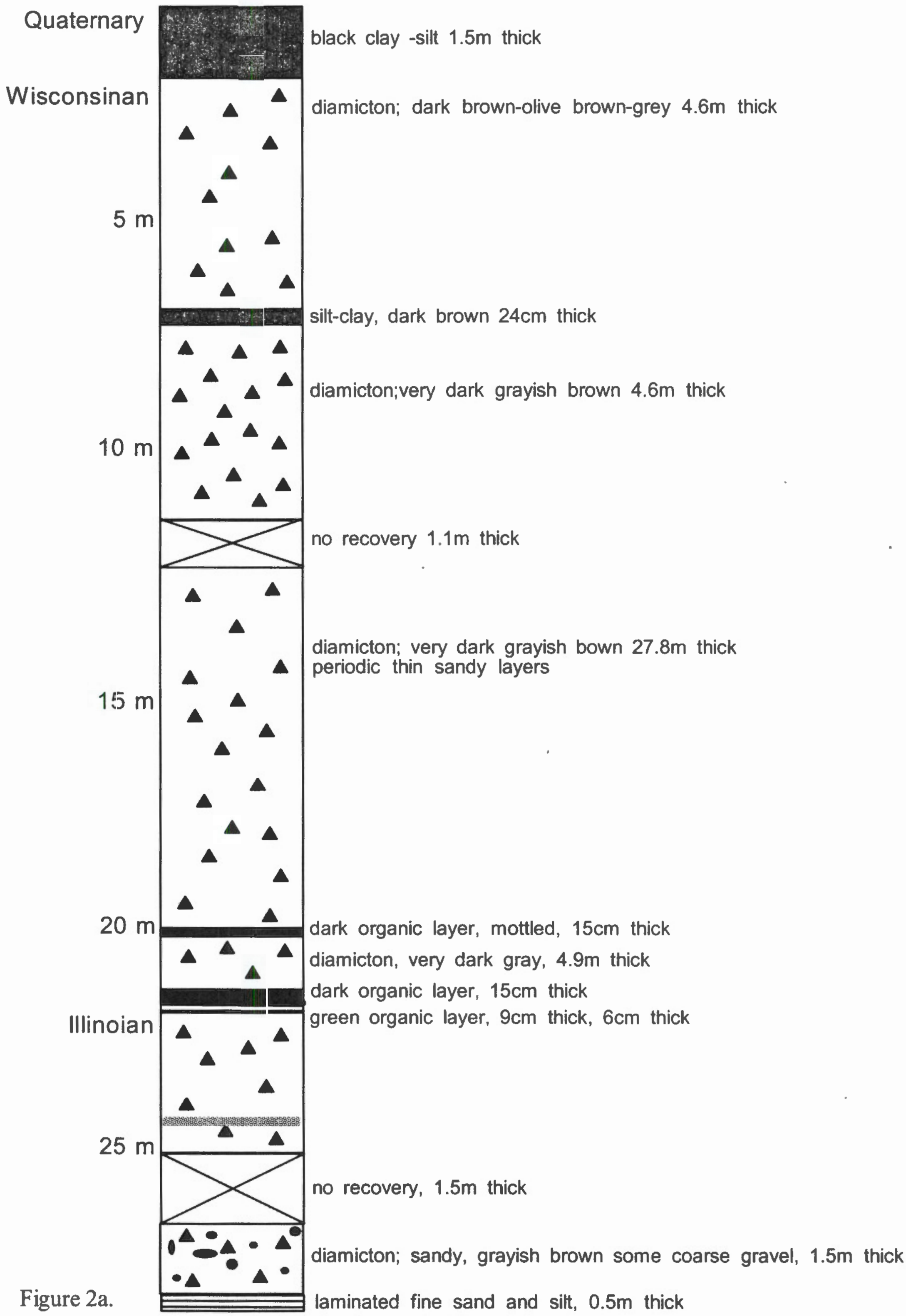
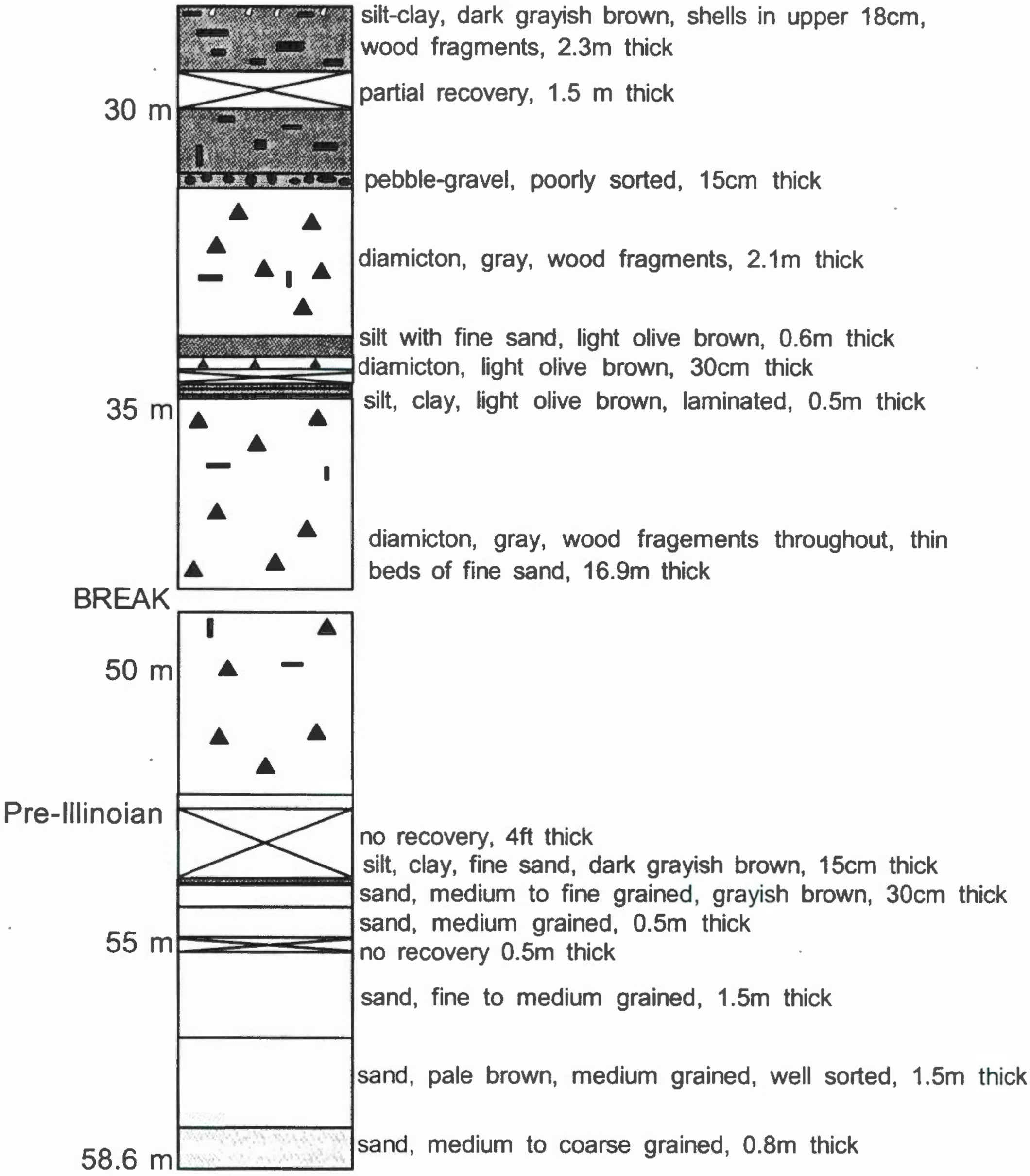


Figure 2a.



silt-clay, dark grayish brown, shells in upper 18cm, wood fragments, 2.3m thick
partial recovery, 1.5 m thick
30 m
pebble-gravel, poorly sorted, 15cm thick
diamicton, gray, wood fragments, 2.1m thick
silt with fine sand, light olive brown, 0.6m thick
diamicton, light olive brown, 30cm thick
silt, clay, light olive brown, laminated, 0.5m thick
35 m
diamicton, gray, wood fragements throughout, thin beds of fine sand, 16.9m thick
BREAK
50 m
Pre-Illinoian
no recovery, 4ft thick
silt, clay, fine sand, dark grayish brown, 15cm thick
sand, medium to fine grained, grayish brown, 30cm thick
sand, medium grained, 0.5m thick
55 m
no recovery 0.5m thick
sand, fine to medium grained, 1.5m thick
sand, pale brown, medium grained, well sorted, 1.5m thick
sand, medium to coarse grained, 0.8m thick
58.6 m

Figure 2b.

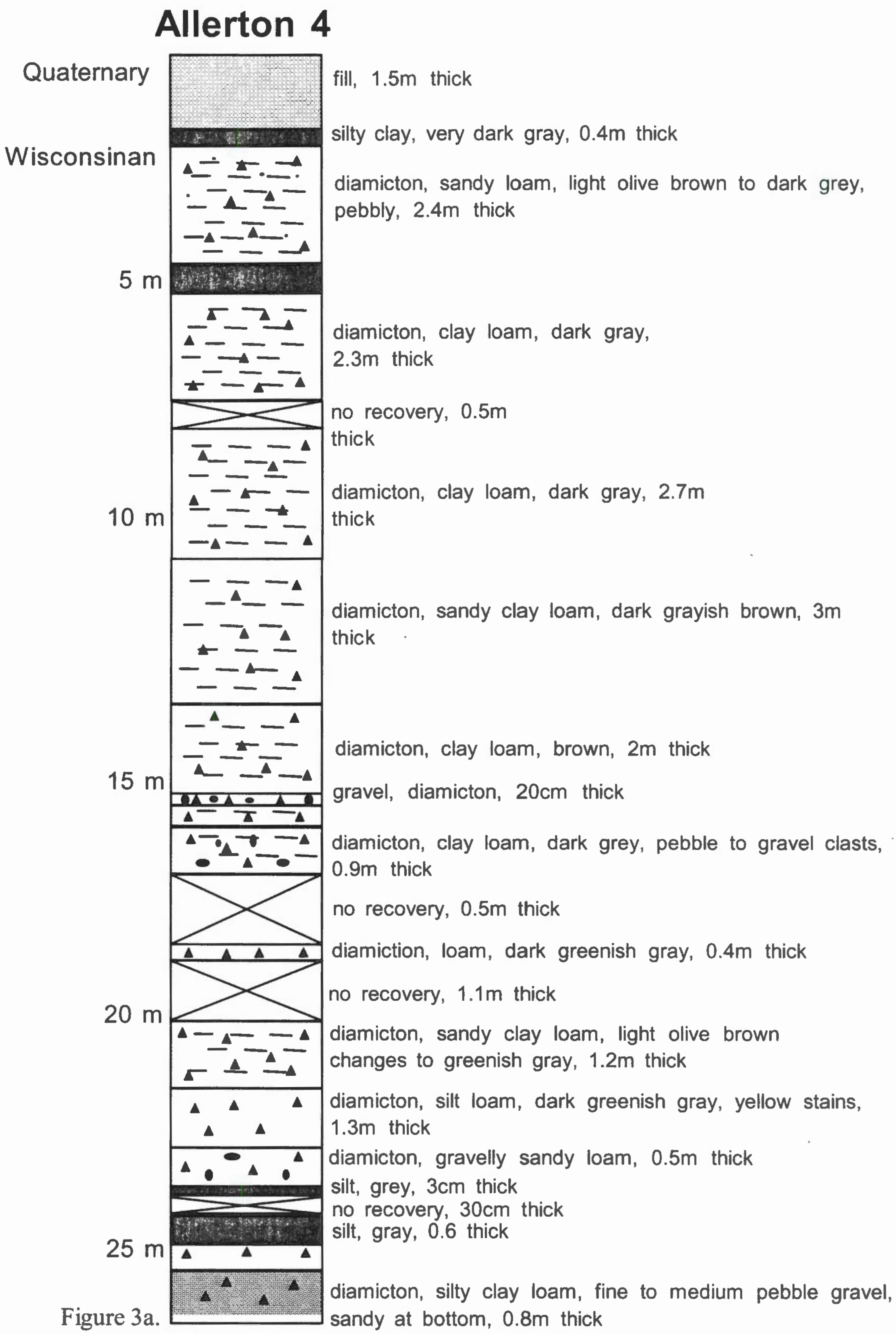

Allerton 4
Quaternary
Wisconsinan
fill, 1.5m thick
silty clay, very dark gray, 0.4m thick
diamicton, sandy loam, light olive brown to dark grey, pebbly, 2.4m thick
5 m
diamicton, clay loam, dark gray, 2.3m thick
no recovery, 0.5m thick
diamicton, clay loam, dark gray, 2.7m thick
10 m
diamicton, sandy clay loam, dark grayish brown, 3m thick
diamicton, clay loam, brown, 2m thick
15 m
gravel, diamicton, 20cm thick
diamicton, clay loam, dark grey, pebble to gravel clasts, 0.9m thick
no recovery, 0.5m thick
diamiction, loam, dark greenish gray, 0.4m thick
no recovery, 1.1m thick
20 m
diamicton, sandy clay loam, light olive brown changes to greenish gray, 1.2m thick
diamicton, silt loam, dark greenish gray, yellow stains, 1.3m thick
diamicton, gravelly sandy loam, 0.5m thick
silt, grey, 3cm thick
no recovery, 30cm thick
silt, gray, 0.6 thick
25 m
diamicton, silty clay loam, fine to medium pebble gravel, sandy at bottom, 0.8m thick

Figure 3a.

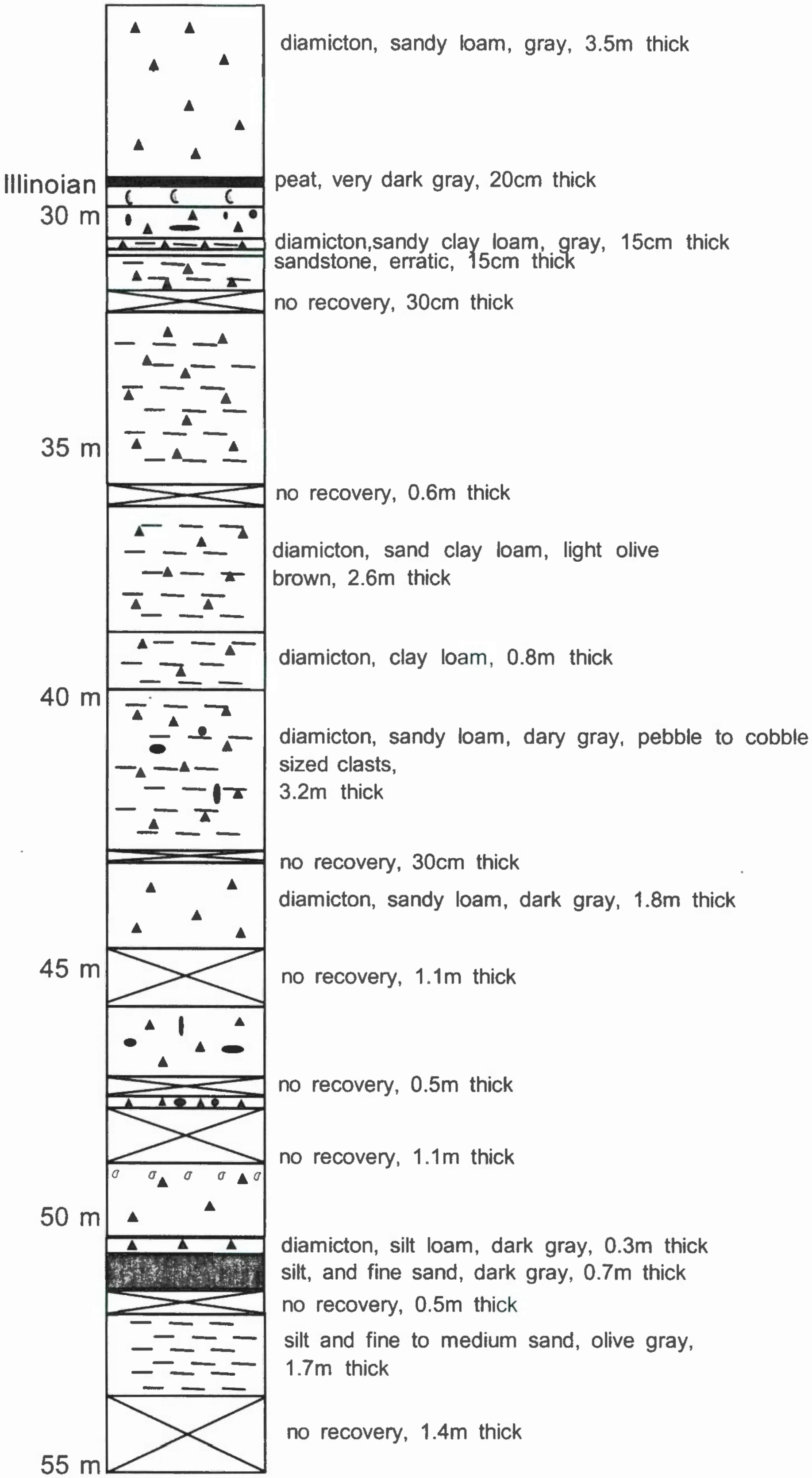

Illinoian
30 m
35 m
40 m
45 m
50 m
55 m
diamicton, sandy loam, gray, 3.5m thick
peat, very dark gray, 20cm thick
diamicton,sandy clay loam, gray, 15cm thick
sandstone, erratic, 15cm thick
no recovery, 30cm thick
no recovery, 0.6m thick
diamicton, sand clay loam, light olive brown, 2.6m thick
diamicton, clay loam, 0.8m thick
diamicton, sandy loam, dary gray, pebble to cobble sized clasts, 3.2m thick
no recovery, 30cm thick
diamicton, sandy loam, dark gray, 1.8m thick
no recovery, 1.1m thick
no recovery, 0.5m thick
no recovery, 1.1m thick
diamicton, silt loam, dark gray, 0.3m thick
silt, and fine sand, dark gray, 0.7m thick
no recovery, 0.5m thick
silt and fine to medium sand, olive gray, 1.7m thick
no recovery, 1.4m thick

Figure 3b.

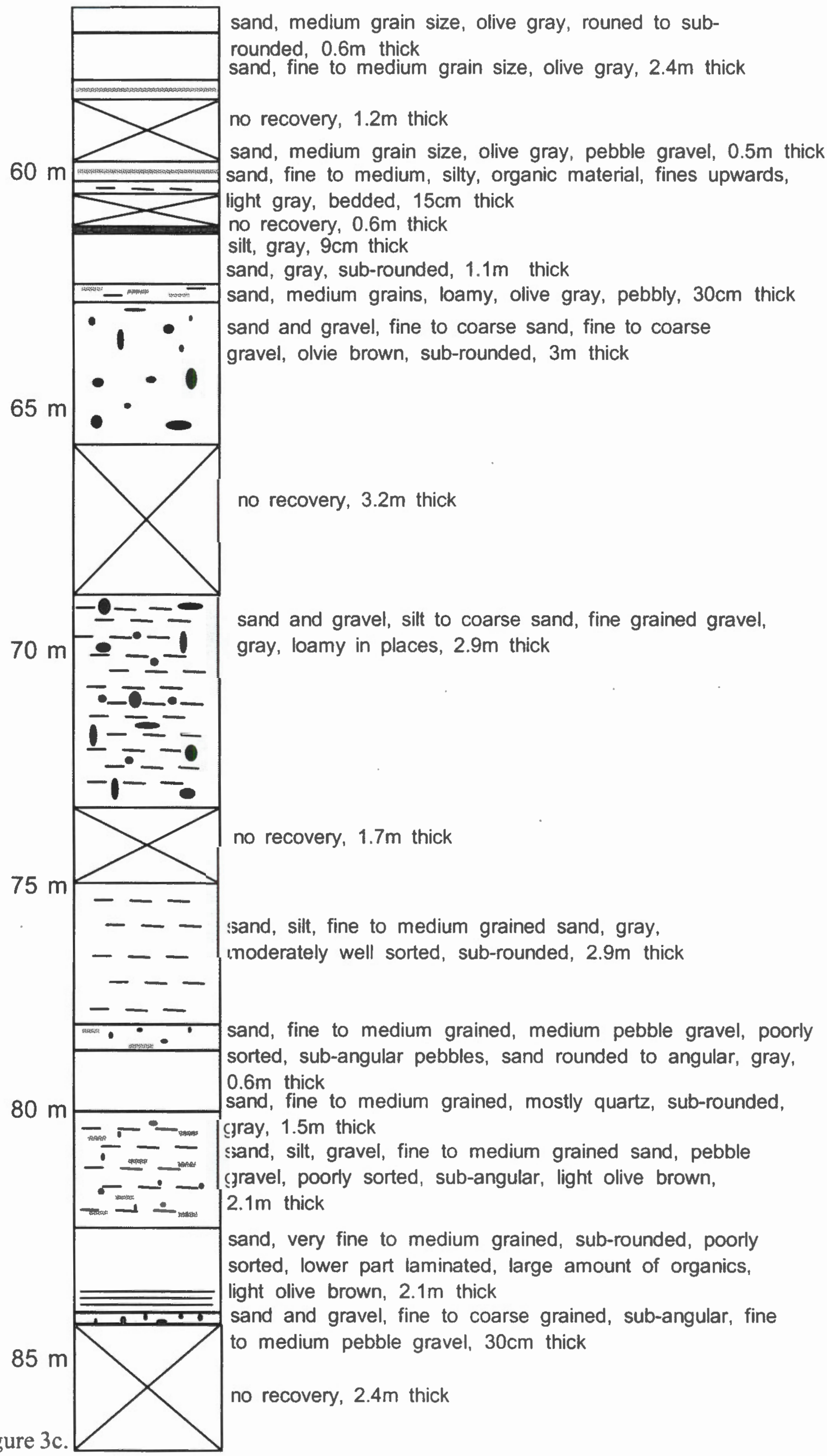

60 m
65 m
70 m
75 m
80 m
85 m
sand, medium grain size, olive gray, rouned to sub-rounded, 0.6m thick
sand, fine to medium grain size, olive gray, 2.4m thick
no recovery, 1.2m thick
sand, medium grain size, olive gray, pebble gravel, 0.5m thick
sand, fine to medium, silty, organic material, fines upwards, light gray, bedded, 15cm thick
no recovery, 0.6m thick
silt, gray, 9cm thick
sand, gray, sub-rounded, 1.1m thick
sand, medium grains, loamy, olive gray, pebbly, 30cm thick
sand and gravel, fine to coarse sand, fine to coarse gravel, olvie brown, sub-rounded, 3m thick
no recovery, 3.2m thick
sand and gravel, silt to coarse sand, fine grained gravel, gray, loamy in places, 2.9m thick
no recovery, 1.7m thick
sand, silt, fine to medium grained sand, gray, moderately well sorted, sub-rounded, 2.9m thick
sand, fine to medium grained, medium pebble gravel, poorly sorted, sub-angular pebbles, sand rounded to angular, gray, 0.6m thick
sand, fine to medium grained, mostly quartz, sub-rounded, gray, 1.5m thick
sand, silt, gravel, fine to medium grained sand, pebble gravel, poorly sorted, sub-angular, light olive brown, 2.1m thick
sand, very fine to medium grained, sub-rounded, poorly sorted, lower part laminated, large amount of organics, light olive brown, 2.1m thick
sand and gravel, fine to coarse grained, sub-angular, fine to medium pebble gravel, 30cm thick
no recovery, 2.4m thick

Figure 3c.

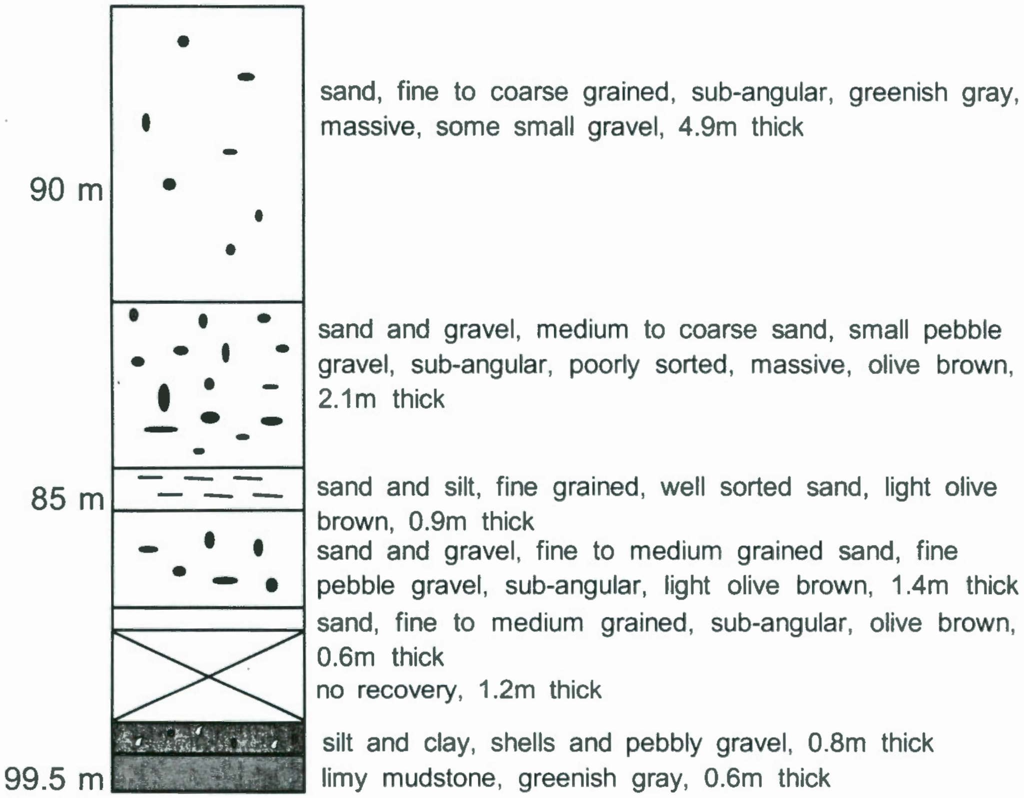

sand, fine to coarse grained, sub-angular, greenish gray, massive, some small gravel, 4.9m thick
90 m
sand and gravel, medium to coarse sand, small pebble gravel, sub-angular, poorly sorted, massive, olive brown, 2.1m thick
85 m
sand and silt, fine grained, well sorted sand, light olive brown, 0.9m thick
sand and gravel, fine to medium grained sand, fine pebble gravel, sub-angular, light olive brown, 1.4m thick
sand, fine to medium grained, sub-angular, olive brown, 0.6m thick
no recovery, 1.2m thick
silt and clay, shells and pebbly gravel, 0.8m thick
99.5 m
limy mudstone, greenish gray, 0.6m thick

Figure 3d.

Bayesian and maximum entropy inversion of highly heterogeneous aquifers

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The Bayesian inverse approach proposed by Woodbury and Ulrych (2000) is extended to estimate the transmissivity fields of highly heterogeneous aquifers for steady state groundwater flow. A first-order approximation of Taylor's series for the exponential terms introduced by sinks and sources or Neumann conditions in the governing equation is adopted. Such a treatment leads to a linear finite element formulation between hydraulic head and logarithm transmissivity [denoted as ln (T)] perturbations. The new inversion algorithm is examined against generic examples. It is found that the linearized partial difference equations yield acceptable head approximations for ln (T) variance up to 9 for the test case. The addition of the hydraulic head data is shown to improve the ln (T) estimates, in comparison to simply interpolating the sparse ln (T) data alone.

The Bayesian approach is subsequently applied to the calibration of the Edwards Aquifer. This aquifer is a highly heterogeneous karst aquifer located in south central Texas, and is the sole source of drinking water for more than one million people. Hydraulic conductivity (K) measurements in the Edwards Aquifer are sparse, highly variable (log-K variance of 6.4), and are mostly from single-well drawdown tests that are appropriate for the spatial scale of only a few meters. To support ongoing efforts to develop a groundwater management (MODFLOW) model of the San Antonio segment of the Edwards Aquifer, a multi-step procedure was developed to assign hydraulic parameters to the 402 m × 402 m computational cells intended for the management model. The approach used a combination of nonparametric geostatistical analysis, stochastic simulation, numerical upscaling, and automatic model calibration based on Bayesian updating. The posterior ln (T) field from this application yields a better hydraulic head fit when compared to the prior ln (T) field determined from upscaling and co-kriging. We believe that traditional MODFLOW grids could be imported into the new Bayes inverse code fairly seamlessly and thereby enhance existing calibration of many aquifers.